Pure Appl. Chem., Vol. 80, No. 3, pp. 659–667, 2008.
doi:10.1351/pac200880030659

A family of electron-triggered molecular motors based on aromatic building blocks*

Henri-Pierre Jacquot de Rouville, Guillaume Vives, and Gwénaël Rapenne‡

NanoSciences Group, CEMES-CNRS, 29 rue Jeanne Marvig, BP 94347, F-31055 Toulouse Cedex 4, France

Abstract: We present our strategy to control the rotation in a molecular rotary motor and the synthesis of a family of ruthenium complexes designed to perform such a task. The molecules have a piano-stool structure with a "stator" meant to be grafted on an oxide surface, and a "rotor" bearing redox-active ferrocene groups, so that addressing the molecule with nanoelectrodes would trigger rotation. The rigidity of the structure is allowed by the use of aromatic building blocks both in the stator and in the rotor fragments.

Keywords: molecular motors; ruthenium; ferrocene; half-sandwich complexes; platinum; bicyclo[2.2.2]octane; cyclopentadienyl; indazoles.

INTRODUCTION

In the quest for the miniaturization of molecular machines, molecules are expected to play a major role since multistep chemical synthesis allows chemists to prepare tailor-made compounds with predetermined shape and programmed movement or function. In the bottom-up strategy, artificial molecular machines and motors have recently emerged as a new field of chemistry related to a newly explored dimension of molecular sciences: controlled movement at the molecular scale [1]. This has stimulated the design and synthesis of a variety of compounds that resemble macroscopic machinery, for instance, nanowheels [2], nanocars [3], wheelbarrows [4], nanogears [5], or molecular motors [6].

A mono-molecular motor is a nanoscale machine which consumes energy to produce work via a unidirectional and controlled movement of one of its parts. Some very elegant examples of molecular rotary motors described so far have been studied collectively and have many degrees of freedom [6]. Their behavior is the average behavior of a weak assembly of molecules and not of a single molecule. Moreover, some examples of molecules designed, synthesized, and mounted on a surface for single-molecule experiments do not undergo a unidirectional rotation: their internal motion can in fact be seen as random oscillations around a given axis [7]. On the contrary, the molecules described here have been designed with the intention to study and manipulate them individually with the tip of a scanning tunneling microscope (STM). To recover the work produced by the rotation of the motor, its structure should be as rigid as possible and with a minimum of degrees of freedom in order to be manipulated on a surface with a maximum control on its movement. Recently, we presented the concept of an electrically fuelled, single-molecular rotary motor [8].

*Paper based on a presentation at the 12th International Symposium on Novel Aromatic Compounds (ISNA-12), 22–27 July 2007, Awaji Island, Japan. Other presentations are published in this issue, pp. 411–667.
‡Corresponding author

MOVEMENT OF ROTATION AT THE SINGLE-MOLECULAR SCALE

The ultimate miniaturization of electronic and mechanic devices is reached when addressing one single molecule and not a population of molecules in solution or on a surface. Therefore, operating at the single-molecular level is more important than working at the molecular scale. For mono-molecular machines in general and more specifically for a molecular rotary motor, the major difficulties concern not only the delivery of the required driving energy to a single and always the same molecule, but also the control of the directionality of the rotation [9] and at the same time bringing to the observer experimental information about the exact motion, distortion, or conformational change of the molecule during the experiment.

In the absence of direct time-resolved microscopy to provide an image of the real intramolecular motion or movement of a mono-molecular machine, one has to record those changes via tunnelling current variations [10] or a change in forces using a non-contact atomic force microscope [11]. In both cases, this puts constraints on the molecular design in order to simplify or amplify this recording and the way it is reported to the macroscopic scale.

DESIGN OF AN ELECTRON-TRIGGERED MOLECULAR MOTOR

Looking in more detail at the requirements for true unidirectional rotation, several difficulties can be identified. First, the molecule must be made of two essentially rigid parts. This requirement is frequently absent in many prototypes of molecular motors, which neglect the extreme flexibility of most molecules. In our design of a molecular motor [8a], the source of energy is a tunnel current. Our target molecule is supposed to convert the flow of electrons tunnelling through the molecule into a directionally controlled rotary motion. The molecular motor has been designed to be individually interconnected after its deposition to an *N*-electrode tunnel junction whose nanoelectrodes are separated by a few nanometers. The concept of our electron-fuelled molecular rotary motor is shown in Fig. 1.

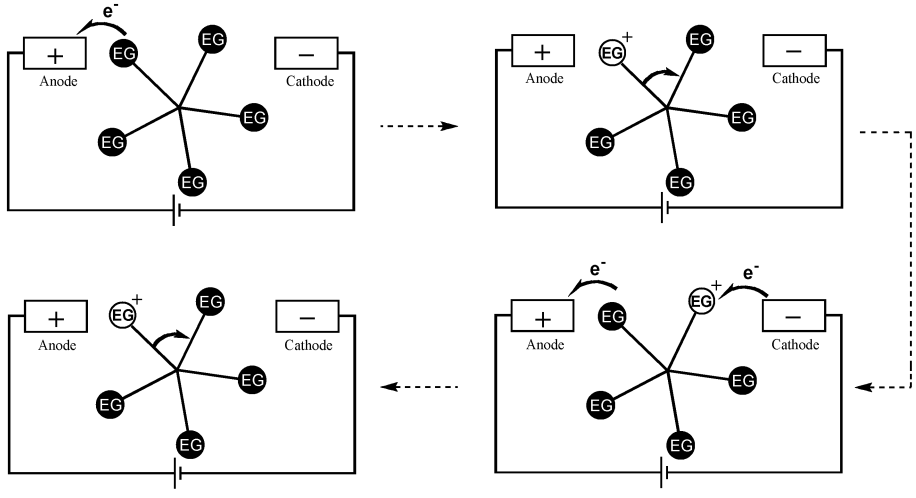
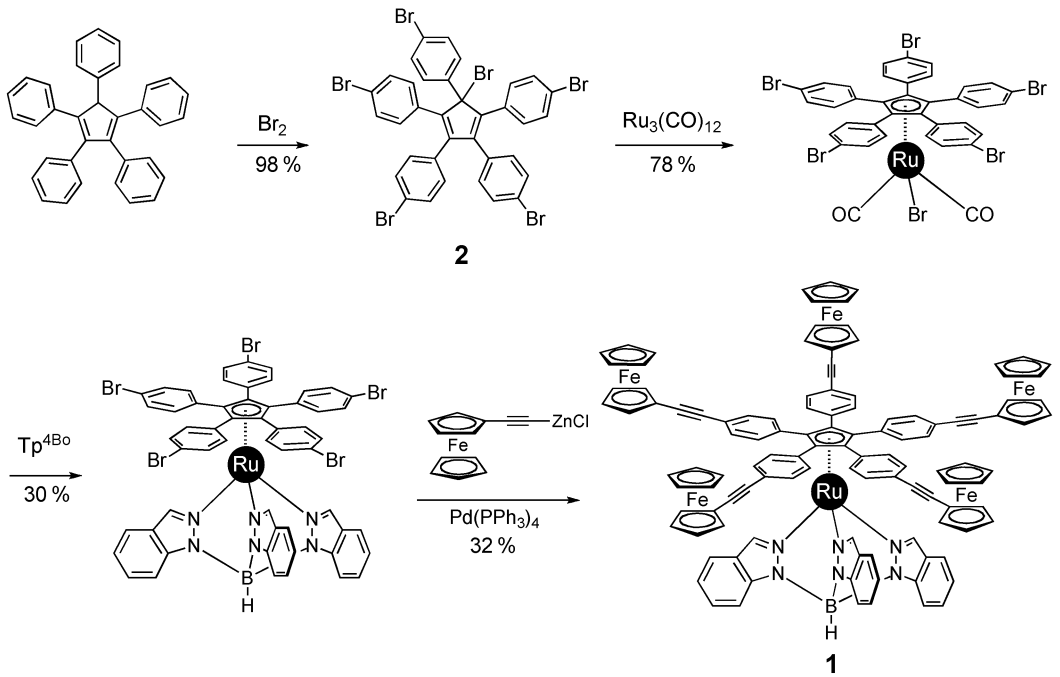


Fig. 1 Schematic representation of a molecule placed between the two electrodes of a nanojunction (EG stands for electroactive group). The transfer of electrons from the cathode to the anode through successive oxidation and reduction processes is expected to result in the clockwise rotation of the entire upper part of the molecule. In this figure, a fifth of a turn, corresponding to the movement induced by the transition of one electron, is represented.

The electroactive group (EG) closest to the anode would be oxidized (oxidized form EG^+ in white) and pushed back by electrostatic repulsion like it has been shown for a [60]-fullerene between two electrodes [12]. This repulsion combined with the attraction by the cathode and the dissymmetry in the positioning of the molecule should help to obtain a unidirectional rotation. This motion corresponds to a fifth of a turn. As a result, the oxidized EG would approach the cathode and subsequently be reduced. At the same time, a second EG would come close to the anode and a second cycle would occur. A complete 360º turn would be achieved after five cycles, corresponding to the shuttling of five electrons from the cathode to the anode. This would represent the conversion of an electron flow into a movement of rotation, i.e., a redox-triggered molecular rotary motor by the irreversible transport of electrons from the negative to the positive electrode through a tunnel junction. In order for the rotation to be directional, the molecule should be placed in a dissymmetrical environment. This could be achieved either by its positioning in the nanojunction, or, for instance, by a secondary electric field applied perpendicularly to the nanojunction. The directionality is illustrated by the two senses of rotation which are not equivalent: this is clear in Fig. 1, as a result of the dissymmetric positioning of the molecule with respect to the electrodes, this arrangement being of course obtained by chance. To achieve directionality in the rotation, one could also think of introducing chirality either on the lower or the upper part. This is useful, but not sufficient: using the sole chirality for a movement driven only by thermal energy would overpass the second principle of thermodynamics [13].

The active part of our molecular motor (**1**) is represented on Scheme 1. It comprises a stator (i.e., one part fixed between two electrodes), and on this stator is connected a rotor which should transform a current of electrons into a unidirectional rotation motion. The rotor is a rigid aromatic platform constructed around a cyclopentadienyl ligand (Cp) with five linear and rigid arms, each terminated by an EG. As EG, ferrocene was selected because it exhibits reversible oxidation in various solvents [14]. The stator is a hydrotris(indazolyl)borate ligand of the family of scorpionates developed by Trofimenko [15].



Scheme 1 Synthetic scheme of the molecular motor. The lower ligand is the stator, and the upper ligand is the rotor with five ferrocene-terminated arms. The ruthenium plays the role of joint between the two ligands.

The joint between the rotor and the stator is a ruthenium(II) ion chosen to obtain a kinetically stable molecule bearing zero net charge. Both criteria are essential for surface deposition and hence in view of performing single-molecule experiments. The upper part should be free to turn whilst the base should stay still, anchored on the surface between the two electrodes of the addressing system. In molecule **1**, there is indeed essentially one degree of freedom: the rotation of the upper part with respect to the lower one. The lower part has a locked conformation. As far as the upper part is concerned, rotation about the single and triple bonds of the arms is of course possible, but it does not alter significantly the geometry of the molecule.

SYNTHESIS OF THE ACTIVE PART OF A MOLECULAR MOTOR

The molecule was synthesized in four steps as shown on Scheme 1, starting from pentaphenyl cyclopentadiene, which was selectively brominated in the *para* positions and at the saturated carbon of the cyclopentadiene ring to obtain the precursor **2** [5b]. This new ligand was coordinated to ruthenium by reaction with $Ru_3(CO)_{12}$, and subsequently the tris(indazolyl)borate ligand (Tp^{4Bo}) was introduced. In the last step, a quintuple coupling of the ethynyl ferrocene EGs occurred with a satisfying 32 % yield [8a].

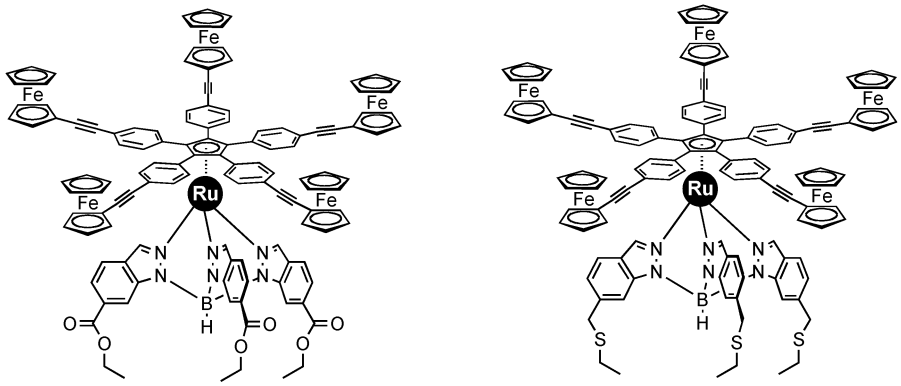
Once the active part of the molecular motor **1** was synthesized, all the requirements for such a molecule to operate as a molecular motor were analyzed: (i) The oxidation potential of the iron is lower (0.52 V/SCE) than that of the ruthenium center (0.82 V/SCE) which is compatible with our objective, in the sense that the ruthenium center will remain inert toward the redox cycles of the peripheral EGs. (ii) Electrochemical processes are reversible, showing the robustness of the molecule toward oxidation. (iii) No intervalence band was observed by spectroelectrochemistry, showing that the electronic communication between two iron centers is very weak. Electronic communication is here an unwanted phenomenon since it would allow a charge transport by intramolecular electron hopping between different ferrocene centers, without real motion of the rotor. (iv) The rotation barrier of the rotor is very low, as shown by NMR and by density functional theory (DFT) calculations. Magnetic equivalents of different nuclei, as observed in solution NMR studies, are a good probe for free rotation. This is a random process in which the rotor part of the molecule explores rapidly many conformations, with back and forth irregular motions. This is very different from the rotation occurring in a macroscopic mechanical motor. At the molecular scale, the inertial forces play a negligible role, and cannot sustain the directionality of the motion [9]. A variable-temperature ^{1}H-NMR study of **1** down to –90 °C did not give any information concerning the barrier of rotation, which is therefore supposed to be lower than 10 kcal mol^{-1}. DFT calculations (B3PW91 functional) allowed us to evaluate this barrier to be 4.5 kcal mol^{-1}.

INTRODUCTION OF FUNCTIONALIZED STATORS

The next step toward a molecular motor has consisted in the design and synthesis of two new tripodal ligands in view of anchoring the ruthenium complexes onto surfaces [16]. The functionalized borate ligands were designed to have three functional groups pointing on the opposite direction of the ruthenium coordination site in order not to interfere sterically with it. Each of the three legs of the tripodal unit bears a functional group connected at the 6-position of indazole, which should be, on the basis of the X-ray structures obtained on the cyclopentadienyl model complexes [16], the optimal orientation for anchoring on a surface. The first one incorporates ester-functionalized indazoles (coordinated in **3**) to anchor complexes onto the oxide surface used as insulator in molecular-scale non-contact atomic force microscope (NC-AFM) experiments. The second synthesized tripode bears thioether-functionalized indazoles (coordinated in **4**) to anchor complexes onto metal surfaces.

The coordination of both ligands took place similarly to the coordination of the unfunctionalized tripode, and the redox potentials are still compatible with our project, the ruthenium center being oxi-

dized at higher potentials than the ferrocene centers. The two ruthenium complexes synthesized are shown in Fig. 2.



3 **4**

Fig. 2 Two molecular motors with different functionalized tripodal stators. **3** is equipped with ester functions to be deposited on alumina between two electrodes of a nanojunction and **4** with thioether groups to be anchored on metallic surfaces.

INCORPORATION OF INSULATING ELECTROACTIVE GROUPS

In such systems, the major difficulty lies in the capacity to control the parameters which favor the desired process over the unwanted ones. In our case, the rotation has to compete with the undesired intramolecular electron transfer without rotation (Fig. 3).

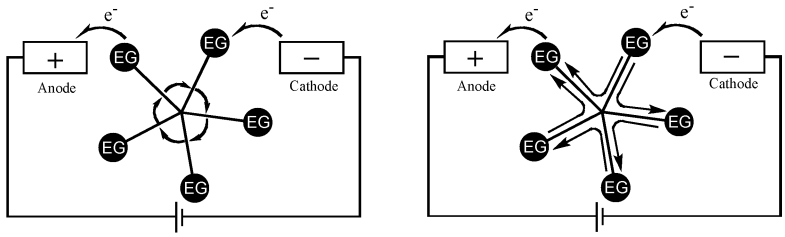
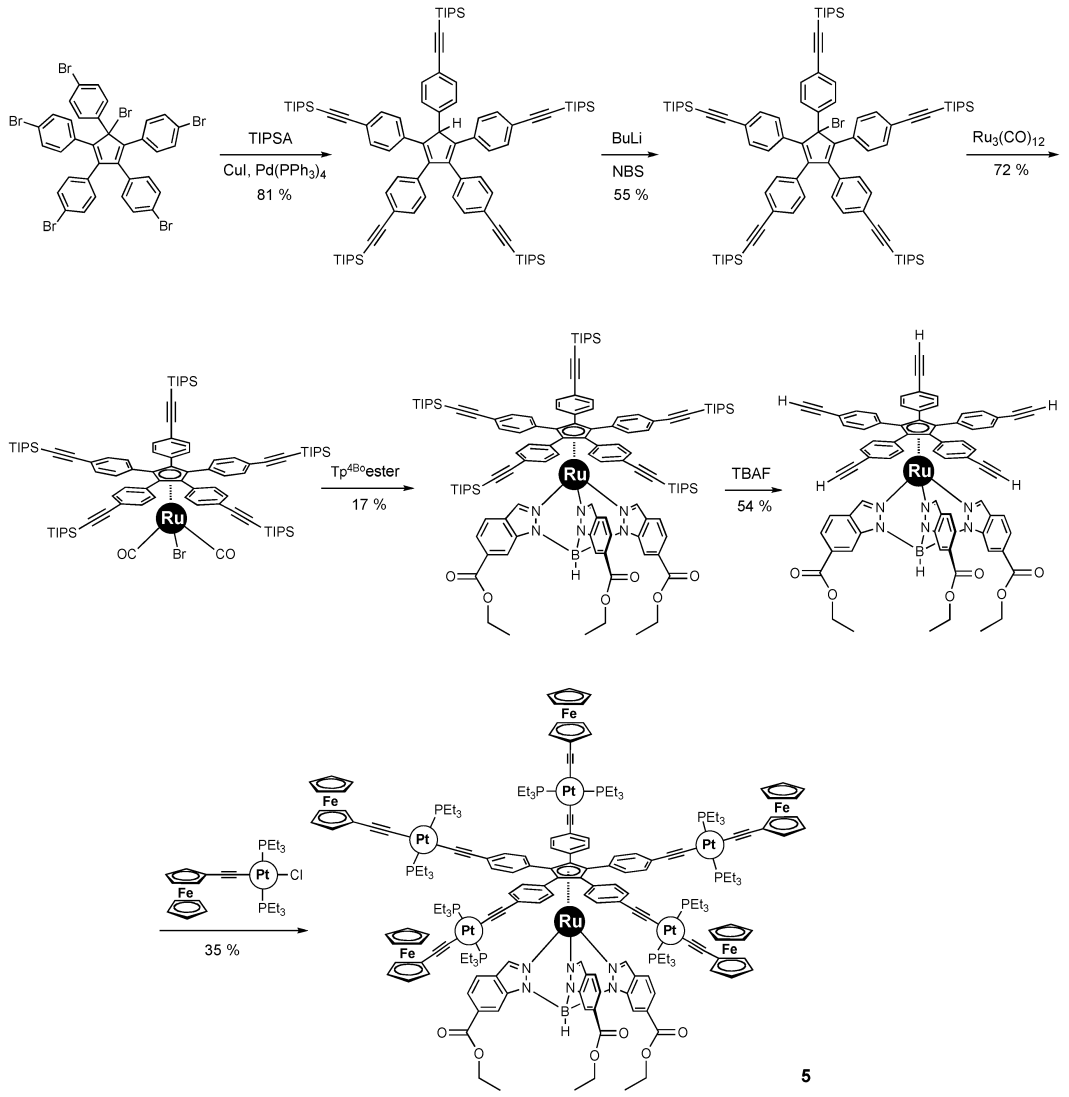


Fig. 3 (Left) The wanted phenomenon corresponding to the electron transport by a rotation of the rotor. (Right) The mechanism to minimize, which is an intramolecular electron transfer without rotation of the rotor.

The rotation, a fifth of a turn in the case of a C_5-symmetric rotor, has to be significantly faster than the intramolecular electron transfer between two electroactive units. If not, the electrons will travel through the carbon skeleton without rotation of the whole rotor. Since a conjugated skeleton can clearly not separate electronically the EGs, we also developed the synthesis of insulating spacers based on platinum acetylide fragments [17]. Such spacers are presumed to insulate the ferrocene groups by disrupting the electronic communication between them, possibly due to the σ character of the Pt–C bonds, which breaks the conjugation of the different submodules. Therefore, the charge localization on one single oxidized ferrocenyl unit, which should be the seat of the oxidoreduction cycles in the desired process, should be favored.

Since the Negishi conditions that were successful for the synthesis of the non-insulated motors failed, a second route was followed (Scheme 2), in which the alkyne functions carried by the ruthenium core are coupled to a chloro ethynylferrocenyl platinum complex [18].



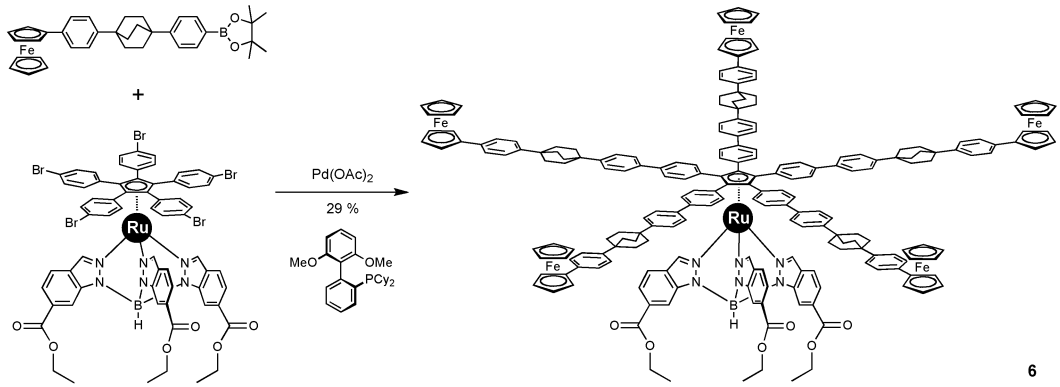
Scheme 2 Synthesis of molecular motor **5** fully equipped with a functionalized tripodal stator and insulated EGs.

The precursor ruthenium complex with five terminal alkyne functions was prepared in five steps starting from 1-bromo-1,2,3,4,5-penta(*p*-bromophenyl) cyclopentadiene. The pentayne cyclopentadiene compound was obtained in a remarkable 81 % isolated yield by a quintuple Sonogashira coupling with mono-triisopropylsilane (TIPS)-protected acetylene. Bromine was introduced back on the Cp ring—using ^{n}BuLi and *N*-bromosuccinimide (NBS) at low temperature. The ruthenium was subsequently coordinated, and then the tripodal ligand with ester anchoring groups (Tp^{4Bo}ester) was introduced. Finally, the TIPS protecting groups were removed by overnight reaction with tetrabutylammonium fluoride (TBAF) to yield the pentayne ruthenium precursor complex. Its quintuple coupling with the chloro ethynylferrocenyl platinum complex gave the desired product **5** in 35 % isolated yield.

In this complex, the electronic communication between the ferrocene units is again not measurable by spectroelectrochemistry, but a theoretical approach combining geometry optimization by DFT and extended Hückel calculations on bis-ferrocenyl model compounds allowed us to estimate the elec-

tronic communication parameter V_{ab} between ferrocene units, showing a fourfold attenuation in the presence of a *trans*-platinum spacer between the two iron centers [17].

In order to obtain a better insulation, we also synthesized the molecular motor **6** (Scheme 3) where the EGs are separated by bicyclo[2.2.2]octane spacers [19]. DFT and extended Hückel calculations showed in this case a 12-fold decrease of the electronic coupling. Moreover, the absence of triple bonds in the backbone gives rise to a more rigid structure that should be more stable toward the deposition process.



Scheme 3 Synthesis of molecular motor **6** with the improved insulating organic spacers.

PERSPECTIVES

Work is now underway to anchor these molecules on an oxide surface in view of addressing them as single molecules with two metallic nanoelectrodes. The demonstration of a controlled rotary movement will then need further experimental developments by physical methods such as scanning probe microscopy or the analysis of the time dependence of the current in a two-electrode configuration. For that purpose, we also developed the synthesis of analogous molecules dissymmetrized by the absence of one electroactive ferrocene group. Lowering the symmetry of the molecule should help to prove a movement and maybe to monitor the rotation, the missing ferrocene acting as a probe for the position of the rotor [20]. Moreover, the synthesis of the next generation of molecular motors is also in progress using chirality in the backbone [21] to enhance the dissymmetry of the system and to maximize the unidirectionality of the rotation.

ACKNOWLEDGMENTS

H.-P.J. thanks the French Ministry of National Education for a Ph.D. Fellowship. G.V. thanks the French Ministry of National Education and the Ecole Normale Supérieure of Lyon for a Ph.D. Fellowship. Dr. Alexandre Carella is especially acknowledged for his seminal research on this project as a highly motivated Ph.D. student. Prof. Jean-Pierre Launay and Dr. Christian Joachim are gratefully acknowledged for having welcomed me in their group and for their constant help on the subject. Dr. Isabelle M. Dixon is warmly acknowledged for her corrections and comments on this manuscript.

REFERENCES

1. (a) Special Issue on Molecular Machines, *Acc. Chem. Res.* **34** (6), pp. 409–522 (2001); (b) G. Rapenne. *Org. Biomol. Chem.* **3**, 1165 (2005).
2. L. Grill, K. H. Rieder, F. Moresco, G. Rapenne, S. Stojkovic, X. Bouju, C. Joachim. *Nature Nanotech.* **2**, 95 (2007).
3. (a) Y. Shirai, Y. Zhao, L. Chen, J. M. Tour. *Org. Lett*. **6**, 2129 (2004); (b) Y. Shirai, A. J. Osgood, Y. Zhao, K. F. Kelly, J. M. Tour. *Nano Lett*. **5**, 2330 (2005); (c) Y. Shirai, A. J. Osgood, Y. Zhao, Y. Yao, L. Saudan, H. Yang, C. Yu-Hung, L. B. Alemany, T. Sasaki, J.-F. Morin, J. M. Guerrero, K. F. Kelly, J. M. Tour. *J. Am. Chem. Soc.* **128**, 4854 (2006); (d) J.-F. Morin, Y. Shirai, J. M. Tour. *Org. Lett.* **8**, 1713 (2006).
4. (a) G. Jimenez-Bueno, G. Rapenne. *Tetrahedron Lett.* **44**, 6261 (2003); (b) G. Rapenne, G. Jimenez-Bueno. *Tetrahedron* **63**, 7018 (2007).
5. (a) F. Chiaravalloti, L. Gross, K. H. Rieder, S. Stojkovic, A. Gourdon, C. Joachim, F. Moresco. *Nat. Mater.* **6**, 30 (2007); (b) A. Carella, J. Jaud, G. Rapenne, J.-P. Launay. *Chem. Commun.* 2434 (2003).
6. (a) T. R. Kelly, H. D. Silva, R. A. Silva. *Nature* **401**, 150 (1999); (b) N. Koumura, R. W. J. Zijlstra, R. A. van Delden, N. Harada, B. L. Feringa. *Nature* **401**, 152 (1999); (c) D. A. Leigh, J. K. Y. Wong, F. Dehez, F. Zerbetto. *Nature* **424**, 174 (2003); (d) V. Balzani, M. Clemente-León, A. Credi, B. Ferrer, M. Venturi, A. H. Flood, J. F. Stoddart. *Proc. Natl. Acad. Sci. USA* **103**, 1178 (2006); (e) N. Armaroli, V. Balzani, J.-P. Collin, P. Gaviña, J.-P. Sauvage, B. Ventura. *J. Am. Chem. Soc*. **121**, 4379 (1999); (f) T. C. Bedard, J. S. Moore. *J. Am. Chem. Soc*. **117**, 10662 (1995); (g) T. Muraoka, K. Kinbara, T. Aida. *Nature* **440**, 512 (2006); (h) Y. Naorikane, N. Tamaoki. *Org. Lett*. **6**, 2595 (2004); (i) D. Horinek, J. Michl. *J. Am. Chem. Soc.* **125**, 11900 (2003); (j) M. Ikeda, M. Takeuchi, S. Shinkai, F. Tani, Y. Naruta, S. Sakamoto, K. Yamaguchi. *Chem.—Eur. J.* **8**, 5541 (2002); (k) H. Jian, J. M. Tour. *J. Org. Chem.* **68**, 5091 (2003).
7. (a) J. K. Gimzewski, C. Joachim, R. R. Schlitter, V. Langlais, H. Tang, J. Johanson. *Science* **281**, 531 (1998); (b) X. Zheng, M. E. Mulcahy, D. Horinek, F. Galeotti, T. F. Magnera, J. Michl. *J. Am. Chem. Soc.* **126**, 4540 (2004).
8. (a) A. Carella, G. Rapenne, J.-P. Launay. *New J. Chem.* **29**, 288 (2005); (b) A. Carella, C. Coudret, G. Guirado, G. Rapenne, G. Vives, J.-P. Launay. *Dalton Trans.* 177 (2007).
9. C. Joachim, J. K. Gimzewski. *Struct. Bonding (Berlin)* **99**, 1 (2001).
10. F. Moresco, G. Meyer, K. H. Rieder, H. Tang, A. Gourdon, C. Joachim. *Phys. Rev. Lett.* **87**, 088302 (2001).
11. C. Loppacher, M. Barmmerlin, M. Guggisberg, O. Pfeiffer, E. Meyer, R. Luthi, R. R. Schlitter, J. K. Gimzewski, H. Tang, C. Joachim. *Phys. Rev. Lett.* **90**, 066107 (2003).
12. H. Park, J. Park, A. K. L. Lim, E. H. Anderson, A. P. Alivisatos, P. L. McEuen. *Nature* **407**, 57 (2000).
13. A. P. Davis. *Angew. Chem., Int. Ed.* **37**, 909 (1998).
14. (a) N. G. Connelly, W. E. Geiger. *Chem. Rev.* **96**, 877 (1996); (b) D. Astruc. *Acc. Chem. Res.* **33**, 287 (2000).
15. (a) S. Trofimenko. *Scorpionates: The Coordination Chemistry of Polypyrazolylborate Ligands*, Imperial College Press, London (1999); (b) A. L. Rheingold, B. S. Haggerty, G. P. A. Yap, S. Trofimenko. *Inorg. Chem.* **36**, 5097 (1997).
16. A. Carella, G. Vives, T. Cox, J. Jaud, G. Rapenne, J.-P. Launay. *Eur. J. Inorg. Chem.* 980 (2006).
17. G. Vives, S. Sistach, A. Carella, J.-P. Launay, G. Rapenne. *New J. Chem.* **30**, 1429 (2006).
18. G. Vives, A. Carella, J.-P. Launay, G. Rapenne. *Chem. Commun.* 2283 (2006).
19. G. Vives, A. Gonzalez, J. Jaud, J.-P. Launay, G. Rapenne. *Chem.—Eur. J.* **13**, 5622 (2007).
20. G. Vives, G. Rapenne. *Tetrahedron Lett.* **47**, 8741 (2006).

21. (a) J. C. Chambron, C. Dietrich-Buchecker, G. Rapenne, J. P. Sauvage. *Chirality* **10**, 125 (1998); (b) E. Tur, G. Vives, G. Rapenne, J. Crassous, N. Vanthuyne, C. Roussel, T. Lombardi, T. Freedman, L. Nafie. *Tetrahedron: Asymmetry* **18**, 1911 (2007).