LETTER

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Design and synthesis of the active part of a potential molecular motor†‡

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The design and synthesis of a ruthenium complex are described, together with its physico-chemical properties, showing its potential to work as a single molecule rotary motor.

Artificial molecular machines and motors have recently emerged as a new field in chemistry related to a newly explored dimension of molecular sciences: controlled movement on the molecular scale.[1] Two groups of machines can be distinguished: those working linearly, like shuttles[2] or muscles,[3] and rotary machines. A motor is a machine that consumes energy to create work continuously *via* a unidirectional and controlled movement. The inspiration of such motors comes both from nature, with the fascinating machinery of ATP-synthase,[4] and in the macroscopic world where rotary motors are very common. Some examples of molecular rotary motors have been described by a few groups[5] and a rotor[6] has been proposed, but the molecule needs its neighbours in a supramolecular arrangement to act as a rotor. The major difficulties reside in the directional control of the rotation, the continuous response to the stimulus and the manipulation of a single molecule.

We present here the design and synthesis of the active part of a molecular motor, designed to work as a single molecule. This molecule comprises a stator, that is, one part designed to be deposited on the surface between two electrodes 3–4 nm apart (*e.g.*, nano-junction), and on this stator is connected a rotor, which should be capable of transforming a current of electrons into a unidirectional rotational motion. Our model complex (**3**) for solution studies is represented in Fig. 1 and is constituted of three parts.

The rotor is a rigid aromatic platform constructed around a cyclopentadienyl ligand with five linear and rigid arms, each being terminated by an electroactive group (EG). As the EG, ferrocene has been selected because it exhibits reversible oxidation in various solvents.[7] The stator is a hydrotris(indazolyl) borate ligand (Tp^{4Bo}) of the family of scorpionates developed by Trofimenko and co-workers,[8] giving a piano stool shape. The joint between the rotor and the stator is a ruthenium(II) ion. The upper part should be free to turn, whilst the base should stay still, anchored on the surface below the gap between the two electrodes of the addressing system. The concept is shown in Fig. 2. The EG closest to the anode would be oxidized (oxidized form: EG^+) and pushed back by electrostatic repulsion, as has been previously shown with a [60]-fullerene between two electrodes.[9] This motion corresponds to a fifth of a turn. As a result, the oxidized electroactive group would approach the cathode and subsequently be reduced. At the same time, a second electroactive group would come close to the anode and a second cycle would occur. A complete 360° turn would be achieved after five cycles, corresponding to the transport of five electrons from the cathode to the anode. We would then observe the conversion of an electron flow into a movement of rotation, that is, a redox-triggered molecular rotary motor. In order for the rotation to be directional, the molecule would have to be placed in a dissymmetric fashion with respect to the nano-junction, as shown in Fig. 2. With such a disposition, which should occur with high probability, it can be seen that, for a clockwise rotation (as shown), the oxidized form of the electroactive group travels the shortest route between the electrodes, while for a counterclockwise rotation, it would travel a longer and non-equivalent route.

In addition, and if necessary, the two directions of rotation could be further dissymmetrized by a secondary electric field perpendicular to the nano-junction. Note that this effect is already used in nature, in the F_0 unit of ATP-synthase: in this part of the enzyme, a mobile rotor carries protonation sites (carboxylate/carboxylic acid of aspartic acid 61 on subunit c). Depending on the rotation direction, the protonated sites can encounter either hydrophobic or hydrophilic regions. The interaction with the latter being favoured, a unidirectional rotation occurs.[4] It is important to note that this molecule is particularly rigid and exhibits essentially one degree of freedom, namely the intramolecular rotation of the rotor with respect to the stator. Other rotational degrees of freedom, such

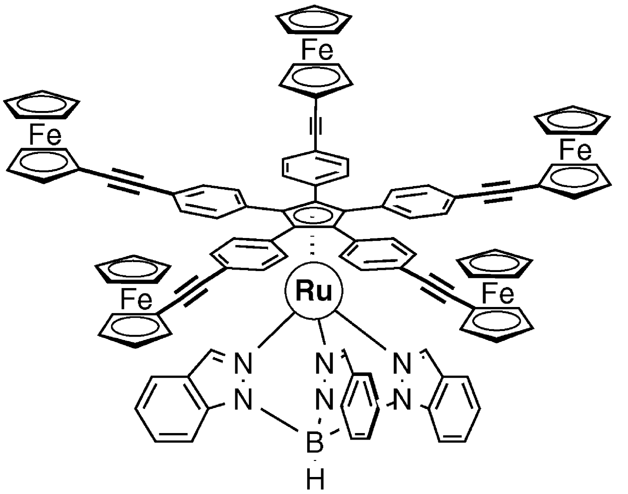

Fig. 1 Chemical structure of complex **3**. The lower part can be functionalized to allow grafting onto various surfaces.

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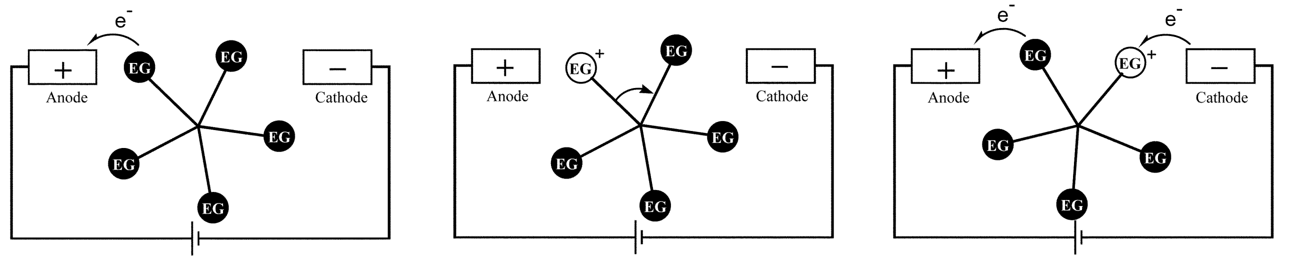
† This paper is dedicated to Dr Jean-Pierre Sauvage on the occasion of his 60th birthday.

‡ Electronic supplementary information (ESI) available: full ^1H NMR spectrum with enlargements of the ferrocene and aromatic proton regions. See http://www.rsc.org/suppdata/nj/b4/b415214j/



Step 1: Oxidation of the electroactive group closest to the anode

Step 2: repulsion of the ferrocenium cation and rotation

Step 3: reduction of the cation (right) and oxidation of a second ferrocene (left)

Fig. 2 Schematic representation of a molecule placed between the two electrodes of a nano-junction (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. On this figure is represented a fifth of a turn corresponding to the movement induced by the transfer of one electron.

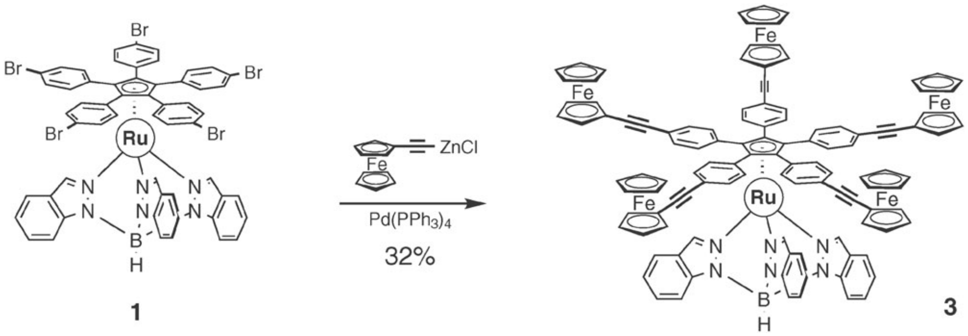
as the rotation around the ethynyl moieties connecting the electroactive groups to the cyclopentadienyl (Cp) ring, do not modify greatly the overall geometry. To our knowledge, this makes our system unique amongst the many examples of molecular motors described in the literature.

Recently, we reported the synthesis of ruthenium(II) 1,2,3,4,5-penta(*p*-bromophenyl)cyclopentadienylhydrotris(indazolyl) borate (**1**), a piano stool complex described as an organometallic molecular turnstile.[10] This synthon can lead to final molecules bearing zero net charge, making them particularly well-suited for surface deposition and, hence, for building single molecule nanomotors. The presence of the five aryl bromide groups allows the direct connection of the electroactive groups, leading to complex **3** after a quintuple coupling reaction provided by the powerful chemistry of Pd-catalyzed C–C bond formation. All attempts performed under Sonogashira conditions[11] with various catalysts and phosphines, and even the very bulky and electron-rich tris(*tert*-butyl)phosphine, resulted in no reaction. This may be due to the high electron density of the bromide derivative, which is covalently linked to a formally anionic entity (Cp). The electron-rich character of the C–Br bond precludes oxidative addition on the palladium catalyst. However, the five electroactive groups could be simultaneously covalently attached to the rotor by a quintuple coupling of ethynylferrocene (**2**) with **1** under Negishi conditions (Scheme 1).[12] The specificity of this protocol resides in the use of a freshly prepared alkynyl zinc chloride solution instead of an alkynyl cuprate generated *in situ*.

For the synthesis of **3**, **1** was reacted with a total of 40 equiv. (two times 4 equiv. per bromide) of freshly prepared [(ferrocenyl)ethynyl]zinc chloride in the presence of $Pd(PPh_3)_4$ in refluxing THF (see Experimental). **3** was isolated by column chromatography in 32% yield, which corresponds to a yield of 80% per coupling. ^1H NMR spectroscopy clearly showed an AA'BB' pattern for the phenyl groups attached to the central Cp ring and the signals of the ferrocene units integrated for 45 protons (see Electronic supplementary information, ESI). The presence of the five ethynylferrocene units was also confirmed by mass spectrometry.

Our objective requires an almost free rotation of the rotor. A variable low temperature ^1H NMR study of **3** up 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}. Oxidation of the five iron centres occurred simultaneously at a potential of 0.52 V_{SCE}, that is, slightly lower than ethynylferrocene (0.59 V_{SCE}, see Table 1), followed by the oxidation of the ruthenium centre at 0.82 V_{SCE}, which is similar to the value obtained with **1**. This lower oxidation potential for the iron moiety in **3** *versus* **2** is in line with the replacement of a hydrogen atom by an electron-rich aromatic substituent. The relative oxidation potentials are compatible with our objective, in the sense that the ruthenium centre will remain inert towards the redox cycles of the peripheral electroactive groups. Indeed, the cyclic voltammogram presented in Fig. 3 shows that the two oxidation processes do not overlap, which means that oxidation of the ferrocene fragments will not affect the ruthenium centre.

Preparative electrolysis of **3** was performed on a platinum grid, first to oxidize the ferrocene sites, then to oxidize the ruthenium site. After back-reduction, the starting material was recovered unchanged, showing the robustness of the molecule towards oxidation. However, a further problem must be addressed: electronic communication between redox sites is here an unwanted phenomenon, since it would allow charge transport *via* intramolecular electron hopping (ferrocene/ferricenium self-exchange), without real motion of the rotor. To investigate this aspect, we performed a partial oxidation of the ferrocene sites, in a search for intervalence transitions. No such transitions were observed, showing that electronic communication between these sites is nonexistent or very weak. However, the absence of intervalence transition does not guarantee that the rate of ferrocene–ferricenium exchange will be sufficiently small for our purpose. Thus, additional synthetic work is in progress to develop linkers incorporating insulating groups.



Scheme 1 Synthesis of the target molecule **3**. The lower ligand is the stator and the upper ligand the rotor with five ferrocene-terminated arms. The ruthenium atom acts as the junction between the two ligands.

Table 1 Cyclic voltammetry (CH_2Cl_2, $^nBu_4NPF_6$, Pt working and counter electrode, in V *versus* SCE). All waves were reversible

	1	**2**	**3**
$E_{1/2}$(ox) Fe^{II}/Fe^{III}	—	0.59	0.52
$E_{1/2}$(ox) Ru^{II}/Ru^{III}	0.80	—	0.82

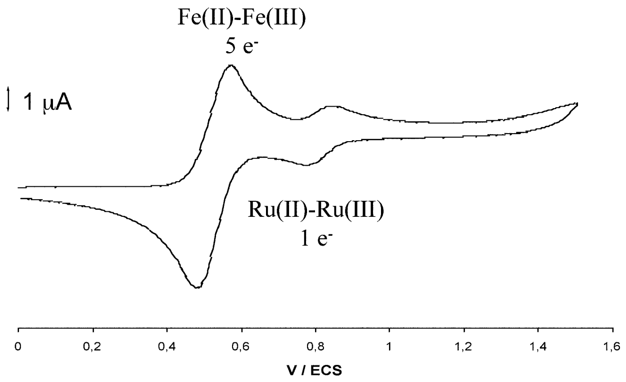


Fig. 3 Cyclic voltammogram of **3**. Sweep rate is 100 mV s^{-1}.

In conclusion, a rotor composed of five terminal electroactive groups has been prepared and connected to a tripodal ligand (stator) by means of a ruthenium(II) centre. This system can be considered as the heart of a future molecular motor, since it is particularly well-suited for the preparation of a family of molecules through variations of the hydrotris(indazolyl) borate ligand. The stator will be functionalized to allow its deposition on various surfaces. Observation of the conversion of an electric current into a controlled rotary movement will then be attempted using scanning probe microscopes, associated with other physical techniques adapted to nano-objects. Work is currently under way to achieve this goal.

Experimental

Preparation of [(ferrocenyl)ethynyl]zinc chloride

In a Schlenk tube, a 2.5 M solution of ^nBuLi in hexane (410 μl, 1.025 mmol) was added to a solution of ethynylferrocene (**2**; 210 mg, 1 mmol) in 5 ml of freshly distilled THF at −78 °C. The reaction mixture was stirred at −78 °C for 30 min and the temperature was then allowed to raise up to room temperature. Separately, zinc chloride (190 mg, 1.4 mmol, 1.4 equiv.) was flame-dried in a Schlenk tube under vacuum. The lithium acetylide solution was added to the zinc chloride and the reaction mixture was stirred under argon at room temperature for 1 h. This solution was used without further purification.

Synthesis of ruthenium penta{4-[(ferrocenyl)ethynyl]phenyl}cyclopentadienylhydrotris(indazolyl) borate (3)

In a three-neck flask, a solution of ruthenium penta(4-bromophenyl)cyclopentadienylhydrotris(indazolyl) borate (**1**; 70 mg, 0.053 mmol) and $Pd(PPh_3)_4$ (30 mg, 26 μmol, 0.5 equiv.) in 10 ml of freshly distilled THF was degassed. A solution of [(ferrocenyl)ethynyl]zinc chloride (1 mmol, 4 equiv. per bromide) prepared as described above was then added. The mixture was heated under reflux for 24 h. Additional catalyst (30 mg) and reactants {1 mmol of [(ferrocenyl)ethynyl]zinc chloride} were added with a syringe under argon and the mixture was kept under reflux for 24 h. The crude reaction mixture was evaporated under vacuum. The product was adsorbed on silica and purified by flash column chromatography (SiO_2; cyclohexane–CH_2Cl_2 0–30%, $R_f = 0.12$) to give an orange solid (33 mg, 0.017 mmol, yield 32%), which was fully characterized and identified as pure **3**.

MALDI-TOF MS: calcd *m*/*z* for M^+ ($C_{116}H_{81}BN_6Fe_5Ru$) 1950.2463; found 1950.3480 (100%); high resolution LSI MS: calcd *m*/*z* for $[M + H]^+$ ($C_{116}H_{82}BN_6Fe_5Ru$) 1951.2599; found 1951.2631 (100%). ^1H NMR (250 MHz, $CDCl_3$): $\delta = 8.0$ (d, 3H, $^3J = 8.4$ Hz); 7.94 (s, 3H); 7.5–7.3 (m, 16H); 7.20–7.10 (d, 10H; $^3J = 8.0$ Hz); 7.02 (t, 3H, $^3J = 7.5$ Hz); 4.43 (t, 10H, $^3J = 2$ Hz); 4.21 (s, 25H); 4.19 (t, 10H, $^3J = 2$ Hz); ^{13}C NMR (66 MHz, $CDCl_3$) $\delta = 143.40$; 140.23; 133.36; 133.17; 130.41; 126.42; 122.94; 122.72; 122.41; 120.03; 111.65; 89.28; 87.49; 85.47; 71.36; 69.95; 68.79; 65.02. UV/vis (CH_2Cl_2): λ_{max} (ε) = 264 (225000), 306 (169200), 359 (58000), 436 (10400) nm. Cyclic voltammetry (CH_2Cl_2, $^nBu_4NPF_6$,): $E_{Fe(II)/Fe(III)}/V_{SCE} = +0.52$ rev, (5 e^-); $E_{Ru(II)/Ru(III)}/V_{SCE} = +0.82$ rev (1 e^-).

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