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Breaking the symmetry in the molecular motor family: synthesis of a dissymmetrized pentaphenyl cyclopentadienyl ligand and its ruthenium tris(indazolyl)borate complex

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Abstract—In order to demonstrate a movement of rotation in a family of rotary molecular motors, 1-bromo-1-(4-tolyl)-2,3,4,5-tetra(4-bromophenyl) cyclopentadiene has been synthesized. The coordination of this C_{2v} cyclopentadiene to a ruthenium tris-indazolylborate complex and the quadruple coupling reaction with ethynylferrocene led to the dissymmetrized motor (**1**).

In the field of nanotechnology, a growing interest has appeared in the design and synthesis of molecular machines.[1] Among theses machines, molecular rotary motors represent a particular challenge for the control of a unidirectional movement.[2] In our laboratory we have designed an electrically fuelled molecular rotary motor with the aim to study it as a single molecule by near field microscopy techniques.[3] This motor is based on a piano stool ruthenium complex with a tripodal hydrotris(indazolyl)borate ligand[4] functionalized to be anchored on a surface (i.e., the stator) and a substituted cyclopentadienyl (Cp) ligand with five arms terminated by electroactive groups (i.e., the rotor). The principle is to deposit the molecule anywhere between two electrodes of a nano junction and to control the rotation by the flow of electrons. Physical studies are underway but a crucial problem is to evidence the rotation. Due to the high symmetry of the molecule, every 72°, there is no way to distinguish two images with a C_5-symmetric rotor such as a Cp substituted by five identical substituents.

This major issue can be partly addressed by using compounds of lower symmetry. For that purpose, we designed the molecular motor **1** (Fig. 1) in which a ferrocene electroactive group is missing. 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.

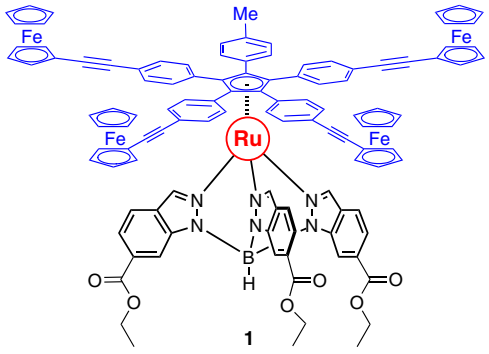

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Figure 1. Molecular motor (**1**) with one missing ferrocene group.

Since the coupling of ethynylferrocene with 1-bromo-1,2,3,4,5-*p*-bromophenylcyclopentadiene can only give access to a statistical mixture of penta-, tetra-, tri-, di- and mono-ferrocenyl compounds which cannot be separated, we decided to prepare the tetra-ferrocenyl derivative through a controlled synthesis.

The key feature of our strategy is to block one position of the Cp ring during the synthesis, in order to differentiate it from the other four substituents.

In this letter, we present the synthesis and characterization of a dissymmetrized pentaphenyl cyclopentadienyl

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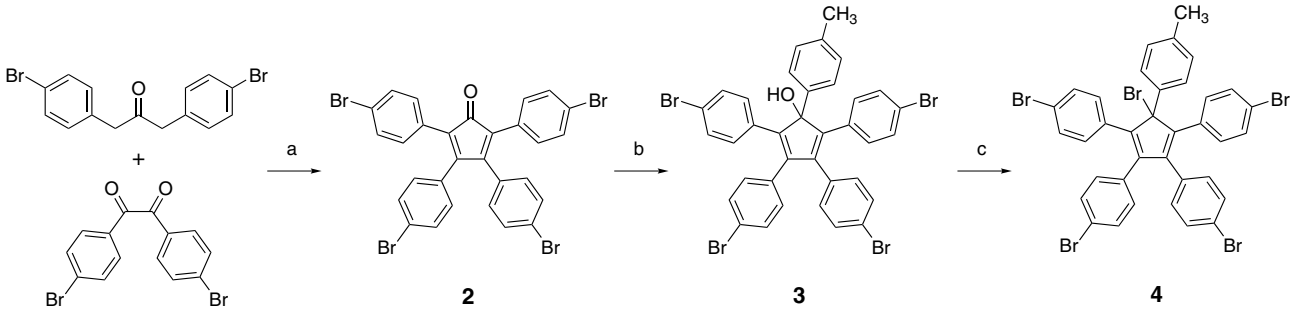


Scheme 1. Reagents and conditions: (a) KOH, EtOH, reflux, 40 min, 70%; (b) *p*-TolMgBr, THF, 25 °C, 2 h, 88%; (c) HBr, AcOH, 95 °C, 2 h, 60%. Compound **4** is obtained as a mixture of three regioisomers, the two others are shown in Figure 2.

ligand (**4**) bearing four bromide substituents for the subsequent coupling reaction and a methyl group to block the fifth position. We also present the synthesis of its ruthenium tris(indazolyl)borate complex (**1**).

As shown in Scheme 1, the first step is the condensation of 1,3-di(4-bromophenyl)propan-2-one[5] with 4,4′-dibromo benzile[6] under basic conditions yielding the tetrabrominated cyclopentadienone[7] **2** as a purple solid in 70% yield after recrystallization in ethanol. The *p*-tolyl substituent is then introduced by a nucleophilic addition of the Grignard reagent *p*-tolylmagnesium bromide[8] on a suspension of **2** at room temperature for 2 h in THF. The functionalized cyclopentadienol **3** was obtained after recrystallization in hexane in a 88% yield as a single regioisomer.

In the pentaphenylcyclopentadiene family, it is known[9] that coordination is not possible via the classical cyclopentadienide generated under basic conditions, and this may be due to steric hindrance. Coordination of ruthenium to this type of ligand can only take place if there is a bromine atom on the Cp ring, following Manner's methodology[10] which consists in the oxidative addition of the carbon–bromine bond on the ruthenium carbonyl cluster. For that purpose, the hydroxy group of **3** was replaced by a bromine atom.[11] After reaction with HBr in acetic acid, the brominated Cp **4** was purified by column chromatography (SiO_2:cyclohexane/CH_2Cl_2 10%, $R_f = 0.53$) and was obtained in 60% yield as a mixture of three regioisomers (Scheme 1 and Fig. 2). The regioisomers of **4**, formed due to the SN_1 mechanism of this reaction, can be quantified by ^1H NMR, using the methyl group of the tolyl substituent as a probe.

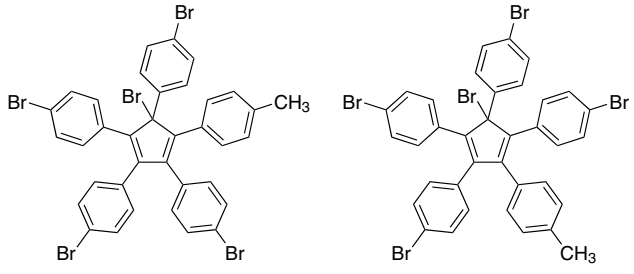


Figure 2. The two other regioisomers were formed simultaneously during the synthesis of the brominated cyclopentadiene **4**.

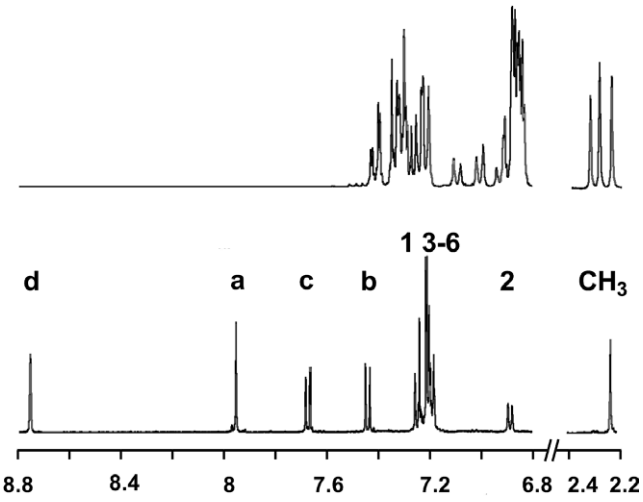
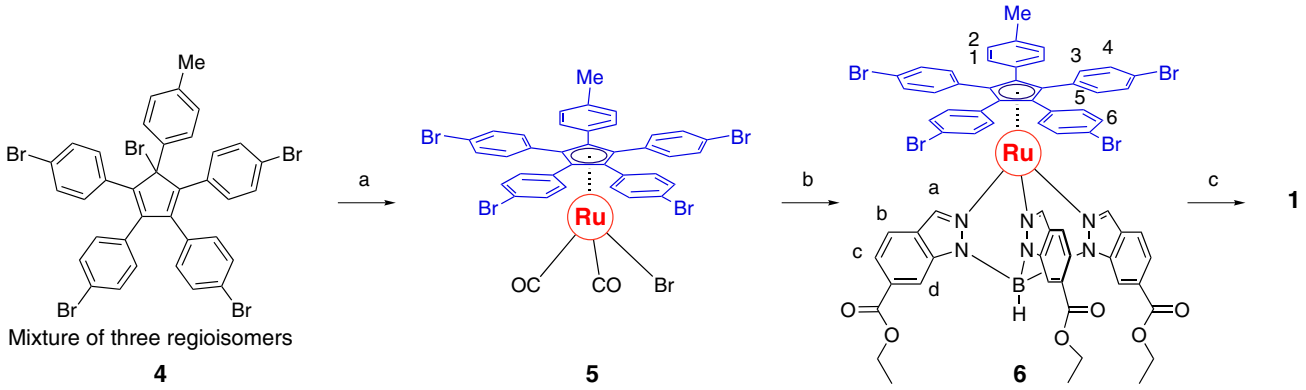


Figure 3. Top: ^1H NMR (CD_2Cl_2, 250 MHz) spectra of **4** with the three singlets corresponding to the three regioisomers in the 2–3 ppm region and the complex signals in the aromatic region. Bottom: ^1H NMR (CD_2Cl_2, 250 MHz) spectra of **6** with one singlet corresponding to the methyl group in the 2–3 ppm region.

Three singlets were obtained (Fig. 3, top), corresponding to the three regioisomers with a 1.4:1.7:1.9 ratio which differs strongly from the statistical mixture 1:2:2, showing the difference of stability of the carbocations involved. It must be stated that the postulated Cp^+ intermediate is antiaromatic but since the mixture obtained is not separable, it has not been possible to check if the latter was the thermodynamic mixture. Anyway, the presence of this mixture of regioisomers is not a problem since in the next step, the aromatization of the Cp ring through its coordination leads to the same compound for the three regioisomers.

As shown in Scheme 2, coordination of the three regioisomers of ligand **4** with $Ru_3(CO)_{12}$ gave complex **5** with a 43% yield after purification by column chromatography (SiO_2:cyclohexane/CH_2Cl_2 10%, $R_f = 0.50$). The two carbonyl groups and the bromide ligand can be substituted by the scorpionate ligand hydrotris[6-(ethoxycarbonyl)indazol-1-yl]borate by heating under microwave irradiation in a sealed tube at 150° for 10 min. The ruthenium precursor of the molecular motor **6** was purified by column chromatography (SiO_2:CH_2Cl_2, $R_f = 0.40$), and it was subsequently reacted using the



Scheme 2. Reagents and conditions: (a) $Ru_3(CO)_{12}$, toluene, 2 h, reflux, 43%; (b) potassium hydrotris[6-(ethoxycarbonyl)indazol-1-yl]borate, microwave, DMF/CH_3CN, 150 °C, 10 min, 30 %; (c) [(ferrocenyl)ethynyl]zinc chloride, $Pd(PPh_3)_4$, THF, reflux, 24 h, 49%.

Negishi cross-coupling conditions. Heating at reflux, a solution of [(ferrocenyl)ethynyl]zinc chloride in the presence of **6** and $Pd(PPh_3)_4$ in THF yielded, after purification by chromatography (SiO_2:CH_2Cl_2, $R_f = 0.40$), the dissymmetrized motor **1** in a 49% yield which corresponds to an 84% yield per coupling reaction. The presence of the ferrocenyl moieties was confirmed by ^1H NMR spectroscopy with an integration of 36 for the protons of the ferrocenyl groups and 3 for the protons of the tolyl group. Moreover the ^1H NMR also clearly showed three AA′BB′ patterns for the phenyl protons of the rotor with a 2:2:1 ratio. MALDI-TOF spectrometry also confirmed the presence of the four ferrocene units.[12]

In summary, we have succeeded in developing a strategy to obtain a dissymmetrized cyclopentadienyl ligand. This ligand has been incorporated in the family of electron-fuelled molecular rotary motors by coordination to a ruthenium tris(indazolyl)borate complex. Scanning probe microscopy studies are underway to prove the rotation of the molecule.

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Ligand **4**: yellow solid; UV/vis (CH_2Cl_2) λ_{max}/nm (ε/mol^{-1} L cm^{-1}) 260 (33,100), 285 (36,100), 373 (3600); ^1H NMR: (250 MHz, CD_2Cl_2) δ 7.4–6.8 (m, 20H), 2.32 (s, 0.84H, regioisomer 1CH_3), 2.29 (s, 1.14H, regioisomer 2CH_3), 2.24 (s, 1.02H, regioisomer 3CH_3); ^{13}C NMR (75 MHz, CD_2Cl_2) δ 149.23; 148.26; 147.63; 147.38; 146.69; 142.57; 141.80; 141.35; 140.72; 140.19; 138.52; 138.02; 137.88; 134.55; 134.52; 133.31; 133.13; 133.03; 133.00; 132.90; 132.78; 132.66; 132.05; 131.98; 131.86; 131.74; 131.70; 131.66; 131.64; 131.41; 131.28; 131.22; 131.05; 130.93; 130.70; 130.19; 129.75; 129.47; 129.36; 129.30; 128.96; 128.59; 127.31; 122.32; 122.22; 122.03; 121.99; 121.92; 121.90; 121.82; 121.66; 21.08; 20.98; 20.85. MS: (DCI/NH_3) 856 [M^-]; HR-FAB$^-$-MS (*m*-NBA/*m*/*z*) 849.7654 ($M+H^+$, calcd for $C_{36}H_{23}Br_5$: 849.7717).
Complex **6**: yellow solid; ^1H NMR: (500 MHz, CD_2Cl_2) δ 8.76 (s, 3H, H_d), 7.96 (s, 3H, H_a), 7.68 (d, 3H, $J = 8.5$ Hz, H_c), 7.44 (d, 3H, $J = 8.5$ Hz, H_b), 7.21 (s broad, 18H, H_1 H_{3-6}), 6.89 (d, 2H, $J = 8.0$ Hz, H_2), 4.47 (q, 6H, $J = 7.1$ Hz, CH_2), 2.23 (s, 3H, $PhCH_3$), 1.48 (t, 9H, $J = 7.1$ Hz, CH_3). ^{13}C NMR: (126 MHz, CD_2Cl_2) δ 166.77; 143.07; 140.73;

137.98; 135.15; 135.07; 133.26; 132.26; 131.94; 130.73; 130.67; 129.02; 128.89; 128.31; 125.25; 121.99; 121.87; 121.05; 119.73; 113.85; 90.17; 88.05; 87.28; 61.29; 20.87; 14.24. MS: (DCI/NH_3) 1474 $[M+NH_4]^+$, 1457 $([M+H]^+$ calcd for $C_{66}H_{52}BBr_4N_6O_6Ru$: 1456.6).

Complex **1**: orange solid; ^1H NMR: (500 MHz, CD_2Cl_2) δ 8.79 (s, 3H, H_d), 8.07 (s, 3H, H_a), 7.67 (d, 3H, $J = 8.5$ Hz, H_c), 7.48 (d, 3H, $J = 8.5$ Hz, H_b), 7.36 (m, 8H, H_3 H_5), 7.27 (d, 2H, $J = 8.2$ Hz, H_1), 7.18 (m, 8H, H_4 H_6), 6.91 (d, 2H, $J = 8.2$ Hz, H_2), 4.47 (q, 6H, $J = 7.1$ Hz, CH_2), 4.44 (t, 8H, $J = 1.8$ Hz, subs Cp), 4.21 (m, 8H, subs Cp), 4.20 (s, 10H, Cp), 4.19 (s, 10H, Cp), 2.25 (s, 3H, CH_3), 1.48 (t, 9H, $J = 7.1$ Hz, CH_3). ^{13}C NMR: (126 MHz, CD_2Cl_2) δ 166.86; 143.09; 140.87; 137.75; 133.56; 133.49; 133.39; 132.99; 132.82; 130.27; 130.22; 129.48; 128.88; 128.21; 125.36; 123.13; 123.03; 120.97; 119.75; 113.85; 89.82; 89.52; 89.46; 88.58; 88.29; 85.18; 71.38; 70.66; 69.93; 68.98; 64.87; 61.27; 22.71; 14.25; UV/vis (CH_2Cl_2) λ_{max}/nm (ε/mol^{-1} L cm^{-1}) 262 (97,000), 308 (85,500), 365 (42,600). MS: (MALDI/TOF) 1972 $[M]^+$ HR-FAB$^+$-MS (*m*-NBA/*m*/*z*) 1972.4070 ((M^+), calcd for $C_{114}H_{87}BFe_4N_6O_6Ru$: 1972.3221).