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Design and Synthesis of a Nano-winch

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Abstract Technical progress in the field of Scanning Probe Microscopy (SPM) has opened the way for the development of new surface-mounted artificial molecular machines, which can be addressed at the single molecular scale. In this context, a ruthenium-based molecular motor has been shown to undergo controlled unidirectional and reversible rotation when fueled with electrons delivered by the tip of a Scanning Tunneling Microscope. In this chapter, we report our efforts towards a deeper understanding of the mechanical properties of this molecular motor. In view of complementary force measurements to be performed at the single molecule scale using SPM techniques, the organometallic structure of the motor has been derivatized to append a long chain terminated by a hook. We detail here the design of this nano-winch architecture and the modular synthesis of a first prototype dedicated to Atomic Force Microscopy-based Single Molecule Force Spectroscopy experiments.

Keywords Molecular Motor - Nano-winch - Ruthenium complex - Single molecule - Scanning Probe Microscopy

1. Introduction

In the field of molecular machines,[1] molecular motors represent a subclass of systems able to convert various sources of energy into unidirectional mechanical motion. In Nature, biological molecular motors are ubiquitous and commonly exploit chemical energy recovered from ATP hydrolysis or electrochemical potential gradients as energy input.[2] Well-known examples of biomolecular motors inducing linear motion include myosins and kinesins, responsible in particular for muscle contraction and intracellular cargo transport. In contrast, rotary motion is generated in bacterial flagellar motors and in ATP synthases, for which reversibility of the rotation allows mutual conversion of chemical energy and electrochemical potential. These motors thus accomplish a variety of complex chemical and mechanical tasks, vital to biological systems. The operating conditions at the nanoscale involve high viscosity and constant Brownian motion, which has to be harnessed in order to ensure directionality in the movements. Strategies to reduce degrees of freedom and allow out-of-equilibrium operating conditions have been implemented by evolution, such as tracks for linear motors or compartmentalization by lipid barriers for rotary motors. This organization is critical for the collective emergence of useful work.

Far from the complexity of biological systems, chemists have designed and synthesized artificial molecular machines over the past forty years, with the aim of triggering controlled large-amplitude motions in response to a broad range of stimuli (light, electrochemistry, pH, bond formation/cleavage, ion binding, etc...).[3-5] The tremendous efforts in this new field were recognised by the 2016 Nobel Prize in Chemistry, awarded to Jean-Pierre Sauvage,[6] Sir Fraser Stoddart [7] and Ben Feringa [8] for their major contributions. In particular, control of directionality in translational and rotational systems was tackled in order to ultimately obtain molecular motors, able to perform work by progressive and repetitive operations. Since the late 1990s, many types of chemically-fueled and light-fueled motors have been reported, based on diverse architectures and mechanisms.[9-12] Seminal work by Kelly et al. on a ratchet-type compound based on triptycene and helicene units led to an important milestone, with a 120° unidirectional rotation around a C-C single bond driven by successive chemical steps.[13] Light driven directional rotary motion was initially developed by Feringa et al. in chiral overcrowded alkenes, in which successive photoisomerization and thermal relaxation steps induced repetitive unidirectional 360° rotation around C=C double bonds.[14] Chemically- and light-fueled translational motors were also conceived, as exemplified by the molecular walkers [15] reported by Leigh et al., and by various mechanically-interlocked molecules such as catenanes [16] and rotaxanes.[17,18]

These systems have been mostly studied in solution, which hampers the recovery of work due to random orientation of the population of molecular motors. Collective behaviours were however obtained after suitable organization of the assemblies of motors, leading to the emergence of controlled motion up to the macroscale.[19] In this regard, the light-fueled overcrowded alkenes developed by Feringa et al. have been intensively studied, among others, and led upon irradiation to the rotation of a micrometric glass rod deposited over a liquid crystal phase doped with the motor,[20] or to the macroscopic contraction of a polymeric gel incorporating the motor as reticulation unit.[21] Organization on surface also promoted collective behaviours of rotaxane-based machines, leading to reversible bending of cantilever beams in response to chemical stimuli,[22] or to directional transport of a droplet under irradiation.[23] The latter examples highlight the frequent adaptation to interfacial conditions of systems initially designed to be operated in solution.

Alternatively, several research groups adopted the opposite strategy and considered adsorption on surface as key requirement for the molecular design, in view of controlling the relative orientation of the motors. On-surface studies were also considerably facilitated by the technical progress made in the field of Scanning Probe Microscopy. In particular, thanks to the high-resolution imaging capabilities of Scanning Tunneling Microscopy (STM), it has been possible to precisely study motions on surface of entire molecules and within molecules, at the single molecular scale and in self-assemblies. STM is not only a tool to probe organization and motion on surface, but it can also be used for the mechanical manipulation of atoms and molecules, which is crucial to gain knowledge in fundamental processes occurring at the nanoscale.[24,25] Moreover, the tip of the STM can act as a localized atomic scale electrode, particularly appealing for the development of electron-fueled molecular motors. Since the report of a surface-bound butyl methyl sulfide by Sykes in 2011,[26] several electrically-driven systems have been developed, undergoing on metallic surfaces controlled unidirectional [27] or rotational motion. In the

latter case, rotation of the whole molecule around an anchoring point can occur (the surface acts as stator) [26,28,29] or motion can be restricted to one sub-molecular fragment rotating around an internal degree of freedom (the stator subunit is then anchored onto the surface).[30,31] It is important to note here that such molecular motors have been studied at low temperature, thereby decreasing random thermal fluctuations and increasing control over targeted electrically-driven motion. In these conditions, our group demonstrated the reversible unidirectional rotation of a piano-stool ruthenium complex studied at the single molecule scale.[30]

From macro- to nano-scale motors, central questions concern their efficiency and the useful work they are able to perform.[32] On these aspects, biological systems outcompete artificial molecular motors, as their evolution was driven by functionality, and as they achieve energy conversion efficiencies over 40%, along with a force-per-mass ratio comparable to that of modern macroscale engines.[33,34] To get further insight on the intrinsic performances of our surface-bound electron-fueled ruthenium-based molecular motor, incorporation of the organometallic scaffold into a winch structure was envisioned, allowing for various force measurements at the single molecule scale.

2 A Reversible Electron-Fueled Molecular Motor

Since the early 2000s, our group has designed and synthesized a series of electrically-driven azimuthal rotors,[35-37] to be studied on surface as single molecules [30,31] or as self-assemblies [38] by means of STM. Electric energy delivered by the STM tip is converted into a rotation movement, which was shown to be unidirectional and reversible in the case of a piano-stool ruthenium complex incorporating a dissymmetric rotor subunit (Figure 1).[30]

2.1 Architecture of the Organometallic Motor

The architecture of the unidirectional and reversible electron-fueled molecular motor is based on a piano-stool ruthenium(II) complex, involving a hydrotris(indazolyl)borate ligand as tripodal stator and a pentaaryl cyclopentadienyl platform as rotor. The central ruthenium atom thus acts as a linker between both subunits, but also as ball bearing to favour azimuthal rotation over other degrees of freedom (Figure 1).

The rigid hydrotris(indazolyl)borate scaffold exhibits a dual function: the facial coordination of the nitrogens to the ruthenium center lifts the upper rotor subunit away from the surface, while an appropriate functionalization on the opposite face allows tight anchoring on surface.[39] Indeed, the three ethylthioether groups appended to the indazole moieties provide high stability on metallic surfaces by preventing translation, rotation and rocking motions of the stator.

The rotating subunit is a rigid aromatic platform based on a central cyclopentadienyl moiety carrying four identical ferrocenylphenyl arms and one shorter tolyl arm. This structural dissymmetry finds two origins. First, in the absence of time-resolution in STM, molecular motion is probed by comparing static images and following a chemically or sterically “tagged” part of the molecule. Here, the shorter tolyl arm acts as a tag, which is easily traceable on STM images. Second, with the aim of achieving unidirectional rotation, the symmetry of the rotor had to be lowered as compared to the parent pseudo C_5 penta(ferrocenylphenyl)cyclopentadienyl ligand, so as to generate a dissymmetric energy landscape for rotary motion.

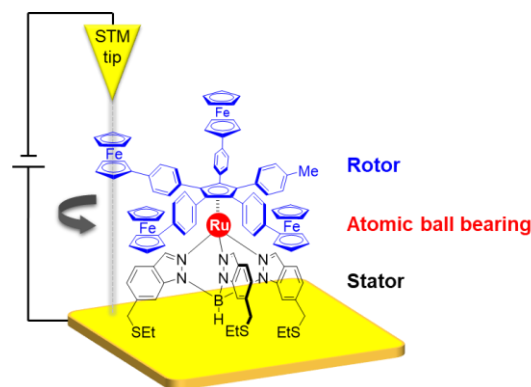
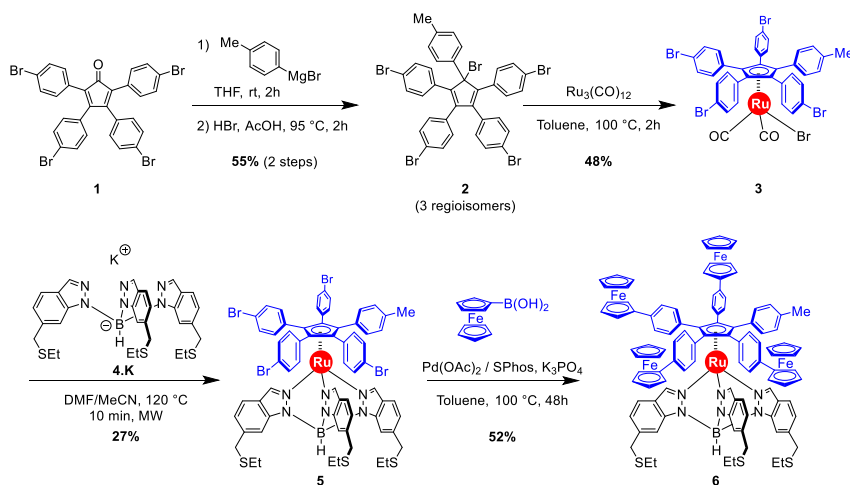


Figure 1. Structure of the ruthenium-based molecular motor adsorbed on a gold surface and related electron-fueled unidirectional rotation.

2.2 Synthesis and On-Surface Characterization

Molecular motor **6** was obtained in five steps starting from cyclopenta-2,4-dienone **1**, incorporating four identical *p*-bromophenylene arms in view of further functionalization with ferrocene moieties in the final step (Scheme 1).^[40] Introduction of the fifth arm was achieved via 1,2-addition of *p*-tolylmagnesium bromide to yield the corresponding cyclopentadienol, which was subsequently converted into bromocyclopentadiene **2** under acidic conditions. Bromocyclopentadiene **2** was obtained in 55% yield over two steps, as a 2:2:1 mixture of regioisomers. Oxidative addition on ruthenium(0) cluster $\text{Ru}_3(\text{CO})_{12}$ afforded half-sandwich ruthenium complex **3**, which underwent ligand exchange in the presence of the thioether-functionalized potassium hydrotris(indazolyl)borate **4.K** to yield the precursor of the dissymmetrized motor **5**. Finally, a four-fold Pd-catalyzed Suzuki-Miyaura coupling with ferroceneboronic acid led to molecular motor **6** in 52% yield.

After full characterization, the solid ruthenium complex **6** was deposited by sublimation on a Au(111) surface and subsequently studied by STM under ultra-high vacuum (UHV) at low temperature at the single molecule scale. STM images confirmed that some complexes remain intact after deposition and are adsorbed on the surface via the three thioether anchoring groups, as expected. At 80 K, the molecule undergoes rotation of the upper cyclopentadienyl ligand around the B-Ru axis, thereby confirming that this is the privileged degree of freedom. However, this rotation is purely related to Brownian motion and is thus a random oscillation with no directionality. Interestingly, when the temperature is lowered to 5 K, the motion is stopped and a contrast between the two different types of arms is observed on STM images, as expected from the incorporation of a tag on the rotor subunit.^[30]



Scheme 1. Synthesis of the ruthenium-based molecular motor in five steps, starting from 2,3,4,5-tetra(*p*-bromophenyl)cyclopenta-2,4-dienone.

2.3 Electron-Fueled Unidirectional and Reversible Rotation

At 5 K, excitation of the motionless complex by a voltage pulse delivered on one arm by the STM tip induces a unidirectional rotation of the upper rotor subunit. In this set-up, motion is thus triggered by an inelastic electron tunnelling process leading to stepwise rotation with angles being multiples of 24° , in line with the predicted 15 potential wells in a full 360° rotation.[30] Directionality originates from the asymmetric character of the energy landscape in the excited state, itself related to the dissymmetric architecture of the complex.

Moreover, it was observed that the direction of rotation directly depends on the nature of the excited arm, i.e. on the nature of the excited state that is addressed. The direction can thus be reversed at will by locating the STM tip apex above one of the ferrocenyl arms or above the truncated arm (Figure 2).

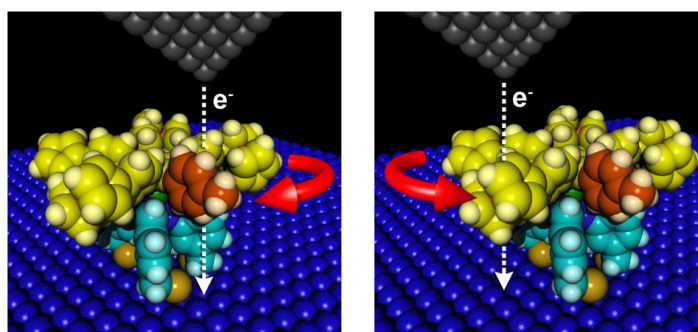


Figure 2. Electrically-driven unidirectional and reversible rotation of the ruthenium-based molecular motor, on Au(111) surface at low temperature. The direction of rotation can be reversed at will by locating the STM tip apex above one of the ferrocenyl arms (right image, counterclockwise rotation) or above the truncated tolyl arm (left image, clockwise rotation).

This organometallic structure, deposited on surface and studied as a single molecule at low temperature under ultra-high vacuum, was thus shown to convert electric energy provided by the STM tip into reversible directed motion. Following this breakthrough, new questions arose about the forces developed by this rotary motor and its ability to provide useful work, and thorough mechanical studies were thus envisioned.

3 Towards Complementary Mechanical Studies of the Molecular Motor: the Nano-winch

To gain insight in the mechanical properties of the ruthenium-based rotary motor, complementary direct and indirect studies were devised. Both approaches allow to probe forces exerted by single molecules, but they rely on different operating conditions and scanning probe microscopy techniques.

In a direct approach, force spectroscopy experiments will be performed by means of an atomic force microscope (AFM) at the solid-liquid interface in ambient conditions to determine the stall force of the rotary motor. In a second approach, the surface-bound motor will be loaded with various molecular fragments adsorbed on surface, and the electrically-driven mechanical motion of the motor at low temperature in UHV will be studied by STM as a function of the loading.

In both cases, it appears necessary to derivatize the motor structure and append a long chain, crucial for Single Molecule Force Spectroscopy (SMFS) experiments and for the connection of molecular loads. Following technomimetic principles of molecular machine design,[41,42] this derivatized rotary motor displaying a long chain can be viewed as a nano-winch.

3.1 Design of a Nano-winch Architecture

As in a macroscopic winch, the nanometer-sized counterpart will include three main parts: the motor, a long rope and a terminal hook to attach loads. The structure of the ruthenium-based rotary motor will thus be integrated in the nano-winch, in a way to maintain directionality and reversibility in the electron-fueled motion. This implies to operate minimal changes both in the architecture of the complex and in its electronic structure. It was thus envisioned to connect the long chain to the truncated arm of the cyclopentadienyl rotor, and use a chemical spacer to minimize steric and electronic interactions (Figure 3).

Polyethylene glycol (PEG) was selected as polymeric chain, since it exhibits the required adsorption properties for AFM-based force spectroscopy experiments. Additionally, the availability of monodisperse PEG chains with a broad range of polymerisation degrees is an asset to fine tune mechanical studies, and adjust the length of the chain depending on the operating conditions in the direct and indirect approaches.

Finally, a chemical hook located at the PEG chain extremity will allow the connection of various molecular loads.

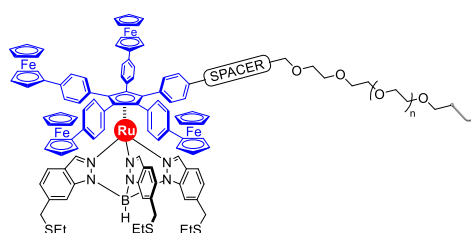


Figure 3. Architecture of the nano-winch, including the rotary motor subunit linked via a chemical spacer to a long PEG chain terminated by a hook.

3.2 Direct Strategy: AFM-Based Single Molecule Force Spectroscopy on an Unloaded Nano-winch

AFM-based single molecule force spectroscopy allows to probe mechanical forces in individual molecules and has been used to investigate various biological and artificial systems,[43] including small molecular machines such as rotaxanes [44] and catenanes.[45] AFM-based force spectroscopy is performed at the solid-liquid interface on surface-bound single molecules, i.e. the nano-winch will be adsorbed on a gold surface in a dilute distribution and immersed in a high boiling-point solvent. Bringing the AFM tip into contact with the surface will allow the PEG chain of a single nano-winch to adsorb on the tip, and the latter will be progressively moved away from the surface, leading to a stretching of the PEG chain (Figure 4). It is important to note that these experiments will be carried out at room temperature, meaning that the ruthenium-based motor will undergo random thermal motion and particularly random oscillation of the cyclopentadienyl platform. This rotation will be stopped by moving the tip further away from the surface, and the force applied on the nano-winch at that stage will give access to the stall force of the motor.

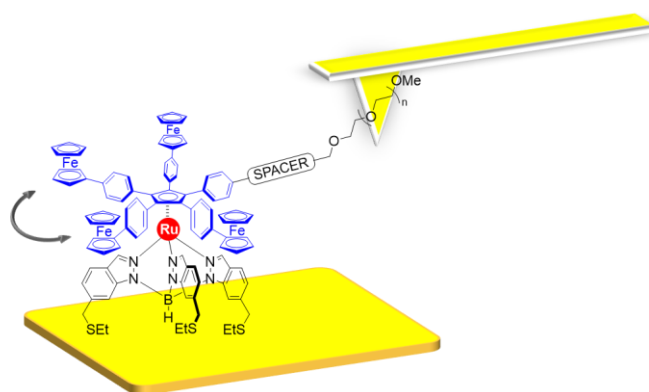


Figure 4. Principle of the AFM-based Single Molecule Force Spectroscopy experiments, performed at the solid-liquid interface under ambient conditions.

From a structural point of view, the nano-winch used in such force spectroscopy experiments will require a long PEG chain of ca. 8 nm, with a non-functionalized end. As starting point, a methoxy-terminated PEG-24 chain could thus be connected to the motor, and further fine tuning of the tether length will be possible provided a modular synthetic route towards nano-winch is devised.

3.3 Indirect Strategy: STM Study of a Loaded Nano-winch

In this alternative strategy, our aim is to study by UHV-STM at low temperature the electrically-driven rotary motion of the loaded motor, i.e. of the nano-winch connected to various molecular fragments (Figure 5).[46] After deposition on Au(111) and subsequent adsorption of the motor subunit linked to its load, lateral mechanical manipulation of the load will be performed with the STM tip at 77 K to extend the PEG chain. This layout will then be frozen by lowering the temperature to 5 K and the rotation of the motor will be triggered by a voltage pulse on one of the motor arms. Directional rotation of the rotor subunit is expected to result in a translation of the load if the force output of the motor is sufficient. It is important to note that gravity is irrelevant at the nanoscale, and the term “load” is thus not related here to weight but refers to the force exerted by the molecular fragment on the motor. Using fragments with increasing diffusion energies upon adsorption on surface, the maximal output force of the motor will be surpassed at some point, as witnessed by the absence of translation of the load. Comparison of the diffusion energies of the last translated fragment and of the first motionless one will thus give an estimation of the maximal work delivered by the single-molecule motor, and by extension of its maximal output force.

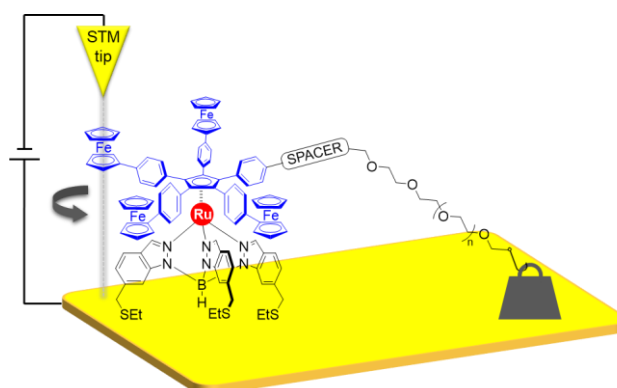


Figure 5. Principle of the LT-UHV-STM experiments on the nano-winch connected to various molecular loads, adsorbed on a gold surface. Rotary motion of the motor is triggered by a voltage pulse and subsequent translational motion of the load occurs if the maximal output force of the motor is sufficient.

From a structural point of view, the length of the PEG chain should be much shorter than for force spectroscopy experiments, and a PEG-8 building block is envisioned as starting point. The loads should be covalently bound to the chain under reliable, mild and high-yielding conditions, which is reminiscent of click reaction requirements.[47] An azide function will thus act as a hook to allow for azide-alkyne cycloaddition, yielding a 1,2,3-triazole as connector between the chain and the load.

Three different molecular loads displaying a terminal alkyne function have been synthesized, with incremental numbers of triptyceny units to induce increasing diffusion energies on surface (Figure 6).[48]

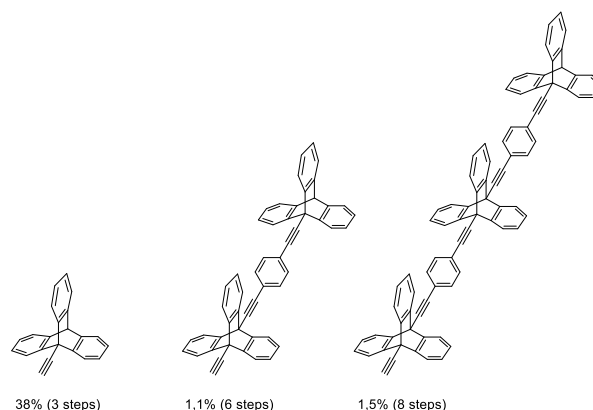


Figure 6. Structures of the three molecular loads already available, displaying a terminal alkyne function and incremental numbers of triptyceny units. The yields over the complete synthetic sequence are given below.

4 Synthesis of the Nano-winch

4.1 Preliminary Synthetic Studies and Selection of an Appropriate Spacer

In preliminary synthetic studies, attempts were made to graft the PEG chain of the nano-winch directly on the truncated arm of the motor by replacing the tolyl moiety with a PEGylated phenyl ether group.[49] However, this approach failed to afford the desired compound and introduction of a spacer between the rotor phenylene unit and the PEG chain was envisioned.

This spacer should exhibit two functions: it should allow spacial and electronic decoupling of the motor from the chain, and favour modular syntheses of nano-winches via late-stage functionalization of the motor scaffold with variable PEG derivatives. Following these guidelines, the *N*-propargyl amide fragment appeared particularly attractive due to the high availability of monodisperse carboxylic acid-terminated PEG-chains.

In our modular synthetic strategy, the common key precursor thus incorporates a dissymmetrized cyclopentadienyl ligand, with four phenylferrocenyl arms and a single phenylpropargyl amine arm. Final stage condensation with the appropriate PEGylated carboxylic acid derivative delivers the targeted nano-winch structure. However, due to the limited stability of the free propargyl amine derivative, it was decided to use the *tert*-butyloxycarbonyl-protected (BOC-protected) parent compound **7** as common precursor (Figure 7).

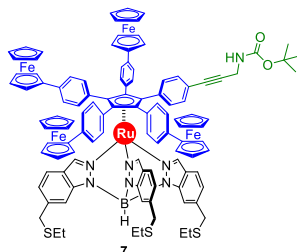


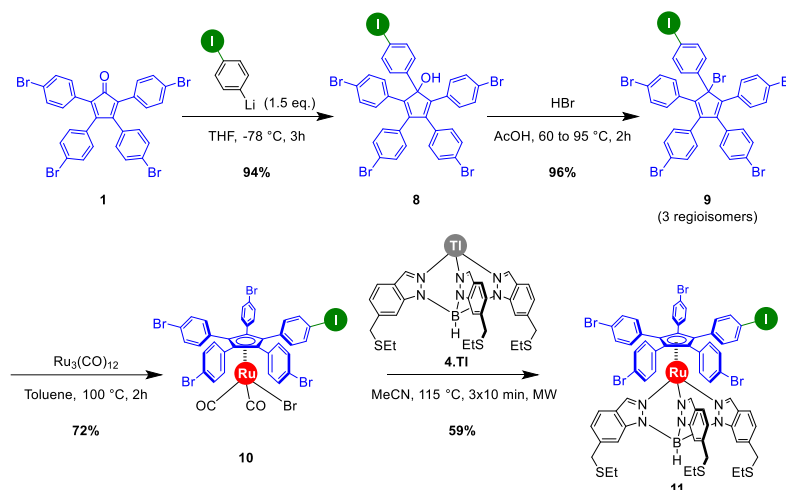
Figure 7. Structure of the key precursor to various nano-winches, featuring a *tert*-butyloxycarbonyl-protected propargyl amine fragment.

4.2 Modular Synthetic Strategy towards a Common Nano-winch Precursor

With the *N*-propargyl amide fragment selected as spacer for the diverse nano-winch prototypes, the synthetic route to the BOC-protected propargyl amine common precursor **7** was devised.

As for the parent molecular motor, the presence of a dissymmetrized rotating subunit requires the discrimination of one arm along the synthesis. Introduction of the distinct phenylpropargyl amine moiety may be performed at an early stage via a nucleophilic addition on 2,3,4,5-tetra(*p*-bromophenyl)cyclopenta-2,4-dienone **1**, similarly to the molecular motor synthetic route described above (Scheme 1). However, this linear strategy inherently limits the structural diversity of the winch spacers, and issues for the coordination to ruthenium may also be encountered with a pre-functionalized cyclopentadiene derivative. A modular strategy was thus devised, involving a late-stage functionalisation of a 1,2,3,4,5-penta(*p*-halogenophenyl)cyclopentadienyl hydrotris(indazolyl)borate ruthenium(II) precursor, carrying one single activated *p*-iodophenyl group and four *p*-bromophenyl moieties.[50] This strategy exploits the enhanced reactivity of aryl iodides compared to aryl bromides in palladium-catalyzed cross-couplings, and more particularly under Sonogashira conditions. The dissymmetrized precursor **11**, with a single *p*-iodophenyl arm, would then allow for a chemoselective Sonogashira cross-coupling to install the *N*-protected propargyl amine function, followed by a four-fold cross-coupling to incorporate the ferrocenyl moieties on the remaining brominated positions. More generally, this modular strategy was also applied to the synthesis of dissymmetric molecular gear prototypes via sequential cross-couplings (see chapter 5 "*Prototypes of molecular gears with an organometallic piano-stool architecture*" in this book).

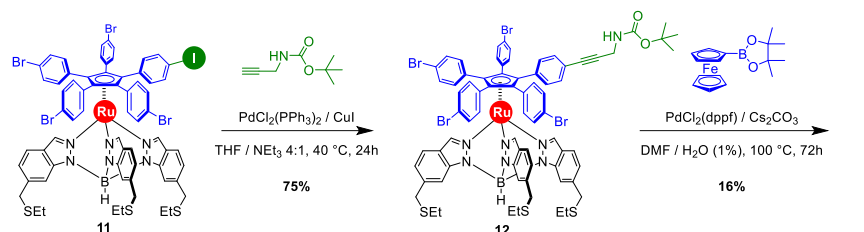
The synthesis of the dissymmetrized 1-(*p*-iodophenyl)-2,3,4,5-tetra(*p*-bromophenyl)cyclopentadienyl hydrotris(indazolyl)borate ruthenium(II) complex **11** was carried out in four steps starting from 2,3,4,5-tetra(*p*-bromophenyl)cyclopenta-2,4-dienone **1** (Scheme 2). Introduction of the iodinated arm was performed by 1,2-addition of 4-iodophenyllithium to give the corresponding alcohol **8**, which was smoothly converted to 5-bromocyclopenta-1,3-diene **9**, obtained as a mixture of three regioisomers. Subsequent reaction with ruthenium(0) cluster $\text{Ru}_3(\text{CO})_{12}$ led to a selective insertion into the central C-Br bond to yield ruthenium(II) complex **10**, carrying a dissymmetrised penta(*p*-halogenophenyl)cyclopentadienyl ligand. Finally, ligand exchange in the presence of the thallium salt of thioether-functionalized hydrotris(indazolyl)borate **4.Tl** afforded the desired precursor **11** in 38% overall yield.



Scheme 2. Synthesis of 1-(*p*-iodophenyl)-2,3,4,5-tetra(*p*-bromophenyl)cyclopentadienyl hydrotris(indazolyl)borate ruthenium(II) key intermediate.

The key pentahalogenated building block, carrying one pre-activated *p*-iodophenyl arm, was next engaged in sequential chemoselective cross-couplings to introduce successively the *N*-protected propargyl amine moiety followed by the four ferrocenyl groups (Scheme 3). The Sonogashira reaction was carried out under mild conditions using *tert*-butyloxycarbonyl-protected propargyl amine as coupling partner in the presence of Pd(0) and Cu(I) co-catalysts in a THF/triethylamine mixture at 40 °C. Chemoselective functionalization of the *p*-iodophenyl group was achieved to afford ruthenium complex **12** in 75% yield. In the next step, the four remaining *p*-bromophenyl moieties were engaged in Suzuki-Miyaura cross-couplings with ferrocene boronic acid pinacol ester as a coupling

partner, in the presence of PdCl₂(dppf) as a catalyst and a large excess of cesium carbonate as a base in a DMF/water system. The desired tetraferrocenyl product **7** was obtained in 16% yield, which corresponds to a yield of 63% per C-C bond newly formed.



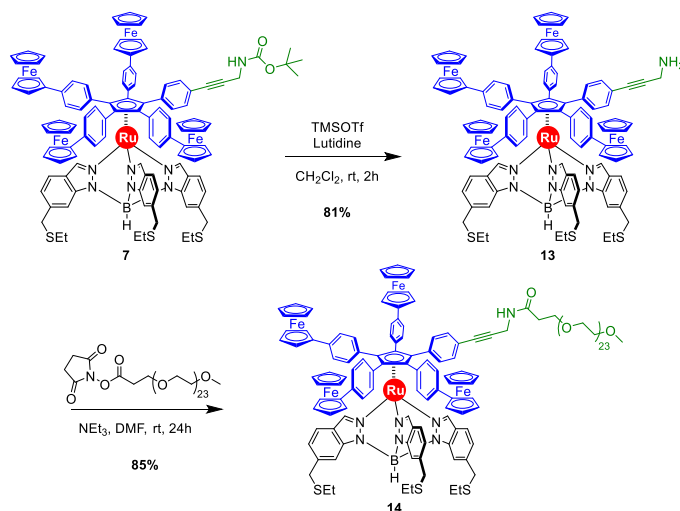
Scheme 3. Two-step synthesis of nano-winch key precursor **7** via chemoselective sequential cross-coupling reactions.

The ruthenium complex **7**, carrying four phenylferrocenyl arms and a single BOC-protected phenylpropargyl amine arm, was obtained in six steps from 2,3,4,5-tetra(*p*-bromophenyl)cyclopenta-2,4-dienone **1** in 4.6% overall yield. This compound was used as key building block in the synthesis of various nano-winch prototypes, since it proved stable enough to be stored for several months, as opposed to the corresponding deprotected amine. The preparation of each nano-winch prototype, dedicated to targeted mechanical studies, was thus further achieved in two steps involving propargyl amine deprotection followed by a condensation with the appropriate PEG chain.

4.3 Application to the Synthesis of an Unloaded Nano-winch for Single Molecule Force Spectroscopy Experiments

In view of Single Molecule Force Spectroscopy experiments, the first prototype of unloaded nano-winch was subsequently synthesized in two steps from the BOC-protected propargyl amine intermediate **7** (Scheme 4). For this first prototype, a long polyethylene glycol (PEG-24) chain was selected to ensure an efficient adsorption of the chain on the AFM tip.

Deprotection of the propargyl amine moiety in **7** was conducted under mild conditions, using trimethylsilyl triflate in the presence of lutidine to give the corresponding free amine in 81% yield. Such unusual conditions for BOC cleavage were required to maintain a buffered medium, as the ruthenium(II) complex appeared unstable under standard acidic deprotection conditions. The free propargyl amine **13** then underwent condensation with the carboxylic acid-functionalized PEG chain to generate the desired *N*-propargyl amide spacer and thereby covalently link the long chain to the motor scaffold. To maximize the efficiency of this final synthetic step, monodisperse methoxy-PEG24-propionic acid activated as an *N*-hydroxysuccinimidyl ester was selected as coupling partner. Under very mild conditions involving triethylamine in DMF at room temperature, the target compound **14** was obtained in 85% yield. Full characterization unambiguously confirmed the connection of both the *N*-propargyl amide spacer and the PEG-24 chain to the molecular motor structure, leading to a first nano-winch prototype. AFM-based Single Molecule Force Spectroscopy studies on nano-winch **14** are currently underway.



Scheme 4. Synthesis of the first nano-winch prototype dedicated to Single Molecule Force Spectroscopy experiments, in two steps from BOC-protected propargyl amine derivative 7.

5 Conclusion and Perspectives

A nano-winch architecture has been designed to get further insight in the mechanical properties of the electron-fueled molecular motor developed in our group. In view of complementary force measurements at the single molecule scale, derivatization of the organometallic motor structure was performed by appending a long polyethylene glycol chain, possibly terminated by a hook. This general nano-winch architecture has to be adjusted according to the investigation technique, such as AFM-based Single Molecule Force Spectroscopy on the oscillating unloaded motor or as low-temperature STM studies on the loaded motor.

The first nano-winch prototype incorporating a methoxy-terminated PEG24-chain has been successfully synthesized following a highly modular approach, and force spectroscopy measurements are currently underway to determine the stall force of the ruthenium-based motor.

Synthetic efforts are now dedicated to the preparation of a new nano-winch prototype displaying a terminal chemical hook, such as an azide moiety, to covalently link molecular loads (Figure 8). Electron-fueled motion of the resulting loaded nano-winch will then indirectly give access to the maximal work delivered by this rotary motor.

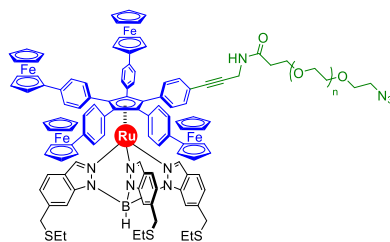


Figure 8. Structure of a future nano-winch prototype carrying an azide hook, in view of subsequent loading with alkynyl-derived molecular fragments.

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