Chapter 6

Redox-driven motion

In this chapter, an electrochemical study of a second generation overcrowded alkene molecular rotary motor is described. The overall aim was to achieve, for the first time, redox-driven unidirectional rotation of a molecular rotary motor. The overcrowded alkene was found to undergo irreversible oxidation and two products were observed. The reactions that occur upon oxidation were studied using electrochemical techniques and UV/Vis spectroelectrochemistry. The data obtained regarding these reactions provide a window of opportunity for the motor to be driven electrochemically, without degradation due to chemical reactions of the oxidised motor.
Introduction
Efforts to achieve redox-driven molecular motion have drawn inspiration from nature. One of the most famous examples is ATP-ase, which is driven by a proton gradient across a membrane. This gradient creates a potential difference, which provides the energy to synthesize ATP and rotate. Many other biological systems use a potential difference across a membrane to create motion, such as the flagella that bacteria use for propulsion. Several groups have translated these systems into molecular designs.
Sauvage and co-workers used a change in the coordination number of copper to induce rotation of two interlocked rings in a catenane. The initial copper(I) complex is tetracoordinate with two phenanthrolines. Upon oxidation to copper(II) the ion prefers pentacoordination, and ligand exchange of one of the phenanthrolines with a terpyridine occurs. By locking these two ligands in one ring and interlocking with the third ligand as a catenane, molecular rotation can take place (Figure 6-1).

![Figure 6-1](image)

*Figure 6-1* Molecular motion powered by a change in oxidation state. Reproduced with permission, copyright ACS (1997).

Another example using redox chemistry to obtain molecular motion was developed by the Stoddart group. They developed a rotaxane, which they attached to a gold cantilever. Upon oxidation, the rings of the rotaxane move ‘station’. By attaching those rings to a surface they could translate the molecular motion into macroscopic motion (Figure 6-2).
Previously the addressability of diarylethenes was expanded from light driven switches to electro- and photochromic switches.\(^3,4\) Since then the application of diarylethenes switches in molecular electronics has increased tremendously.\(^5,6\) Therefore it is interesting to expand the scope also to other systems. The opportunities presented by redox switching have been recognised by others, as Charles Sykes wrote recently: “However, as one thinks about longer-term applications, the real advantages of electrically driven synthetic molecular motors will be that one can excite single or small groups of molecules with electricity more easily than with either chemical fuel or light.”\(^7\)

A few steps have already been taken towards the development of electrochemically driven motors.

The first electrically driven motor was recently developed by Feringa and coworkers.\(^8\) In the design of the first molecular car, four molecular motors were connected via a ‘chassis’ (Figure 6-3). The motors were used to move the molecule on a surface powered by voltage pulses from a STM tip. Upon applying a 500 mV pulse, \textit{cis-trans} isomerisation was achieved. Upon applying a pulse of 200 to 350 mV, thermal helix inversion was achieved, but \textit{cis-trans} isomerisation was not observed. This was indicated by a change in contrast of the molecules on the surface, but movement was not observed. When using the appropriate stereoisomer, the \textit{meso-(R,S-R,S)} isomer, where all motors rotate in the same direction, a lateral movement over the surface was observed. For the other stereoisomers, a circular motion was observed.
The goal of the study described here is to expand the reach of redox-driven motion into applications at room temperature and in solution, in which the cis-trans isomerisation is powered electrochemically, but the thermal helix inversion is not. The thermal helix inversion is the step giving rise to unidirectional rotation in the molecular motors.

Recently electrochemical studies of bisthiaxanthylidenes were reported, which in solution can undergo three state switching, via a dicationic intermediate (Figure 6-4).

Upon oxidation at 1.2 V a dication is formed. This impressively stable dication adopts an orthogonal orientation of the two halves, which was determined by X-ray crystallography. Upon reduction, a twisted species is initially formed, which reverts to an anti-folded species spontaneously at room temperature.
These electrochemically active switches were subsequently immobilized on surfaces as SAMs (Self Assembled Monolayers). The twisted species is, remarkably, more stable on a surface, due to packing effects.

In this chapter the development of an electrochemically driven molecular motor is considered. The system studied is a second generation molecular motor, with a symmetric lower half (Scheme 6-1). Both the upper and lower half contain a sulfur atom, allowing for facile oxidation to a dication. This motor is also specifically chosen due to the long half-life of the unstable species at room temperature, which simplifies analysis.

**Scheme 6-1** Proposed molecular motion driven by oxidation to a dication species and subsequent reduction.

In this design oxidation to a dicationic species is expected, as previously observed for bisthiaxanthylidene switches. This species will twist to an orthogonal conformation, as the
central double bond becomes a single bond. After reduction both stable and unstable isomers are expected to form. Upon thermal helix inversion the unstable form will eventually go back to the more stable form. In this design unidirectionality cannot be tested, since an asymmetric lower half is needed. However, the initial step in developing a redox-driven motor is to understand what processes occur upon oxidation and whether or not a twisted state is formed.

In this chapter a combination of electrochemistry and spectroscopy is employed to gain insight into the first step of rotation in the development of a redox-driven molecular motor. As a starting point DFT (density functional theory) provides an indication as to how the motor and its oxidised form will behave.

**Density Functional Theory Calculations**

DFT calculations (using Gaussian) were performed to find the global minimum conformation for the neutral species and the dication. DFT calculations were performed both in the gas-phase and using dichloromethane as solvent. Similar results were obtained in each case. The structure of the global energy minimum of the stable form of motor A is shown in Figure 6-5.

![Figure 6-5](image)

**Figure 6-5** Optimized geometry for the stable conformation of the neutral motor, A, from DFT calculations; (from left to right) front, back and top view.

The global energy minimum of the optimized geometry for the dication shows an orthogonal conformation of the lower and upper half (Figure 6-6). The two positive charges
are localized on the sulfur atoms. Calculations were also performed on the monocationic species. For this species multiple conformations that are close in energy were calculated. The energy barrier for rotation around the single bond of the dication was also calculated. If the energy barrier is too low, free rotation around the single bond by 360° will occur. This will result in non-unidirectionality. The calculated enthalpy for rotation (for a single molecule in the gas phase) is 151 kJ/mol. This corresponds to a half-life of 1.9 million years at room temperature. In comparison, the energy barrier of the thermal helix inversion of motor C to A is 215 hours at room temperature. Hence, no influence on the unidirectionality is expected from the redox step.

Results
The overcrowded alkene A was synthesized according to literature procedures. The overcrowded alkene undergoes cis-trans isomerisation upon irradiation with UV light (λexc 365 nm), as demonstrated previously. The unstable form can be observed using UV/Vis absorption spectroscopy (Figure 6-7). Upon irradiation to the photo stationary state (PSS) a blue shift of 10 nm is observed.

Electrochemistry
Cyclic voltammetry was performed to determine the potential needed to oxidise A to the dication B²⁺ (Figure 6-8). An irreversible oxidation was observed at 1.00 V, as expected upon formation of B²⁺ (Scheme 6-1). On the return cycle a reversible reduction was observed at -0.05 V. The hysteresis is much larger than that observed for the bisthiaxanthylidene

1 A distinction is made between electrochemical and chemical reversibility. Electrochemical reversibility relates to the rate of electron transfer. A system is called electrochemically reversible when the forward and backward electron transfer rates are faster than the time scale of the experiment. Chemical reversibility refers to the stability of the species formed after reduction or oxidation towards conversion to other species.
switches (Figure 6-4), suggesting that the observed redox chemistry is not similar to that observed for the bisthiaxanthylidenes.\textsuperscript{9, 10} This difference in potential could be caused by a chemical reaction, which follows oxidation, rather than a switch from an antifolded to an orthogonal conformation, forming a new species, $D^*$.\textsuperscript{14}

![Cyclic voltammetry of A](image)

**Figure 6-8** Cyclic voltammetry of A (thick line = first cycle), scan rate = 0.1 V/s, 0.1 M TBAPF$_6$ in CH$_3$CN.

The irreversibility of the oxidation is expected to be due to a fast subsequent chemical reaction; first a conformational change would be expected to occur, as observed for the bisthiaxanthylidenes. Subsequently a chemical transformation occurs, the rate of which is faster than the time scale of the experiment.

Microelectrodes were used to further study the first oxidation. With a microelectrode, radial diffusion is observed, which allows for determination of the number of electrons transferred in the oxidation.\textsuperscript{15} At low scan rates the steady state current relates to the number of electrons passed with the following equation:

$$i_{ss} = 4nFDr[A]$$

Where: 
- $n =$ number of electrons
- $F =$ Faraday's constant
- $D =$ Diffusion constant
- $r =$ radius of the electrode
As reference compound, decamethylferrocene was added to quantify the number of electrons involved in the oxidation; the concentration ratio of motor to decamethylferrocene was 1.08. The difference in current upon oxidation ($\Delta i$) for decamethylferrocene = $\sim 3.85 (\pm 0.1) \times 10^{-9}$ A, $\Delta i$ for motor = $\sim 5.31 (\pm 0.1) \times 10^{-9}$ A. The ratio of motor to decamethylferrocene with respect to the number of electrons passed is $\sim 1.5$. This value indicates it is not a one electron oxidation. The number of $n$ being lower than two is consistent with a more complicated mechanism, such as an EEC or ECE mechanism, where an electrochemical step is followed by a chemical reaction.\textsuperscript{15} It should be noted that decamethylferrocene is not innocent in this experiment, as the oxidation of the motor does not show a typical microelectrode CV as observed before (Figure 6-9, left vs right). However, other methods used for determination of the number of electrons cannot be used, since the oxidised motor undergoes chemical reactions to species that also undergo redox reactions.

Cyclic voltammetry over a wider potential window revealed a second irreversible oxidation at 1.30 V (Figure 6-10). The second oxidation was assigned to oxidation of the initial product D. On the return cycle two reduction waves were observed, one irreversible at 0.30 V and one reversible at -0.05 V.
The conclusion that two chemical reactions occur after oxidation of A is supported by cyclic voltammetry in dichloromethane. In dichloromethane a similar cyclic voltammogram is observed as in acetonitrile, however, a different ratio in terms of the first and second oxidation waves was observed (Figure 6-11). Especially the relative current of the second oxidation is lower in dichloromethane. Importantly, the initial oxidation at 1.00 V becomes quasireversible, with a reduction wave at 0.60 V. The shift in potential of the second oxidation (from D⁺ via D²⁺ to E²⁺) indicates this is not purely electron transfer, but likely proton coupled electron transfer (vide infra).

Figure 6-10 Cyclic voltammetry of A in CH₃CN (thick line = first cycle), scan rate = 0.1 V/s, 0.1 M TBAPF₆ in CH₃CN.

Figure 6-11 Effect of solvent on the rate of formation of D⁺ and E²⁺, in CH₂Cl₂ (thick) and CH₃CN (thin), scan rate = 0.1 V/s, 0.1 M TBAPF₆.
The differences between cyclic voltammetry in acetonitrile and dichloromethane may be due to differences in water content. This was investigated by comparing dry dichloromethane and with dichloromethane saturated with water. The reduction at 0.60 V was not observed in wet dichloromethane (Figure 6-12). Water can play a number of roles in chemical reactions, since water can act as an acid, a base and a nucleophile. This will be discussed further below.

![Graph showing cyclic voltammetry results](image)

**Figure 6-12** Influence of water of the rate of the subsequent chemical reaction (to form D'), dry CH₂Cl₂ (thick) and CH₂Cl₂ with 10% water (thin), scan rate = 0.5 V/s, 0.1 M TBAPF₆.

An overview of the various species observed by cyclic voltammetry is shown in Scheme 6-2.

![Scheme 6-2](image)

**Scheme 6-2** An overview of the various processes observed by cyclic voltammetry.

A scan rate dependence in dichloromethane was performed to investigate the relative importance of oxidative product formation versus motor function. The reduction (at 0.60 V) is not observed at the lowest scan rate (0.01 V/s), although the reduction of the first
product ($D^+$) is observed. At higher scan rates the reduction at 0.60 V increases, showing relatively less conversion of $A$ to $D^+$.  

![Graph showing scan rate dependence, current normalized for the scan rate, 0.1 M TBAPF$_6$ in CH$_2$Cl$_2$.](image)

**Figure 6-13** Scan rate dependence, current normalized for the scan rate, 0.1 M TBAPF$_6$ in CH$_2$Cl$_2$.

**Bulk-electrolysis and isolation**
The product formed upon oxidation at 1.00 V was prepared and isolated using bulk electrolysis at 1.20 V. Purification was performed using column chromatography. A monocationic compound (with PF$_6^-$ as counterion) was obtained after crystallization and characterised by X-ray diffraction.

![X-ray structure of compound $D^+$.](image)

**Figure 6-14** X-ray structure of compound $D^+$.

In the obtained X-ray structure a flat lower half is observed, indicating charge localization on the lower half. C26 is sp$^2$ hybridised, in correspondence with the loss of a proton. The bond between C13 and C14 is 1.500 Å long, indicating single bond behaviour, while the bond between C14 and C26 is 1.352 Å long, indicating a double bond. The CV measured before
and after bulk electrolysis shows a reversible reduction at -0.05 V. Upon cycling to higher potentials, the oxidation of $D^+$ at 1.3 V to the second product (E) is observed (Figure 6-15). This indicates that formation of $D^+$ occurs prior to formation of E. A mass of 407 was observed (M+) for the isolated compound $D^+$.

**Figure 6-15** Cyclic voltammetry before (upper) and after (lower) bulk-electrolysis at 1.2 V, scan rate = 0.1 V/s, 0.1 M KPF$_6$ in CH$_3$CN.

**Spectroelectrochemistry**

UV/Vis spectroelectrochemistry was employed to gain insight into the structure of the products formed upon oxidation. An Otle cell (Optically Transparent Thin-Layer (spectro)Electrochemical Cell) was used. The thin layer arrangement and cell resistance necessitates slow scan rates, and as a result the formation of the electrochemical products was essentially complete and could be studied. However, ‘motor behaviour’ could not be observed on the time scale of the experiment. Upon oxidation to 1.2 V, formation of $D^+$ was observed (Figure 6-16).
The UV/Vis spectrum changed when a potential of 1.2 V was applied, with isosbestic points, indicating a clean conversion to D⁺. A broad absorption in the visible region is observed, as well as at 390 nm. However, on the return cycle no further changes were observed (Figure 6-17). The UV/Vis absorption spectrum is characteristic of a thioxanthylidinium cation⁹, consistent with the X-ray structure of the product isolated.
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Figure 6-17 UV/Vis absorption spectra of A before (thick) and D\(^+\) after (thin) electrochemistry (to 1.2V) in an Ottle cell.

Upon continued cycling to 1.4 V a second oxidation of the primary product (D\(^+\)) is observed as explained before (Figure 6-18). As observed before, both oxidations are irreversible.

Figure 6-18 Electrochemistry of A in OTTLE-cell, up to 1.4 V, in 0.1 M TBAPF\(_6\) in CH\(_2\)Cl\(_2\).

Upon oxidation at a potential higher than 1.3 V a shift of 10 nm is observed in the abs\(_{max}\) at 400 nm. The absorption bands in the visible region change shape (Figure 6-19). This spectrum is typical of a cationic species, but is distinct from that of D\(^+\). The absence of isosbestic points indicate multiple transitions occur simultaneous, i.e. A to D\(^+\) to E\(^{2+}\). Upon reduction at 0.2 V the absorption bands in the visible region disappear, indicating full reduction to a neutral species. In this case isosbestic points are observed, indicating a clean reduction from E\(^{2+}\) to E.
Figure 6-19 UV/Vis spectroelectrochemistry to 1.4 V, (left) oxidation, potential increase from 0.8 V to 1.4 V, (right) subsequent reduction, potential decrease from 0.2 V to -0.4 V.

The UV/Vis absorption spectrum of the final product is red shifted by ca. 35 nm with respect to A, indicating increased conjugation. The absence of bands between 400 and 700 nm indicate that it is a neutral species (Figure 6-20).

Figure 6-20 UV/Vis absorption spectra of A before (thick) and E after (thin) electrochemistry (up to 1.6 V).

Discussion
The cyclic voltammetric data reveals a strong role played by the solvent and the presence of water in the electrochemistry of A. In dichloromethane the anticipated behaviour of A, as discussed in the introduction, was observed. Oxidation of A to a dication (A$^2^+$, step 1 in Scheme 6-3) is followed instantly by conversion of the central double bond to a single bond between the lower and upper half, and hence a closed shell species (B$^{2+}$, step 2). Due to this single bond an orthogonal conformation is adopted, to release steric strain. This stabilizes the dication, changing the reduction potential to less positive potentials than the oxidation. This orthogonal species is equivalent to the bisthiaxanthylidinium ion studied previously and consistent with DFT calculations.9, 10 Upon reduction the double bond is restored via a
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diradical combination reaction (step 3). This can be both the stable or unstable state of the motor. Upon formation of the unstable form (C), thermal helix inversion recovers the stable form (step 4). However, the ratio of unstable to stable was not determined. An overview of the various processes is presented in Scheme 6-3.

![Scheme 6-3](image)

**Scheme 6-3** Different electrochemical and chemical steps in the redox-driven rotation of A.

However, in the presence of water the dication (B$^{2+}$) readily undergoes deprotonation. A monocationic species is formed (D$^+$), which can be reduced at -0.05 V. This species was isolated and a crystal structure was obtained. The formation of this species supports the model in which initial oxidation leads to a dication, otherwise a single bond between the lower and upper half would not be expected. Spectroelectrochemistry at 1.20 V shows the formation of the first product (D$^+$), with isosbestic points, indicating a clean conversion. The species that is formed remains cationic, as deduced from the strong absorption in the visible region and by comparison with the bisthiaxanthylidenes.$^{9,16}$

Further increasing the potential shows a second oxidation at 1.30 V, and formation of a second product E$^{2+}$ is observed. Comparison with the CV of D$^+$ showed this oxidation at a similar potential. UV/Vis spectroelectrochemistry indicates that upon reduction a neutral species is obtained, with an extended conjugated system with respect to the starting motor A. The reduction of E$^{2+}$ to E is a clean transition, as indicated in the spectroelectrochemistry by the presence of isosbestic points. Electrochemical hysteresis is still observed, since it still is an overcrowded alkene (electrochemical) switch. However, due to loss of the stereogenic centre it is no longer a unidirectional motor.

An overview of the electrochemistry and the chemical reactions is presented in Scheme 6-4.
Scheme 6-4 Overview of the various electrochemical and rotation steps involved upon oxidation of A.
A challenge in the development of the redox-driven motor A is apparent from the cyclic voltammetry. Upon oxidation, the dicationic species (B^{2+}) that is formed is not stable, but can undergo a reaction with water and form a monocationic product (D^+). This can be further oxidised to form a second product (E^{2+}) at 1.30 V. Kinetic data of these two reactions needs to be obtained to understand the limits in which to work. Based on the cyclic voltammetry a 1 : 1 ratio of motor rotation and reaction towards D^+ is observed, when using dichloromethane and a scan rate of 0.1 V/s. A model was used to fit to the obtained cyclic voltammograms, these results are presented below. However, the key challenge will be to work in fully dry conditions.

Conclusions
Although the initial goal to develop a redox-driven motor has proven to be more challenging than expected, the data presented in this chapter demonstrate that it is possible. There are a few limiting situations in which the electrochemically driven motor could work. The solvent systems needs to be chosen carefully and the presence of Bronsted bases should be avoided, as well as the presence of water. The reaction that follows oxidation of the motor leads to a cationic product, with a low potential for reduction, typical of the thiaxanthylidene cation. The electrochemical and chemical reactions are remarkably clean and allow for fitting of the data to obtain kinetic values for the side reaction. Knowing these limitations allows for the further development of an electrochemical driven overcrowded alkene motor. A possible solution would be the use of a quaternary stereogenic centre; although this remains synthetically challenging.

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Experimental section
Materials and instrumentation
All chemicals were purchased from Aldrich, Acros, or Fluka and used as received. All solvents used were analytical grade or better unless stated otherwise. Motor A was synthesized according to literature procedures.\textsuperscript{11, 13} Electrochemical measurements were carried out using a CHInstruments 600C or 760C (bi) potentiostat. All potentials are quoted with respect to the SCE. A standard electrochemical cell using a glassy carbon working electrode, Pt wire counter electrode and SCE reference electrode was used unless state otherwise. Tetra-butylammonium hexafluorophosphate (TBAPF\textsubscript{6}) was used as electrolyte in 0.1 M
concentration. UV/Vis absorption spectroelectrochemistry was carried out using a three electrode Quartz Otridge cell and an Analytik Jena Specord S600 diode array spectrometer.

**Isolation of D⁺**
A potential of 1.2 V was applied to solution of 30 mg of A in acetonitrile containing 0.1M KPF₆. A vitreous carbon working electrode, carbon rod counter electrode and Ag/AgCl wire reference electrode were used in an undivided cell. After 30 min of electrolysis the solvent was removed in vacuo. The product was dissolved in CH₂Cl₂ and filtered to remove excess electrolyte. Crystals were obtained from acetone/toluene. Mass (DART-MS, M⁺, [C₂₇H₁₉S₂]⁺, calc. 407.09) exp. 407.17.

**Fitting of cyclic voltammetry**
The kinetics of the first chemical reaction after oxidation were calculated using simulation software (CHInstruments). Using experimentally determined parameters (such as the oxidation potentials) a reasonable mechanism was proposed. Cyclic voltammetry was simulated using the CHI software. This was compared with the obtained data. A range of scan rates were run to determine the appropriate rates.

\[
\begin{align*}
A - e &\rightarrow A^+ & k_0 &= 1 \text{ s}^{-1} & E_0 &= 1.05 \text{ V} \\
A^+ - e &\rightarrow A^{2+} & k_0 &= 1 \text{ s}^{-1} & E_0 &= 1.05 \text{ V} \\
A^{2+} &\rightarrow B^{2+} & k_f &= 500 \text{ s}^{-1} & k_b &= 0.1 \text{ s}^{-1} \\
B^{2+} &\rightarrow D^+ & k_f &= 0.2 \text{ s}^{-1} & k_b &= 0.1 \text{ s}^{-1} \\
D^+ + e &\rightarrow D^{2+} & k_0 &= 10 \text{ s}^{-1} & E_0 &= 0 \text{ V} \\
B^{2+} + e &\rightarrow B^+ & k_0 &= 1 \text{ s}^{-1} & E_0 &= 0.75 \text{ V} \\
B^+ + e &\rightarrow B & k_0 &= 1 \text{ s}^{-1} & E_0 &= 0.75 \text{ V} \\
B &\rightarrow C & k_f &= 100 \text{ s}^{-1} & k_b &= 0.1 \text{ s}^{-1} \\
C &\rightarrow A & k_f &= 0.01 \text{ s}^{-1} \\
A - e &\rightarrow A^+ & k_0 &= 1 \text{ s}^{-1}
\end{align*}
\]

*Scheme 6.5* Proposed mechanism for simulation of oxidation of A.
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Figure 6-21 Simulated cyclic voltammogram of A in CH₂Cl₂, thin line = simulated data, thick line = experimental data 0.1 M TBAPF₆ in CH₂Cl₂.

X-ray crystallography

D⁺, [C₂₇H₁₉S₂][PF₆]⁺, Mᵣ = 552.54, monoclinic, P2₁/c, a = 13.900(2), b = 13.6778(19), c = 12.9211(18) Å, β = 102.8518(18)°, V = 2395.0(6) Å³, Z = 4, Dₓ = 1.532 g cm⁻³, D₀(000) = 1128, μ = 3.52 cm⁻¹, λ(MoKα) = 0.71073 Å, T = 100(1) K, 21316 reflections measured, Goof = 1.062, wR(F²) = 0.1222 for 5905 unique reflections and 401 parameters and R(F) = 0.0464 for 4559 reflections obeying F₀ ≥ 4.0 σ(F₀) criterion of observability. The asymmetric unit consists of two moieties: a cationic S-complex and a PF₆⁻ anion.

References


