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Electrochiroptical Response in Aqueous Media: 9,10-Dihydrophenanthrene-9,10-diyl Dications with Michlar's Hydrol Blue Chromophores Attached with Oligoethylene Glycol Units

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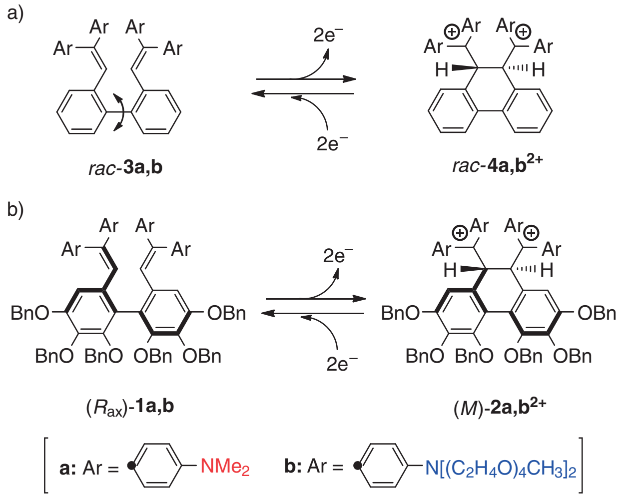
Upon electrochemical oxidation of configurationally stable biphenyl-based electron donors (R_{ax})-**1a** and -**1b** to butane-1,4-diyl dications (*M*)-**2a**$^{2+}$ and -**2b**$^{2+}$, drastic changes were induced not only in UV–vis but also in CD spectra. Because of the hydrophilic oligoethylene glycol units on the amino nitrogens, (R_{ax})-**1b** and (*M*)-**2b**$^{2+}$ are soluble in water, thus realizing the electrochiroptical behavior not only in organic solvents but also in aqueous media.

Butane-1,4-diyl dications belong to an interesting class of carbocations with high reactivity. In general, they are short-lived due to the rapid deprotonation to give the corresponding 1,3-dienes.[1] During the course of our continuing studies[2] on novel electrochromic systems[3] based on organic cationic dyes, attachment of strong electron-donating aryl groups at the 1,4-positions was shown to stabilize these intriguing dications by electronic effects.[4] For example, we previously found that 9,10-dihydrophenanthrene-type dication *rac*-**4a**$^{2+}$ with two MHB (Michler's hydrol blue) chromophores was generated upon the two-electron oxidation of 2,2′-bis[2,2-bis(4-dimethylaminophenyl)ethenyl]biphenyl (*rac*-**3a**) (Scheme 1a). The dication was isolated as a stable salt, from which *rac*-**3a** was regenerated upon reduction.[4b] The high-yield interconversion indicates that *rac*-**3a** and *rac*-**4a**$^{2+}$ can be considered as a "reversible" redox pair, although C–C bond formation–breaking is accompanied by electron transfer ("dynamic redox behavior").[5]

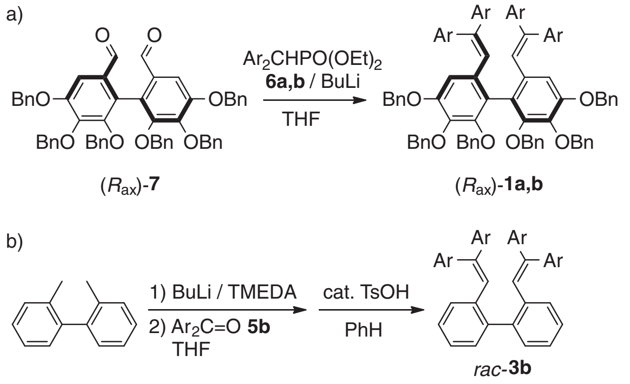


Scheme 1. Butane-1,4-diyl dication-based dynamic redox pairs.

Another interesting feature of this redox pair is the drastic change in helical geometry (e.g., the twisting angle of the biphenyl unit) upon electron transfer. Hence, the pair might be used as a redox-switchable dopant for the chiral nematic phase of lyotropic liquid crystals, which form mesophases by mixing amphipathic molecules with water. To employ the *rac*-**3a**/*rac*-**4a**$^{2+}$ pair for this purpose, there are two major issues to be concerned: 1) good solubility of the redox pair in aqueous media and 2) configurational stability of the redox pair for interconversion, without loss of enantiomeric purity.

Regarding the first point, we envisaged that attachment of hydrophilic substituents (e.g., 2-{2-[2-(2-methoxyethoxy)ethoxy]ethoxy}ethyl group, TEG) to the amino nitrogens would make it possible to conduct an electrochromic response not only in organic solvents but also in aqueous media. Thus, we designed the *rac*-**3b**/*rac*-**4b**$^{2+}$ pair as a promising candidate for less well-developed electrochromic systems working in aqueous media (Scheme 1a). The MHB-type chromophore in *rac*-**4b**$^{2+}$ is expected to be less electrophilic and would remain intact in neutral water (p$K_a$$^+$ of MHB: 5.61).[6] The second point concerns the common requirements in developing electrochiroptical response systems,[4b,4c,7] which exhibit dual electrochromic behavior of UV–vis and circular dichroism (CD). Thus, we designed a redox pair attached with benzyloxy groups on the biphenyl skeleton by assuming high configurational stability of the axial chirality in (R_{ax})-**1a** and helicity in (*M*)-**2a**$^{2+}$ (Scheme 1b). By combining the two strategies for modification shown above, we then designed the configurationally stable redox pair with TEG units, (R_{ax})-**1b**/(*M*)-**2b**$^{2+}$. By using this pair, we successfully demonstrated an electrochiroptical response in aqueous media for the first time, as detailed below.

Diarylketone **5b**[8] with four TEG units was prepared from the benzophenone derivative with two diethanolamine moieties[9] in 96% yield. This ketone was converted to the corresponding Horner–Emmons reagent **6b**[8] in 61% yield. By using **6b**, optically pure dial (R_{ax})-**7**[10] was converted to chiral donor (R_{ax})-**1b**[8] in 75% yield (Scheme 2a). When $(4\text{-}Me_2NC_6H_4)_2CHPO(OEt)_2$ **6a**[11] was used, (R_{ax})-**1a**[8] was similarly obtained in 41% yield. All these hexabenzyloxy derivatives were configurationally stable, and there was no sign of racemization upon transformation or standing. Configurationally unstable *rac*-**3b**[8] was more conveniently prepared, as in the case of *rac*-**3a**,[4b] by the reaction of ketone **5b** with 2,2′-bis(lithiomethyl)biphenyl generated from 2,2′-bitolyl and BuLi/TMEDA, followed by dehydration under acidic conditions, in two-step yield of 52%



Scheme 2. Preparation of new electron donors, (R_{ax})-**1a**, **-1b** and *rac*-**3b**.

Table 1. Redox potentials of (R_{ax})-**1a**, **-1b** and *rac*-**3a**, **-3b**, and their bond-dissociated dications (M)-**2a**$^{2+}$, **-2b**$^{2+}$ and *rac*-**4a**$^{2+}$, **-4b**$^{2+}$ measured by cyclic voltammetry (E/V vs. SCE)

Donor/dication	E^{ox}(donor)/E^{red}(dication)	
	CH_2Cl_2^{a,b}	MeCN–H_2O (1:1)^{a,c}
(R_{ax})-**1a**/(M)-**2a**$^{2+}$	+0.64/−0.23	—
(R_{ax})-**1b**/(M)-**2b**$^{2+}$	+0.77/−0.26	+0.36/−0.36
rac-**3a**/*rac*-**4a**$^{2+}$	+0.66/−0.27	—
rac-**3b**/*rac*-**4b**$^{2+}$	+0.70/−0.28	+0.33/−0.39

^{a}Two-electron processes. ^{b}0.1 M Bu_4NBF_4, Pt electrode, scan rate 100 mV s^{-1}. ^{c}0.1 M Et_4NClO_4, glassy carbon electrode, scan rate 100 mV s^{-1}.

(Scheme 2b). Although (R_{ax})-**1a** is insoluble in water, (R_{ax})-**1b** and *rac*-**3b** with TEG units are highly soluble not only in organic solvents but also in water.

According to voltammetric analysis,[12] the benzyloxy groups on the biphenyl skeleton seldom affect the redox behavior. Thus, the configurationally stable donor (R_{ax})-**1a** exhibits redox properties similar to those of *rac*-**3a** in CH_2Cl_2: the 2e-oxidation peak appeared +0.64 V vs. SCE, whereas the corresponding reduction peak was found in the far cathodic region (−0.23 V) (Table 1 and Figure S1[8]). The observed large separation of redox peaks is consistent with the dynamic redox behavior,[5] where (R_{ax})-**1a** was transformed into the corresponding dication (M)-**2a**$^{2+}$ with concomitant C–C bond formation between the two vinylic carbons. Unlike *rac*-**3a**/*rac*-**4a**$^{2+}$ pair, the electrochromic behavior of (R_{ax})-**1a**/(M)-**2a**$^{2+}$ is accompanied by a drastic change in CD (Figure 1), demonstrating the successful electrochiroptical response.[7] The presence of several isosbestic points indicates clean conversion from (R_{ax})-**1a** to (M)-**2a**$^{2+}$.

In fact, upon treatment of (R_{ax})-**1a** with iodine (3.3 equiv) in CH_2Cl_2, dication salt (M)-**2a**$^{2+}$(I_3^-)$_2$[8,13] was obtained in quantitative yield. Upon treatment of the salt with excess Zn dust in THF, (R_{ax})-**1a** was recovered in 97% yield, showing the high reversibility of the (R_{ax})-**1a**/(M)-**2a**$^{2+}$ pair. This holds true for the TEG-modified redox pairs, (R_{ax})-**1b**/(M)-**2b**$^{2+}$ and *rac*-**3b**/*rac*-**4b**$^{2+}$. Thus, oxidation of (R_{ax})-**1b** and *rac*-**3b** with iodine in CH_2Cl_2 gave (M)-**2b**$^{2+}$(I_3^-)$_2$[8,13] and *rac*-**4b**$^{2+}$(I_3^-)$_2$,[8,13] respectively, in quantitative yields. The resulting salts regenerated the corresponding neutral donors in respective yields of 95% and 92% upon treatment with Zn dust. The configurational stability was confirmed by the identical CD spectrum of the regenerated sample of (R_{ax})-**1b** from the (M)-**2b**$^{2+}$(I_3^-)$_2$ salt.

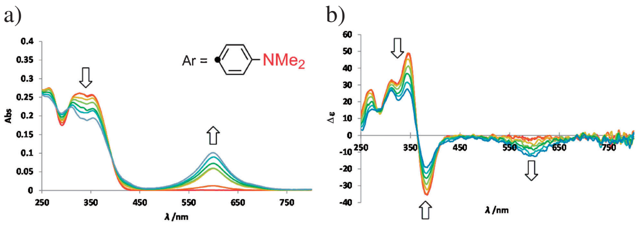


Figure 1. Continuous changes in a) UV–vis and b) CD spectra upon constant current electrochemical oxidation of (R_{ax})-**1a** (5.8 μM) in CH_2Cl_2 containing 0.05 M Bu_4NBF_4 (30 μA, every 0.5 min).

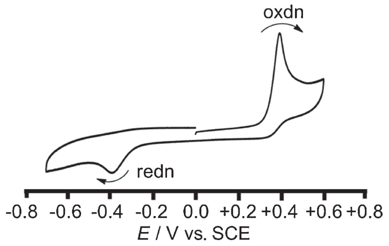


Figure 2. Cyclic voltammogram of (R_{ax})-**1b** in MeCN–H_2O (1:1) using glassy carbon as a working electrode and 0.1 M Et_4NClO_4 as a supporting electrolyte.

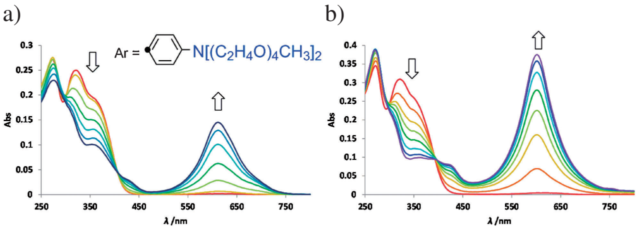


Figure 3. A continuous change in UV–vis spectrum upon constant current electrochemical oxidation of *rac*-**3b**. a) In CH_2Cl_2 containing 0.05 M Bu_4NBF_4 (5.3 μM, 30 μA, every 1 min); b) In MeCN–H_2O (1:1) containing 0.05 M Et_4NClO_4 (7.2 μM, 80 μA, every 20 min).

The voltammetric analyses[12] of (R_{ax})-**1b** and *rac*-**3b** with TEG units could be also carried out in aqueous media because of their solubility in water. As shown in Figures 2 and S1,[8] the voltammograms quite similar to those measured in CH_2Cl_2 were obtained (Table 1), showing that the electrochromic response would be also realized in aqueous media by using these TEG-modified dynamic redox pairs. Figure 3a shows a continuous change in the UV–vis spectrum upon electrochemical oxidation of *rac*-**3b** in CH_2Cl_2, and quite similar electrochromic response was observed when electrolysis was conducted in MeCN–H_2O (1:1) (Figure 3b).

By using the water-soluble chiral redox pair of (R_{ax})-**1b**/(M)-**2b**$^{2+}$, both UV–vis and CD spectra changed upon electrolysis in MeCN–H_2O (Figure 4). This is the first successful demonstration of the electrochiroptical response of an organic

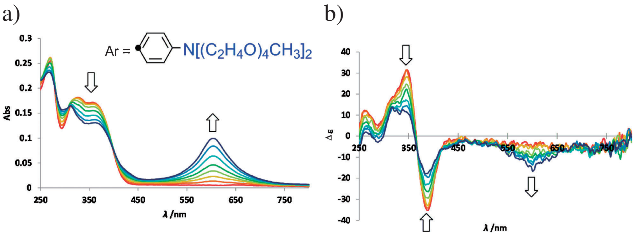


Figure 4. Continuous changes in a) UV–vis and b) CD spectra upon constant current electrochemical oxidation of (R_{ax})-**1b** (4.4 µM) in MeCN–H_2O (1:1) containing 0.05 M Et_4NClO_4 (80 µA, every 10 min).

dye in aqueous media. Studies on (R_{ax})-**1b**/(M)-$\mathbf{2b}^{2+}$ and related systems[14] are now in progress to better understand their potential for use as chiral dopants to change the molecular alignment in lyotropic liquid crystals by redox reactions.

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12 The oxidation and reduction potentials were estimated as $E_{\mathrm{anode}}{}^{\mathrm{peak}} - 0.03$ V and $E_{\mathrm{cathode}}{}^{\mathrm{peak}} + 0.03$ V, respectively. The values are reported in E/V vs. SCE at the scan rate of 100 mV s^{-1}. Cyclic voltammetry in CH_2Cl_2 was conducted by using Pt electrode and 0.1 M Bu_4NBF_4 as a supporting electrolyte. Ferrocene undergoes one-electron oxidation at +0.53 V under the similar conditions in CH_2Cl_2. Voltammetry in MeCN–H_2O (1:1) was conducted by using glassy carbon as a working electrode and 0.1 M Et_4NClO_4 as a supporting electrolyte. When H_2O was used as solvent (glassy carbon electrode, 0.1 M $NaClO_4$), quite similar redox potentials to those in MeCN–H_2O (1:1) were observed: +0.33/−0.35 V for (R_{ax})-**1b**/(M)-$\mathbf{2b}^{2+}$ and +0.29/−0.40 V for *rac*-**3b**/*rac*-$\mathbf{4b}^{2+}$, respectively.

13 In our previous studies (refs 4b and 4c), upon oxidative cyclization of (R_{ax})-biphenyl derivative, the configuration of C9 and C10 positions in the (M)-dihydrophenanthrene was arranged as (R,R).

14 Preliminary studies showed that TEG-modified chiral redox pair based on the binaphthyl skeleton acts as a chiral dopant, which can change the helical pitch of a chiral nematic phase upon electrolysis.