CHIRAL MEMORY UNITS BASED ON DYNAMIC REDOX SYSTEMS
WITH A DIBENZOXEPINONE SKELETON: DRASTIC CHANGE IN
RACEMIZATION BARRIER AND ELECTROCHEMICAL BISTABILITY

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Dedicated to Professor Victor Snieckus on the occasion of his 77th birthday

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Abstract – The configuration of helical dicationic dyes 2 2+ with a dihydrodibenzoxepinone unit is stable, whereas the corresponding neutral electron donors 1 with a tetrahydrophenanthroxepinone skeleton easily undergo ring-flip. Thanks to their electrochemical bistability, electron exchange between 1 and 2 2+ is prohibited. Thus, the above electrochromic pairs 1/2 2+ can serve as new members of less well-explored redox-based chiral-memory units.

The intermolecular transmission of asymmetric information is the very important event in the field of supramolecular chirality.1 Molecules that act as chiral-memory units play important roles in these phenomenon.2 To ensure this function, the chiral unit should be able to adopt an easily-racemized state ("erasable/writable"-state), but must also be intentionally interconvertible with the non-racemized state ("memorizing"-state) under certain conditions. Switching by heating/cooling is successfully realized in the folded polymer chains with a helical structure3 and some macrocyclic molecules.4 However, much less has been reported on compounds whose interstate-switching5 is achieved by electron transfer ("chiral redox memory") except our recent report based on the "dynamic redox pair"6 of phenanthr[4,5-cde]oxepin-type donor 3a and dibenz[c,e]oxepin-type dication 4a 2+.7

During our further studies toward the chiral memory units, we envisaged that more easily-accessible lactone analogues (1/2 2+) can serve as promising new entries (Scheme 1). Thus, the ring inversion of
4,6,10,11-tetrahydrophenanthr[4,5-cde]oxepin-4-one in 1 would occur easily at room temperature (the "erasable/writable"-state) whereas the ring flip of 5,7-dihydrodibenz[c,e]oxepin-5-one skeleton attached with two cationic chromophores at 1,11-positions in 2 would be prohibited (the "memorizing"-state). As redox active chromophores, not only spiroacridan/acridinium (a) but also spiroxanthene/xanthenylium (b) were chosen for tuning the electric potentials at which the switching occurs (Table 1). Here we report redox properties, configurational stability and electrochromic behavior of newly prepared lactone-based redox pairs (1a,b/2a,b2+), that can be applicable for realizing chiral redox memories.

Sterically congested hexaphenylethane-type molecule 1a was planned to prepare via the corresponding bond-dissociated dication 2a2+, and we first pursue generation of diacridinium 2a2+. Thus, 9,9'-{(6,6'-diformylbiphenyl-2,2'-diyl)diacridine (7) was derived from 2,2',6,6'-tetrabromobiphenyl over 3 steps in 52% yield as we reported previously. Upon treating 7 with K_{2}CO_{3} in MeOH, the Tishchenko reaction took place very smoothly to give lactone 8 in 70% yield. According to the X-ray analysis, the 5,7-dihydrodibenz[c,e]oxepin-5-one skeleton in 8 adopts a deeply twisted geometry as expected, and the torsion angle of C1-C11b-C11a-C11 is as large as 52.4(8)º (Figure 1). When diacridine 8 was treated with MeOTf (25 equiv.) in CH_{2}Cl_{2} in the presence of 2,6-di-t-butyl-4-methylpyridine (DTBMP) at room temperature, 2a2+(TFO)_{2} was obtained as an orange-yellow solid containing a small amount of DTBMP-H TFO', which was directly treated with Zn dust in THF to give desired 1a11 in 49% yield over two steps (Scheme 2). In the preparation of spiroxanthene 1b, the Tishchenko Reaction was again featured as a key step. Thus, 4',5'-dibromodispiro[xanthene-9,9'\(9H,10'H\)-phenanthrene-10',9''-xanthene]
9\textsuperscript{13} was converted to the corresponding dialdehyde 10\textsuperscript{14} as we reported previously, and then 10 was treated with K\textsubscript{2}CO\textsubscript{3} in MeOH to give desired 1b\textsuperscript{11} in 33\% yield (Scheme 3).

According to the voltammetric analyses in MeCN, 1a undergoes 2e-oxidation at \(E^{\text{ox}}\) of +0.27 V (irrev.) vs SCE (Figure 2). Under the similar conditions, \(E^{\text{ox}}\) of 1b is +1.08 V (irrev.), thus we can modify the electron donating ability of 1 by changing the heteroatom in the tricyclic spiro-skeletons as designed. In each case, the reduction peak appeared in the far cathodic region, which corresponds to the reduction process of bond-dissociated dication 2a\textsuperscript{2+}(\(E^{\text{red}}\) = −0.07 V; irrev.) or 2b\textsuperscript{2+}(+0.52 V; irrev.). Such a shift in redox peaks is characteristic to the dynamic redox pair undergoing drastic structural changes upon electron transfer.\textsuperscript{6} Thanks to the electrochemical bistability, there would be no chance of electron-exchange between 1 and 2\textsuperscript{2+}, which is one of the most important features in utilizing them as the memory units.
Despite the microscopic irreversibility of electrochemical processes, the voltammograms did not change after many scans, showing that the total redox processes involving interconversion between 1 and 2\textsuperscript{2+} are reversible. In fact, upon treatment of 1\textsubscript{a} with two equiv. of one-electron oxidant [(4-BrC\textsubscript{6}H\textsubscript{4})\textsubscript{3}N\textsuperscript{+}SbCl\textsubscript{6}⁻], 2a\textsuperscript{2+}(SbCl\textsubscript{6}⁻)\textsubscript{2} was isolated as a stable yellow solid in 85% yield. This is also the case of less-donating 1\textsubscript{b}, and thus 2b\textsuperscript{2+}(SbCl\textsubscript{6}⁻)\textsubscript{2} was obtained in 70% isolated yield. Upon treatment with Zn dust in THF, these salts regenerated neutral donors 1\textsubscript{a} and 1\textsubscript{b} in respective yields of 90 and 91%. Based on the reversible interconversion, the redox pairs of 1a,b/2a,b\textsuperscript{2+} can serve as novel electrochromic systems. Thus, upon constant-current electrochemical oxidation, a colorless MeCN solution of 1a turned into yellow, and a continuous change of UV-Vis spectrum into that of 2a\textsuperscript{2+} was observed (Figure 3a). Presence of several isosbestic points indicated clean conversion as well as negligible steady-state concentration of intermediary cation-radical species. The electrolysis of colorless 1b to orange 2b\textsuperscript{2+} was also followed by UV-Vis spectrum (Figure 3b). It is evident that the absorption bands of the dications 2\textsuperscript{2+} differ depending on the kind of heteroatom in the cationic chromophores.

![Cyclic voltammogram of 1a in 0.1 M Et\textsubscript{4}NClO\textsubscript{4} MeCN solution at scan rate of 100 mV s\textsuperscript{-1}. Pt working and counter electrodes were used.](image)

**Figure 2.**

![Changes in the UV-Vis spectra of (a) 1a (2.54 x 10\textsuperscript{-5} M) and (b) 1b (4.01 x 10\textsuperscript{-5} M) in MeCN (containing 0.05 M Et\textsubscript{4}NClO\textsubscript{4}) upon constant-current electrochemical oxidation (39 µA at 2-min interval, and 30 µA at 4-min interval, respectively). In-situ electrochemical reduction of the as-prepared dications 2a,b\textsuperscript{2+} exhibited complete recovery of 1a,b](image)

**Figure 3.** Changes in the UV-Vis spectra of (a) 1a (2.54 x 10\textsuperscript{-5} M) and (b) 1b (4.01 x 10\textsuperscript{-5} M) in MeCN (containing 0.05 M Et\textsubscript{4}NClO\textsubscript{4}) upon constant-current electrochemical oxidation (39 µA at 2-min interval, and 30 µA at 4-min interval, respectively). In-situ electrochemical reduction of the as-prepared dications 2a,b\textsuperscript{2+} exhibited complete recovery of 1a,b.
Finally, the redox control of configurational stability was studied by VT-NMR. The methylene protons of the dihydroxepinone skeleton in spiroacridan 1a in C₆D₆ appeared as the double doublets at 10 ºC, which gradually coalesced (T_c = 45 ºC) and became a sharp singlet at 70 ºC (Figure 4a). Based on the results, the energy barrier of the ring flip in 1a was calculated to be 16 kcal mol⁻¹, which means easy interconversion of enantiomers at room temperature ("erasable/writable"-state). In the case of spiroxanthene 1b, the same ΔG‡ value (16 kcal mol⁻¹ in CDCl₃, T_c = 40 ºC) was determined. These ΔG‡ values are slightly larger than that for the structurally related dihydroxepin 3a (12 kcal mol⁻¹) without a carbonyl group in the seven-membered ring, showing that the lactone unit slightly changes the barrier. However, more drastic changes would be observed upon oxidation of 1a,b. In fact, the ¹H NMR spectra of dications 2a,b²⁺ showed no temperature dependence (Figure 4b), and thus the lower limit of energy barrier of 2a²⁺ was estimated as 21 kcal mol⁻¹ from T_c > 150 ºC in DMSO-d₆. Thus, it is highly probable that the configuration of 2a,b²⁺ is stable enough for their use as "memorizing"-states.

To get more clue to the configurational stability of dications 2²⁺, optical resolution of diacridine 8 was conducted, because this precursor for the dication 2a²⁺ would have the similar energy barrier to that of 2a²⁺. Separation by using chiral HPLC (DAICEL CHIRALPAK IA) was found effective. Although the second fraction was contaminated by the antipode due to partial peak overlap, the first fraction [(M)-8] was isolated as optically pure form. The CD spectrum shown in Figure 5 did not change for a long time without any loss of CD intensity, showing that the energy barrier is quite high (ΔG‡ > 25 kcal mol⁻¹).

Figure 4. VT-NMR spectra of (a) spiroacridan 1a in C₆D₆ and (b) dication 2a²⁺(SbCl₆⁻)₂ in DMSO-d₆

Figure 5. CD spectra of the (M)-8 (1.51 x 10⁻⁵ M) in CH₂Cl₂.
In summary, we designed polycyclic lactone-based redox pairs $1\text{a,}\text{b}/2\text{a,}\text{b}^{2+}$ having spiroacridan/acridinium and spiroxanthene/xanthenyl chromophores as new entries into less well-developed category of redox-based chiral memory units. They were prepared by using the Tishchenko reaction as a key step. The electrochemical bistability characteristic to the dynamic redox systems was confirmed also in $1\text{a,}\text{b}/2\text{a,}\text{b}^{2+}$ by the large shift of redox peaks in the voltammograms. Despite microscopic irreversibility, the redox cycles between $1\text{a,}\text{b}$ are $2\text{a,}\text{b}^{2+}$ are reversible as demonstrated by good isolated-yield interconversion as well as electrochromic behavior exhibiting isosbestic points. The drastic change in racemization barrier of $1\text{a,}\text{b}/2\text{a,}\text{b}^{2+}$ was indicated based on the VT-NMR analyses. In this way, we now conclude that the newly prepared redox pairs $1\text{a,}\text{b}/2\text{a,}\text{b}^{2+}$ are promising candidates for feature use of chiral redox memory units.

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REFERENCES AND NOTES


10. T. Seki, T. Nakajo, and M. Onaka, *Chem. Lett.*, 2006, 35, 824; Typical procedure: A suspension of dialdehyde 7 (150 mg, 266 μmol) and K₂CO₃ (220 mg, 1.59 mmol) in MeOH 6 mL was stirred at 27 °C for 15.5 h. After diluted with water, the whole mixture was extracted with CHCl₃. The combined organic layers were washed with water and brine, and dried over anhydrous Na₂SO₄. After filtration, the crude reaction mixture was concentrated under reduced pressure. The residue was purified by recrystallization from EtOH to give lactone 8 (64.7 mg) as a yellow solid. Mother liquor was purified by flash chromatography on silica gel (CHCl₃ : EtOAc = 1 : 1, 0.5% v/v Et₃N) to give 8 (40.3 mg) as a yellow solid in a total yield of 70%.

11. Data for 1a: ¹H NMR (300 MHz, CDCl₃) δ 7.90 (1H, dd, 1.8 Hz, 7.1 Hz) 7.44 (1H, dd, J = 1.8 Hz, 6.6 Hz), 7.19-7.35 (4H, m), 6.99 (4H, ddd, J = 1.8 Hz, 8.3 Hz, 8.3 Hz), 6.79 (1H, d, J = 7.9 Hz), 6.38-6.64 (7H, m), 6.20 (2H, br-s), 5.77 (1H, d, J = 7.3 Hz), 5.71 (1H, d, J = 7.2 Hz), 5.39 (1H, d, J = 12.5 Hz), 5.22 (1H, d, J = 12.5 Hz), 2.73 (3H, s), 2.72 (3H, s); IR (KBr) ν cm⁻¹ 3069, 2961, 2871, 2820, 1720, 1548, 1475, 1427, 1383, 1363, 1324, 1280, 1245, 1169, 1135, 1101, 1059, 1039, 986, 863, 793, 750, 699, 657; LR-MS (EI) m/z 594 (M⁺, BP), 579 ([M-CH₃]⁺, 98), 535 ([M-CH₃-CO₂]⁺, 9.7), 446 (11), 368 (12), 297 (M²⁺, 21), 278 (74), 185 (13), 171 (11), 157 (16), 129 (29), 97 (24), 83 (28), 57 (51).

Data for 1b: ¹H NMR (300 MHz, CDCl₃) δ 7.99 (1H, ddd, J = 1.8 Hz, 4.4 Hz, 9.0 Hz), 7.54 (1H, td, J = 1.4 Hz, 7.2 Hz), 7.33-7.37 (3H, m), 7.22-7.28 (2H, m), 7.19 (2H, br-s), 7.04 (2H, br-s), 6.82 (2H, br-s), 6.71 (1H, br-s), 6.61 (4H, br-s), 6.46 (2H, br-s), 5.72 (2H, br-s), 5.42 (1H, br-d, J = 9.5 Hz), 5.27 (1H, br-d, J = 9.5 Hz); IR (KBr) ν cm⁻¹ 3066, 2923, 2855, 1713, 1598, 1571, 1477, 1442,
Data for $2a^2^+(\text{SbCl}_6^-)_2$: $^1H$ NMR (300 Hz, CD$_3$CN) $\delta$ 8.46 (2H, dd, $J = 7.9$ Hz, 8.8 Hz), 8.26 (1H, dd, $J = 1.5$ Hz, 6.8 Hz), 8.07-8.14 (1H, m), 8.02 (2H, dd, $J = 1.1$ Hz, 7.9 Hz), 7.63-7.72 (1H, m), 7.68 (2H, dd, $J = 1.5$ Hz, 7.9 Hz), 7.59 (2H, dd, $J = 1.5$ Hz, 7.9 Hz), 7.54 (1H, dd, $J = 1.1$ Hz, 8.6 Hz), 7.32 (1H, ddd, $J = 1.1$ Hz, 6.4 Hz, 8.8 Hz), 7.27 (1H, ddd, $J = 1.1$ Hz, 6.4 Hz, 8.6 Hz), 7.13 (1H, dd, $J = 1.5$ Hz, 7.9 Hz), 7.06 (1H, dd, $J = 1.5$ Hz, 7.9 Hz), 6.41 (1H, dd, $J = 1.1$ Hz, 8.6 Hz), 6.29 (1H, br-d, $J = 8.8$ Hz), 5.66 (1H, d, $J = 12.6$ Hz), 5.50 (1H, d, $J = 12.6$ Hz), 4.54 (3H, s), 4.52 (3H, s). IR (KBr) $\nu$ cm$^{-1}$ 3083, 2957, 1727, 1608, 1578, 1548, 1460, 1445, 1370, 1278, 1192, 1026, 1015, 765, 707, 653, 602.

Data for $2b^2^+(\text{SbCl}_6^-)_2$: $^1H$ NMR (300 MHz, CD$_3$CN) $\delta$ 8.54 (1H, d, $J = 7.2$ Hz), 8.36 (2H, dd, $J = 3.9$ Hz, 7.8 Hz), 8.27 (1H, d, $J = 3.9$ Hz), 8.23 (2H, dd, $J = 2.4$ Hz, 6.6 Hz), 8.14 (1H, d, $J = 7.5$ Hz), 7.79-7.87 (4H, m), 7.54-7.64 (4H, m), 7.29 (1H, d, $J = 7.9$ Hz), 7.23 (1H, d, $J = 7.9$ Hz), 6.80 (1H, d, $J = 8.6$ Hz), 6.70 (1H, d, $J = 8.6$ Hz), 5.74 (1H, d, $J = 12.8$ Hz), 5.57 (1H, d, $J = 12.8$ Hz); IR (KBr) $\nu$ cm$^{-1}$ 3075, 2954, 2925, 2855, 1728, 1621, 1598, 1577, 1537, 1502, 1367, 751.

Data for 8: $^1H$ NMR (300 MHz, CDCl$_3$) $\delta$ 8.08 (1H, d, $J = 8.8$ Hz), 8.03 (1H, d, $J = 8.8$ Hz), 7.95 (1H, dd, $J = 1.5$ Hz, 7.9 Hz), 7.69 (1H, dd, $J = 1.3$ Hz, 7.9 Hz), 7.61 (2H, br-d, $J = 7.9$ Hz), 7.57 (1H, br-d, $J = 6.0$ Hz), 7.41 (2H, dd, $J = 7.9$ Hz, 7.9 Hz), 7.40 (1H, dd, $J = 1.1$ Hz, 7.9 Hz), 7.29-7.37 (3H, m), 7.23 (2H, d, $J = 10.3$ Hz), 7.14 (1H, ddd, $J = 0.9$ Hz, 6.4 Hz, 8.8 Hz), 7.03 (1H, dd, $J = 1.5$ Hz, 7.9 Hz), 6.98 (1H, dd, $J = 1.3$ Hz, 7.9 Hz), 6.70-6.77 (2H, m), 5.79 (1H, d, $J = 8.8$ Hz), 5.68 (1H, d, $J = 8.4$ Hz), 5.57 (1H, d, $J = 11.7$ Hz), 5.36 (1H, d, $J = 11.7$ Hz); IR (KBr) $\nu$ cm$^{-1}$ 3063, 1728, 1626, 1608, 1554, 1538, 1517, 1460, 1436, 1407, 1370, 1353, 1263, 1227, 1083, 1013, 856, 818, 795, 751, 690, 649, 639, 629, 618, 612, 603 cm$^{-1}$; LR-MS (FD) $m/z$ 564 (M$^+$, BP).

12. Crystal data of 8•CHCl$_3$: $C_{41}H_{25}N_2O_2Cl_3$, $M = 564.63$, triclinic $P$-1, $a = 9.506(10)$ Å, $b = 12.48(2)$ Å, $c = 14.54 (2)$ Å, $\alpha = 109.84(2)$ $^\circ$, $\beta = 93.32 (2)$ $^\circ$, $\gamma = 98.47(2)$ $^\circ$, $V = 1594.1(2)$ Å$^3$, $Z = 2$, $D_c = 1.42$ gcm$^{-3}$, independent reflection 6844 (all), 4304 (2$\sigma$), $T = 153$ K, $R = 9.7\%$, CCDC 951650.
