A Bifunctional Molecule that Receives Two Electrons Sequentially through Only One of Its Two Reducible Groups

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We report here the first example of a molecule, containing two electroactive groups, one on either end, that sequentially and reversibly accepts two electrons at the same potential with the electrons being inserted and removed through one end of the molecule.

There are many examples of organic and organometallic species that can be reduced (or oxidized) in a series of two or more steps. In most cases, the introduction or removal of each electron occurs with greater difficulty than that for the previous electron so that, when carried out electrochemically, the reduction (or oxidation) steps occur at distinctly different potentials. An example is the reduction of aromatic hydrocarbons in nonaqueous solvents, which occurs in two steps separated by several hundred millivolts.[1] There are some systems in which two electrons can be introduced at essentially the same potential, a well-known example being the 1,ω-bis(4-nitrophenyl)alkanes **1** ($n = 2-4$).[2] The ease of reduction of the two nitrophenyl groups is very similar by virtue of the fact that they are identical and sufficiently separated so as to interact only very weakly. Obviously, it is not meaningful to ask which group is the first to react. In the cyclohexyl bromide derivatives **2**, the first step of reduction occurs at the substituted benzoate group followed by internal electron transfer with concerted carbon−bromine bond cleavage.[3] The resulting alkyl radical then accepts a second electron to form the carbanion. For **2** the order of reduction is clear, but the overall process is irreversible owing to the internal dissociative electron-transfer reaction.
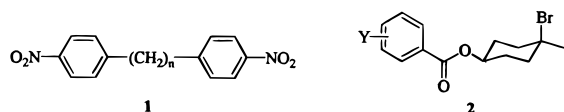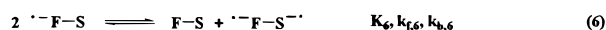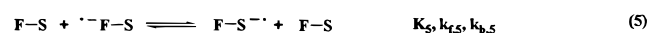

We have prepared the 4-cyanobenzoate ester **3** with the intention of creating a molecule with two reducible groups with almost identical electron-accepting properties but which differ dramatically in the rate of electron transfer to the group.[4] The cyanobenzoate functionality may be considered the "fast" end of the molecule because its electron-transfer kinetics are exceedingly facile as is typical for an aromatic system. The tertiary nitroalkane

portion is the "slow" end, reflecting the peculiarly sluggish electron-transfer kinetics of nitroalkanes, particularly when studied using bulky cations in the supporting electrolyte.
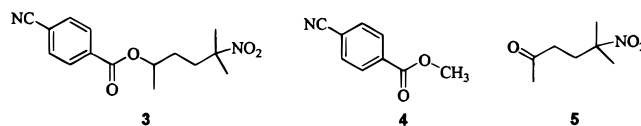
The expected properties of **3** manifest themselves in fragments **4** and **5**. The cyclic voltammograms of **4** (Figure 1A) indicate that it is reduced in a reversible process ($k_s > 0.1$ cm/s) with a formal potential of −2.07 V vs ferrocene.[5] By contrast, nitroketone **5** is reduced irreversibly with a very large separation between cathodic and anodic peaks (Figure 1B). The standard rate constant for reduction of **5** is 2×10^{-3} cm/s which is typical[6] for a tertiary nitroalkane (cf. 4.1×10^{-3} cm/s for 2-methyl-2-nitropropane under the same conditions[6c]). The rate constant was evaluated by fitting digital simulations[7] to the experimental voltammogram from which the formal potential was also evaluated to be −2.06 V, almost identical to that of **4**. Because of the sluggish electron-transfer kinetics of **5**, very little reduction occurs near its formal potential.

A typical cyclic voltammogram for **3** is also included in Figure 1. There is a single reduction peak accompanied by one oxidation peak on the return scan. The peak height corresponds to an overall two-electron reduction that is reversible and occurs near the expected formal potential of the fast end of the molecule. We infer from these results the following reaction sequence:

$$\text{F}-\text{S} \xrightarrow{\text{e}^-} \cdot^-\text{F}-\text{S} \qquad E^\circ_1, k_{s,1}, \alpha_1 \tag{1}$$

$$\cdot^-\text{F}-\text{S} \rightleftharpoons \text{F}-\text{S}^{\cdot -} \qquad K_2, k_{f,2}, k_{b,2} \tag{2}$$

$$\text{F}-\text{S}^{\cdot -} \xrightarrow{\text{e}^-} \cdot^-\text{F}-\text{S}^{\cdot -} \qquad E^\circ_3, k_{s,3}, \alpha_3 \tag{3}$$

$$\text{F}-\text{S} \xrightarrow{\text{e}^-} \text{F}-\text{S}^{\cdot -} \qquad E^\circ_4, k_{s,4}, \alpha_4 \tag{4}$$

$$\text{F}-\text{S} + \cdot^-\text{F}-\text{S} \rightleftharpoons \text{F}-\text{S}^{\cdot -} + \text{F}-\text{S} \qquad K_5, k_{f,5}, k_{b,5} \tag{5}$$

$$2 \cdot^-\text{F}-\text{S} \rightleftharpoons \text{F}-\text{S} + \cdot^-\text{F}-\text{S}^{\cdot -} \qquad K_6, k_{f,6}, k_{b,6} \tag{6}$$

Here F denotes the fast end of the molecule (cyanobenzoate group) and S is the slow end (nitroalkyl group). Recall that the electron affinity of both groups will be almost identical based on the study of fragments **4** and **5**. The reaction is initiated by the introduction of an electron into the fast end forming the radical anion of the cyanobenzoate group (reaction 1). This reaction is followed by

(1) (a) Perichon, J. In *Encyclopedia of Electrochemistry of the Elements*; Bard, A. J.; Lund, H., Eds.; Dekker: New York, 1978; vol XI, pp 71−161. (b) For a discussion of the factors affecting the separation in potentials, see: Evans, D. H.; Hu, K. *J. Chem. Soc., Faraday Trans.* **1996**, *92*, 3983−3990.

(2) Ammar, F.; Savéant, J. M. *J. Electroanal. Chem.* **1973**, *47*, 115−125.

(3) Antonello, S.; Maran, F. *J. Am. Chem. Soc.* **1998**, *120*, 5713−5722.

(4) (a) Compound **5** was prepared by the base-catalyzed addition of 2-nitropropane to methyl vinyl ketone. This nitroketone was reduced to the corresponding alcohol with sodium borohydride. Finally, ester **3** was formed by reaction of the alcohol with 4-cyanobenzoyl chloride. We also prepared 2,4,4-trimethylpentyl 4-cyanobenzoate as a model of **3** by reaction of the commercially available alcohol with 4-cyanobenzoyl chloride. This ester **6**, whose size, shape, and molecular weight are almost identical to those of **3**, was used to confirm our measurement of the diffusion coefficient of **3** by steady-state microelectrode voltammetry or chronocoulometry[4b] with 9,10-anthraquinone ($D = 2.07 \times 10^{-5}$ cm²/s at 298 K in acetonitrile) as standard. The results were $D_6 = 1.35 \times 10^{-5}$ cm²/s and $D_3 = 1.38 \times 10^{-5}$ cm²/s. (b) Oliver, E. W.; Evans, D. H.; Caspar, J. V *J. Electroanal. Chem.* **1996**, *403*, 153−158.

(5) Cyclic voltammetry was carried out with EG&G Princeton Applied Research (PAR) model 283 electrochemistry system, a PAR 303 static mercury drop working electrode (smallest drop size), acetonitrile as solvent with 0.10 M Bu₄NPF₆ electrolyte. Resistance compensation was applied at the level of 310 Ω. The standard heterogeneous electron-transfer rate constant, k_s, is a measure of the reversibility of the electron-transfer reaction. The value given for **4** is approximate because no attempt was made to account accurately for the effects of solution resistance. The potentials are actually the half-wave potentials which differ from the reversible formal potential by a small term (usually less than 10 mV), involving the diffusion coefficients of reactant and product. The potentials have been referred to the reversible half-wave potential of the ferrocenium/ferrocene couple measured under the same conditions as used for **3**−**5**.

(6) (a) Savéant, J. M.; Tessier, D. *J. Electroanal. Chem.* **1975**, *65*, 57−66. (b) Savéant, J. M.; Tessier, D. *J. Phys. Chem.* **1977**, *81*, 2192−2197. (c) Corrigan, D. A.; Evans, D. H. *J. Electroanal. Chem.* **1980**, *106*, 287−304. (d) Petersen, R. A.; Evans, D. H. *J. Electroanal. Chem.* **1987**, *222*, 129−150. (e) Gilicinski, A. G.; Evans, D. H. *J. Electroanal. Chem.* **1989**, *267*, 93−104. (f) Evans, D. H.; Gilicinski, A. G. *J. Phys. Chem.* **1992**, *96*, 2528−2533.

(7) Simulations were performed using the software package DigiSim (Version 2.1, Bioanalytical Systems, West Lafayette, IN). In the simulations a stepsize of 1 mV and an exponential expansion factor of 0.5 were used.
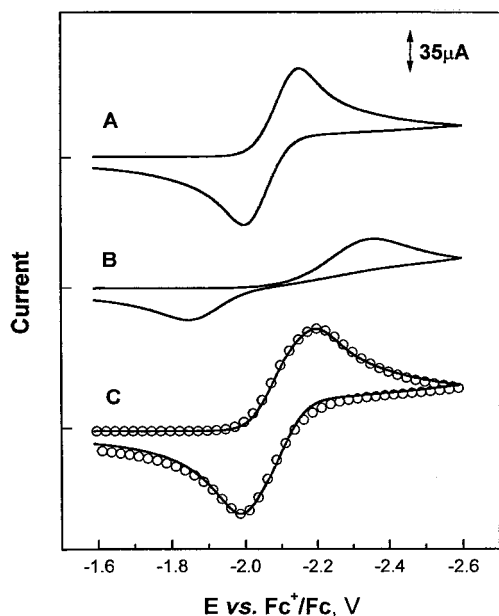
Figure 1. Cyclic voltammograms of **3** and fragments **4** and **5**. Scan rate: 40 V/s. (A) 1.17 mM **4**. (B) 1.00 mM **5**. (C) 0.98 mM **3** (line). Digital simulation (circles). Simulation parameters: $E°_1 = -2.058$ V, $k_{s,1} = 0.076$ cm/s, $\alpha_1 = 0.5$; $K_2 = 0.3$, $k_{2,f} = 2 \times 10^5$ s^{-1}, $E°_3 = -2.080$ V, $k_{s,3} = 0.076$ cm/s, $\alpha_3 = 0.5$. The area of the mercury drop was 9.8×10^{-3} cm^2, and the temperature was 298 K.

intramolecular electron transfer from the fast to slow end of the molecule (reaction 2) with subsequent introduction of a second electron into the fast end to form the dianion final product (reaction 3).

On the return sweep, oxidation occurs by the reverse of the above sequence, i.e., an electron is transferred from the dianion to the electrode through the fast end (reverse of reaction 3), an intramolecular electron transfer occurs (reverse of reaction 2), and finally, the second electron is transferred to the electrode through the fast end.

Reactions 4–6 represent alternative pathways for introducing electrons into the slow nitroalkyl group. The first of these, reaction 4, is the direct electron transfer from the electrode to the slow end, a process that is too slow to contribute significantly. In fact, if one assumes that the formal potentials and rate parameters for reduction of **3** (reactions 1 and 4) are identical to those of fragments **4** and **5**, fewer than 3% of the electrons will enter **3** through the slow end at the formal potential for fast end reduction.[8]

Reaction 5 is the intermolecular transfer of an electron to the slow end. We assessed the importance of this reaction by determining the rate of intermolecular electron transfer between the radical anion of **4** and neutral **5** by the method of homogeneous redox catalysis.[6e,9] The latter reaction should be a good model for reaction 5. It was found that the rate constant for reaction of

the radical anion of **4** with neutral **5** was 6×10^6 M^{-1}s^{-1} and, in the simulations to be described below, it was found that when this value was used for $k_{f,5}$, the effect on the simulated voltammogram was negligible. Disproportionation reaction 6 also involves electron transfer to the slow end of **3** and is only slightly downhill based on the formal potentials of **4** and **5**. Its rate constant, $k_{f,6}$, should be similar to $k_{f,5}$, so that reaction 6 will also make a negligible contribution to the rate of reduction of the slow end of the molecule. Thus, it is concluded that intramolecular electron transfer (reaction 2) is the most important pathway for getting electrons into the nitroalkane functionality of **3**.

What is the rate constant for the intramolecular electron transfer? Clearly it is a rather rapid process because complete, overall two-electron reduction (reactions 1–3) is seen even at 40 V/s (Figure 1C). The separator between the cyanobenzoate group and the aliphatic nitro group is rather short, essentially a four-carbon saturated chain. In addition, the separator is quite flexible, allowing easy attainment of conformations in which the nitro group and the π-system of the cyanobenzoate group are very close to one another. Thus, **3** has been designed for very rapid intramolecular electron transfer.

Simulations of voltammograms of **3** based on reactions 1–3 provided adequate agreement with the experimental results for scan rates from 5 to 40 V/s. Below 5 V/s, some irreversibility sets in due to the cleavage of nitrite from either F–S$^{-\bullet}$ or $^{\bullet-}$F–S$^{-\bullet}$ (probably the latter) as has been observed with the radical anion of *tert*-nitrobutane.[6c] The simulation for **3** at 40 V/s is also given in Figure 1. The parameters used in the simulation (see caption to Figure 1) are quite reasonable. In particular, it is interesting that the simulations are very sensitive to the magnitude of K_2. The value used in the simulation of Figure 1, 0.3, can only be varied between about 0.2 and 0.5 while maintaining adequate agreement, meaning that the intramolecular electron-transfer reaction 2 is unfavorable by 20–40 mV, whereas it is predicted to be favorable by 10 mV on the basis of the study of fragments **4** and **5**. This appears to be quite acceptable agreement because it is not expected that exact prediction of the properties of intact **3** can be achieved by examining fragments **4** and **5**.

The rate constant for intramolecular electron transfer, $k_{f,2}$, cannot be determined accurately because the voltammogram at 40 V/s is very close to the overall two-electron limit. The value used in the simulation, 2×10^5 s^{-1}, may be regarded as an approximate lower limit. Very precise evaluation of the electrode area and diffusion coefficient of **3** would be required to place an error bar on this estimate.

In summary, we have designed and prepared a molecule that accepts two electrons sequentially by the introduction into only one of the two electroactive groups. The cyanobenzoate group serves as a fast and reversible shuttle of electrons into the kinetically impeded nitroalkyl portion of the molecule. The generality of the phenomena discussed above is presently being explored by studies of molecules with both shorter and longer spacer units as well as conformationally immobile separators. The results of these studies will be described in the full paper.

(8) This calculation assumes that the forward heterogeneous electron-transfer rate constant, k_f, is given by the Butler–Volmer equation, $k_f = k_s \exp[-(\alpha F/RT)(E - E°)]$. For the fast end, $k_{f,1} = k_{s,1} > 0.1$ cm/s at $E = E°_1 = -2.07$ V. For the slow end, $k_{f,4}$ was computed using $k_{s,4} = 2 \times 10^{-3}$ cm/s, $\alpha = 0.4$ (as obtained from simulations of the voltammograms of **5**) and $E°_4 = -2.06$ V. The result, $k_{f,1}/k_{f,4} > 40$, leads to the conclusion that <3% of the electrons are entering through the slow end at $E = E°_1$.

(9) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savéant, J. M. *J. Electroanal. Chem.* **1980**, *113*, 19–40.