Reducing ability of supramolecular C_{60} dianion toward C=O, C=C and N–N bonds†

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Different from C_{60} dianion which readily reacts with electrophiles,[1] supramolecular C_{60} dianion (2) generated from γ-cyclodextrin-bicapped C_{60} (1) and $NaBH_4$ (or diborate) in DMSO-H_2O (9:1, v/v) is able to reduce N–N^+, C=C–EWG and C=O bonds to provide the respective dihydro derivatives; 1-mediated reduction of acetophenone with $NaBH_4$ in the presence of $(Me_2N)_2CH_2$ and EtONa gives turn over frequency (TOF)/h of 400.

In contrast to remarkable advances in materials-directed chemistry of C_{60},[2] reagent (or catalyst)-directed chemistry of C_{60} is still in its infancy.[3,4] Very recently[5] we reported that γ-cyclodextrin-bicapped C_{60} (**1**)[6] (Fig. 1) efficiently fixed N_2 in water to provide NH_3 in the presence of $Na_2S_2O_4$ and light under mild conditions,[4] although the C_{60} anion charge was not clear. This situation led us to examine the reduction of N–N, C=C and C=O bonds, in particular, C=O bond by supramolecular C_{60} dianion (**2**). Quantitative generation of **2** (λ_{max} 950 nm, ε 15,000) from **1** was achieved by treating **1** (0.8 μmol) with $NaBH_4$ (26.3 μmol) in H_2O-containing DMSO (DMSO/H_2O = 9/1, v/v) (1 mL) at 25 °C for 12 min.[7,8] No photoirradiation effect was observed. Borates are known to readily form covalent interactions with carbohydrates. Thus, examination of the possibility of generating **2** using diborates bearing two borate units (two minus charge) should be interesting, because monoborates (one minus charge) such as tetramethoxyborate generate the monoanion (1^{1-}) slowly. We found that diborates[9] **3** and **4** (10 μmol) instead $NaBH_4$ also generated **2** though requiring a much longer time (50–90 min.). So diborates seem to be appropriate for the stoichiometric reduction, rather than the catalytic reduction. We infer that the included $C_{60}{}^{2-}$ will be produced by formation of cyclodextrin O^- (which gives its electron to the included C_{60}) by reversible dissociation of B–O linkage, and the successive intramolecular electron transfer from another borate anion unit to the electron deficient boron center linked to γ-cyclodextrin in the γ-cyclodextrin-bicapped C_{60}–diborate complexes.

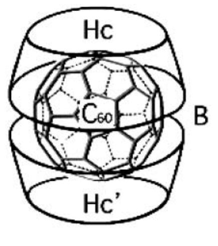

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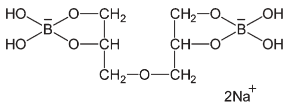
Fig. 1 MOZYME (AM1) structure of γ-cyclodextrin-bicapped C_{60} (**1**). In the present investigation, the belt region (B) can serve as the reaction field because both hydrophobic cavities (Hc, Hc′) are filled with included toluene molecules.

The dianaion (**2**) is quite stable in DMSO/H_2O (9:1) in the absence of air, but oxidized slowly in the presence of oxygen. On the other hand, the free C_{60} dianion spontaneously reacts with O_2.



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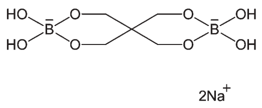

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We examined the reducing ability[10] of **2** (generated with **3** or $NaBH_4$) toward N–N, C=C and C=O bonds by the spectroscopic and/or GLC analysis of the reaction of **2** with triphenyl tetrazolium chloride (TTC) (**5**), styrene, acrylonitrile, methyl methacrylate (MMA) and acetophenone in DMSO–H_2O (9:1, v/v) solution at 25 °C under argon, respectively. As a result, it was observed that (1) N–N bond of TTC, (2) C=C bond of acrylonitrile and MMA and (3) C=O bond of acetophenone were reduced to the respective dihydro derivatives, though the reaction with MMA was slow and the reaction with styrene was not observed to occur under this condition. It should be noted that **2**

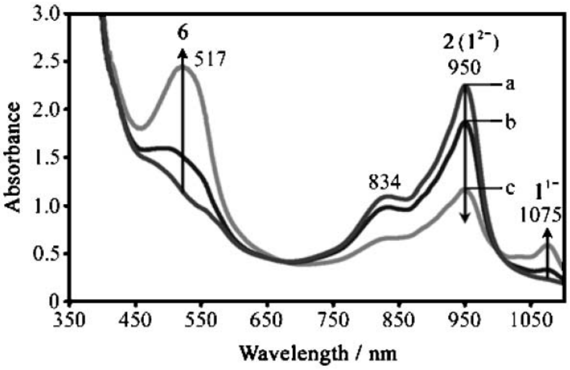

Fig. 2 Spectral change in the reaction of **2** (generated with **3**) with TTC: (a) spectra before adding TTC, (b) spectra after adding TTC (2 min), (c) spectra after reaction (4 min). **2**: 0.08 μmol, TTC: 0.03 μmol, DMSO–H_2O (9:1, v/v): 2 mL + H_2O 0.1 mL, 25 °C. The absorption maxima are shown in nm units.

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† Electronic supplementary information (ESI) available: experimental details. See http://www.rsc.org/suppdata/cc/b4/b414977g/

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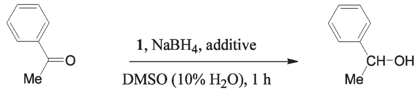
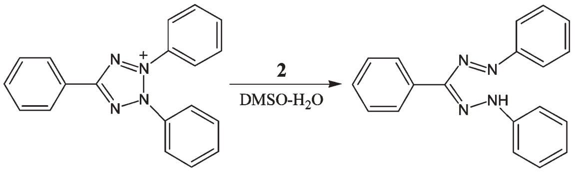
Table 1 Additive effect on **1**-mediated reduction of acetophenone with $NaBH_4$[a]



Entry	$1 \cdot 24H_2O$ (μmol)	Additive (mmol)	Temp. (°C)	Product (μmol)	TOF (h^{-1})
1	0	0	25	24	—
2	2.7 (γ-CyD)[b]	0	25	13	—
3	1.34	0	25	74	55
4	1.34	0	50	106	80
5	0	$(Me_2N)_2CH_2$ 0.73	25	160	—
6	1.34	$(Me_2N)_2CH_2$ 0.73 EtONa 0.73	25	250	186
7	1.34	$(Me_2N)_2CH_2$ 3.5 EtONa 3.5	25	536	400
8	0	$(Me_2N)_3CH$ 0.73	25	140	—
9	1.34	$(Me_2N)_3CH$ 0.73	25	211	157
10	1.34	$(Me_2N)_3CH$ 0.73 EtONa 0.73	25	172	129
11	1.34	$(MeS)_3CH$ 0.73	25	67	50

[a] Condition: acetophenone (833.3 μmol), $NaBH_4$ (131.5 μmol except for Entry 7, 650 μmol for Entry 7), DMSO (10% H_2O) (2.7 mL), 1 h.
[b] γ-cyclodextrin (2.7 μmol) is used instead of **1**.

allows for the preferential reduction of a C=C bond over a C=O or C≡N functionality. In control experiments, we confirm that **3** does not reduce these substrates. Spectral change in the reaction of **2** (generated by diborate **3**) with TTC (colourless) is shown in Fig. 2, which indicates that the formation of deep red triphenylformazan (**6**, λ_{max} 517 nm) and supramolecular C_{60} monoanion ($\mathbf{1}^{1-}$, λ_{max} 1075 nm).



5 **6**

Based on the results, we examined the efficiency of **2** (generated from $NaBH_4$) in ketone reduction by comparison with reduction by $NaBH_4$ in DMSO–H_2O (9:1, v/v) at 25 °C, where acetophenone, α- and β-acetonaphthones and β-ionone were used as substrates. The results demonstrated (1) that **2** is more efficient (several times) than $NaBH_4$, and (2) that **2** functions as a catalyst.[11] We investigated the effect of additive on γ-cyclodextrin-bicapped C_{60} (**1**)-mediated reduction of acetophenone with $NaBH_4$ at 25 °C (or 50 °C) for 1 h. The results are summarized in Table 1. From the Table 1, the catalytic effect of **2** is evident. Although the additives (Entries 6, 7, 9 and 10) other than $(MeS)_3CH$ (Entry 11) enhance the turn over frequency (TOF), it is noteworthy that the dramatic increase in TOF is observed when excess $(Me_2N)_2CH_2$–EtONa (Entry 7) is added. Although a detailed mechanistic study would be necessary to elucidate the reason why additives, in particular, $(Me_2N)_2CH_2$–EtONa effectively increase TOF, it seems due to the effective regeneration of **2** by $NaBH_4$–$(Me_2N)_2CH_2$–EtONa. We have observed that a decrease in absorbance (λ_{max} 950 nm) of **2** is accompanied by an increase in absorbance of new band (λ_{max} 1075 nm) due to γ-cyclodextrin-bicapped C_{60} monoanion ($\mathbf{1}^{1-}$) similarly to TTC reduction (Fig. 2), suggesting that **2** serves as one electron donor in the reaction.

In the catalytic reduction of acetophenone, reversible formation of **2** (λ_{max} 950 nm) from $\mathbf{1}^{1-}$ (λ_{max} 1075 nm) was observed for 1 h by spectroscopy. In the presence of O_2, irreversible change takes place. In the examination of the evolution of the reaction with time under the entry 3 conditions, the product yield (μmol) was 0 at 0 h, 63 at 0.3 h, and 74 at 1 h.

In conclusion, the supramolecular C_{60} dianion (**2**) is able to reduce N–N$^+$, C=C–EWG and C=O bonds to provide the respective dihydro derivative. The **1**-mediated reduction of acetophenone with $NaBH_4$ in the presence of $(Me_2N)_2CH_2$ and EtONa gives TOF (h^{-1}) of 400. Irradiation is not necessary for this reaction.

The previous[5] and present results should open the way to the reduction of other triple, double and single bonds.

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7 We used **1**·24H_2O which includes toluene in the hydrophobic cavity of **1**. It is possible to obtain **1**·24H_2O without toluene [Found: C, 49.91; H, 5.29%, Calcd for $C_{156}H_{208}O_{104}$ (**1**·24H_2O): C, 50.00; H, 5.59%] and **1**·16H_2O (single crystal) by changing the workup condition. X-ray analysis of **1** is not successful yet.

8 Non-quantitative generation of **2**:S. Takekuma, H. Takekuma, T. Matsumoto and Z. Yoshida, *Tetrahedron Lett.*, 2000, **41**, 2929.

9 Preparation and use of diborate (**3** and **4**): The respective tetraol (10 μmol) was reacted with $NaBH_4$ (20 μmol) in water (100 μL) at ambient temperature. After confirmation of complete transformation of $NaBH_4$ into diborate by ^1H NMR, the solution was used for generation of **2** immediately after preparation [MALDI-TOF-MS (negative; matrix: 3,5-dimethoxy-4-hydroxycinnamic acid) for **4**: *m*/*z* 221.5, $[M - 2Na]^-$, 100%].

10 We confirm that the results shown in this work have been reproduced many times in our laboratory. As for the reaction field, we infer that hydrogen-bonded water molecules at the belt region of **1** are removed by DMSO to make channels with around 3–4 Å width, which may serve as the reaction field in the catalytic reaction. Our ESR and ONIOM2 (UB3LYP/6-31G, UFF) investigations support this inference. The spin density distribution in **2** relatively dominates around the belt region (channels).

11 Asymmetric reduction of the ketones used was not observed under our conditions. However, Prof. Uemura has quite recently succeeded in asymmetric reduction of ketones with **2** in collaboration with us.