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COMMUNICATION

NBS-Promoted oxidation of fullerene monoradicals leading to regioselective 1,4-difunctional fullerenes

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We have demonstrated that NBS is able to promote the oxidation of fullerene monoradicals to form 1,4-difunctional fullerenes. The singly bonded fullerene dimers were used as fullerene monoradical precursors, which produced various 1,4-fullerenes with a wide range of functional groups in good to high yields with high regioselectivity in terms of cosolvents and nucleophiles.

Fullerene monoradical has become a useful intermediate for the selective functionalization of fullerenes, which exhibits versatile activity for the synthesis of various novel functional fullerenes through the oxidation to a fullerene cation or direct coupling with other radicals, while its potential reactivity is still less explored.[1-5] Komatsu et al. confirmed the generation of the fullerene cation by treating a singly bonded fullerene dimer as a monoradical precursor with nucleophiles in the presence of a strong acid.[4] Nakamura and Matsuo et al. synthesized 1,2-dihydromethanofullerenes and 1,2-di(organo)fullerenes through the oxidation of the silylmethylfullerene radicals with an excess amount of $CuCl_2$ at high temperature.[5] Herein, we report that N-bromosuccinimide (NBS) is able to oxidize the fullerene monoradical to the fullerene cation species which undergoes an intermolecular electrophilic addition with a wide range of nucleophiles to afford various 1,4-difullerenes in good to high yields with an exclusive regioselectivity under mild reaction conditions (Scheme 1). It should be noted that 1,4-difullerenes possessing two unsymmetrical functional groups on 1,4-position of the fullerene core have been reported as the excellent n-type materials for high performance organic photovoltaics and thin film transistors, which offer the tunable energy level, solubility, and packing structure through the wide structural variations.[6]

Recently, we have developed an efficient and general method for the synthesis of various singly bonded fullerene dimers from the hydrofullerenes catalysed by $Cu(OAc)_2$ or NaOH through the formation of a fullerene monoradical (Scheme 1).[7] We also found that the fullerene monoradicals derived from the fullerene dimers react with the *in situ* formed benzyl and amine radicals efficiently,

resulting in hydrofullerenes, fullerene cycloadducts, and amine-substituted 1,4-fullerenes in high selectivities in the presence of cobalt or copper catalyst (Scheme 1).[8,9] The readily available monoradical fullerene in solution from its dimer led us to explore its radical reactions combining with N-halosuccinimides for the synthesis of new functional fullerenes.
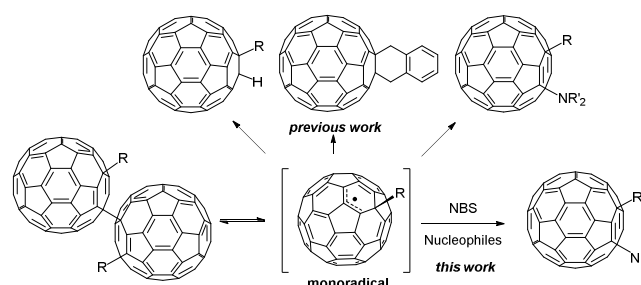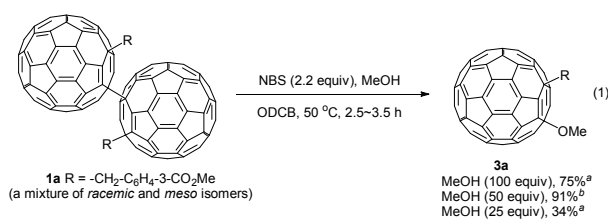

Scheme 1 Reactivity of fullerene monoradicals: our previous and this works.

Table 1 Reaction of fullerene dimer **1a** with N-halosuccinimides in various cosolvents[a]

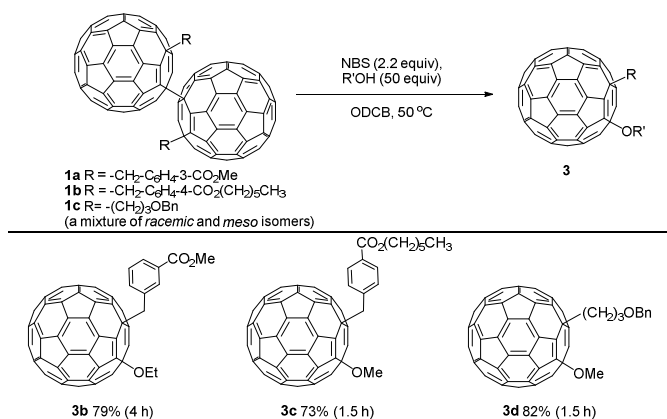| Entry	N-Halosuccinimide	Cosolvent	2a (%)[b]	1a (%)[b]
1	NBS	none	0	95
2	NBS	DMF	76 (64)	0
3	NBS	DMSO	34	0
4	NBS	THF	7	90
5	NCS	DMF	50	0
6	NIS	DMF	trace	trace

[a] Reaction conditions: **1a** (0.05 mmol), N-halosuccinimide (0.2 mmol), ODCB (20 mL), cosolvent (2 mL) under ambient atmosphere for 1.5 h at 50 °C. [b] HPLC yields determined using C_{60} as an internal standard. Isolated yield is shown in parentheses.

The results of the fullerene dimer **1a** with *N*-halosuccinimides are shown in Table 1. The reaction of **1a** with NBS (4 equiv) in 1,2-dichlorobenzene (ODCB) at 50 °C did not afford any products (entry 1). We have verified previously that the use of polar cosolvents with ODCB remarkably increased the efficiency of the fullerene monoradical generation and stability.[7,9] We thus treated the reaction with DMF cosolvent and obtained the 1,4-disubstituted fullerenol **2a** in a 64% isolated yield after silica gel chromatography (entry 2). The other polar solvents such as DMSO and THF gave decreased yields of **2a** (entries 3 and 4). Further investigation showed that *N*-chlorosuccinimide (NCS) produced **2a** in a good yield of 50%, while *N*-iodosuccinimide (NIS) resulted in decomposition of **1a** (entries 5 and 6). We suggest that initially, the reaction of **1a** with NBS forms the bromo-substituted 1,4- or/and 1,2-adducts (**B**) (Scheme 2), which may be hydrolysed readily on silica gel chromatography to produce the fullerenol **2a**.[10]

1a R = -CH₂-C₆H₄-3-CO₂Me
(a mixture of *racemic* and *meso* isomers)

3a
MeOH (100 equiv), 75%[a]
MeOH (50 equiv), 91%[b]
MeOH (25 equiv), 34%[a]

(1)

[a] HPLC yield was determined using C_{60} as an internal standard. [b] Isolated yield.

Table 2 NBS-Promoted reaction of dimers **1** with alcohols[a,b]

1a R = -CH₂-C₆H₄-3-CO₂Me
1b R = -CH₂-C₆H₄-4-CO₂(CH₂)₅CH₃
1c R= -(CH₂)₃OBn
(a mixture of *racemic* and *meso* isomers)

3

**3b** 79% (4 h)   **3c** 73% (1.5 h)   **3d** 82% (1.5 h)

[a] Reaction conditions: **1** (0.05 mmol), NBS (2.2 equiv), ODCB (20 mL), alcohols (50 equiv) under ambient atmosphere for 1.5~4 h at 50 °C. [b] Isolated yield.

Interestingly, when MeOH (100 equiv) was used as a cosolvent, the methoxy-substituted 1,4-fullerene **3a** was obtained in good yield [Eq (1)]. The investigation of the amount of MeOH showed that the yield of **3a** could be improved to 91% with decreasing MeOH to 50 equiv, while further decreasing the MeOH amount lowered the yield. With these results in hand, we studied other alcohols and fullerene dimers (Table 2). The reactions of **1a** with EtOH in the presence of NBS afforded the corresponding ethoxy-substituted 1,4-bisadduct **3b** in 79% yield. The reactions of MeOH with fullerene dimers **1b** and **1c** having a

ester group at the *para*-position of the phenyl ring and a benzyl ether group were also tolerated under the present conditions, affording the corresponding 1,4-adducts **3c** and **3d** in 73% and 82% yields, respectively. All of the reactions were monitored by TLC and HPLC analysis and the corresponding products **3** were purified by silica gel column chromatography.

Table 3 Study of the reaction of **1a** with anisole using DMF and MeOH[a,b]

1a R = -CH₂-C₆H₄-3-CO₂Me
(a mixture of *racemic* and *meso* isomers)

4a
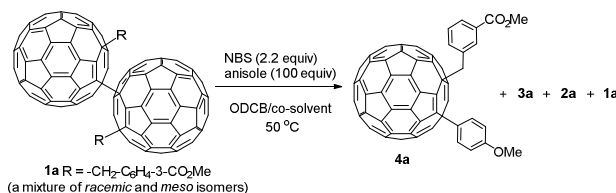
Entry	Cosolvent	Time (h)	**4a** (%)	**3a** (%)	**2a** (%)	**1a** (%)
1	DMF	20	0	0	41	18
2	MeOH	3	0	20	17	30
3	MeOH	20	55	2	3	12
4[c]	MeOH	6	73[d]	0	0	0

[a] Anisole (100 equiv) and NBS (2.2 equiv) were used. [b] HPLC yield determined using C_{60} as an internal standard. [c] NBS (4 equiv) was used at 70 °C. [d] Isolated yield.
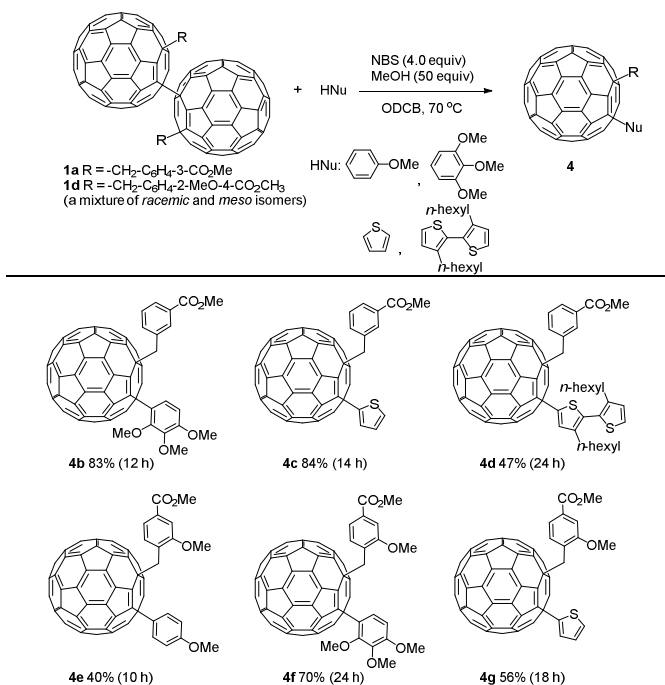
The high reactivity of the fullerene dimer with alcohols led us to examine other nucleophiles in the presence of NBS and the results are presented in Table 3. The reaction of **1a** with anisole as a nucleophile was investigated in the presence of NBS at 50 °C. The use of DMF as cosolvent did not produce the corresponding anisole-substituted 1,4-bisadduct **4a**, instead, the fullerenol **2a** was obtained in 41% yield together with the recovered **1a** (entry 1). When MeOH was used as a cosolvent, the methoxyl-substituted 1,4-fullerene **3a** and **2a** were observed without forming the desired product **4a** after 3 h, while the reaction under the prolonged reaction time (20 h) afforded **4a** as a major product (entries 2 and 3). These results suggest the conversion of **3a** and **2a** to **4a** in MeOH solution. Finally, we were pleased to find that a 73% yield of **4a** was obtained using 4 equiv of NBS at 70 °C for 6 h (entry 4).

Under the optimized conditions, the general applicability of this NBS-promoted electrophilic addition was investigated with other nucleophiles (Table 4). In all cases, the corresponding 1,4-fullerenes were formed exclusively which were determined by HPLC analysis and NMR spectra. The reactions of the fullerene dimers **1a** and **1d** with 1,2,3-trimethoxybenzene, thiophene, 3,3'-dihexyl-2,2'-bithiophene, and anisole as nucleophiles afforded the corresponding 1,4-bisadducts **4b-g** in 40–84% yields. It was noted that, in some cases, only a small amount of the starting dimers remained. The structures of the 1,4-bisadducts were characterized by ¹H, ¹³C NMR, and high resolution mass (ESI). Furthermore, a characteristic broad absorption band around 440 nm in the UV-vis absorption spectra of **4** supports the 1,4-bisadduct structure (ESI).[9]
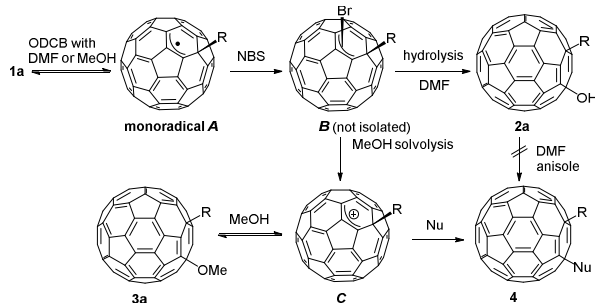
The proposed reaction pathways for the formation of the products **2**, **3**, and **4** are shown in Scheme 2. Initially, the dissociation of the singly bonded fullerene dimer **1a** in solution assisted by polar solvents forms the stable fullerene monoradical species **A**,[2c,7] which may undergo the radical coupling reaction

with the bromine radical of NBS to give the brominated fullerene bisadduct **B**. The intermediate **B** may readily undergo hydrolysis in DMF to give the corresponding fullerenol **2a**,[10] while in MeOH produces the methoxy-substituted 1,4-fullerene **3a** through the formation of the fullerene cation **C**. The result that the product **4** is only formed in the presence of MeOH (Table 3) indicates the involvement of the cation **C** which undergoes the subsequent electrophilic addition of anisole to form **4**.

Table 4 NBS-Promoted reaction of dimers **1** with various nucleophiles[a,b]

1a R = -CH₂-C₆H₄-3-CO₂Me
1d R = -CH₂-C₆H₄-2-MeO-4-CO₂CH₃
(a mixture of *racemic* and *meso* isomers)

4b 83% (12 h)   **4c** 84% (14 h)   **4d** 47% (24 h)

4e 40% (10 h)   **4f** 70% (24 h)   **4g** 56% (18 h)

[a] Reaction conditions: **1** (0.05 mmol), NBS (4 equiv), ODCB (20 mL), MeOH (100 μL), nucleophiles (100 equiv) under ambient atmosphere at 70 °C. [b] Isolated yield.

Scheme 2 Proposed reaction pathways

In conclusion, we have shown that NBS sufficiently promotes the formation of the fullerene cation from the readily available singly bonded fullerene dimer to undergo electrophilic attack to various nucleophiles, leading to the fullerene 1,4-bisadducts. Various nucleophiles with a wide range of functional groups were tolerated, giving the 1,4-fullerenes in good to high yields with an exclusive regioselectivity. Although some methods for the synthesis of 1,4-fullerenes have been developed,[11,12] the present

1,4-difunctionalization provides a new, efficient, and general synthetic entry to the unsymmetric 1,4-difunctional fullerenes under mild reaction conditions.

Notes and references

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† Electronic Supplementary Information (ESI) available: Experimental procedures and characterization data. See DOI: 10.1039/c000000x/

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