ChemComm
www.rsc.org/chemcomm

Nucleophilic substitution of alkylchlorodihydro[60]fullerenes: thermodynamic stabilities of alkylated C_{60} cation intermediates†

Toshikazu Kitagawa,*[a] Yangsoo Lee,[a] Masaaki Hanamura,[b] Harumi Sakamoto,[b] Hirofumi Konno,[a] Ken'ichi Takeuchi[b] and Koichi Komatsu*[a]
[a] *Institute for Chemical Research, Kyoto University, Uji, Kyoto 611-0011, Japan.*
E-mail: kitagawa@scl.kyoto-u.ac.jp; Fax: 81 774 38 3178; Tel: 81 774 38 3173
[b] *Department of Energy and Hydrocarbon Chemistry, Graduate School of Engineering, Kyoto University, Sakyo-ku, Kyoto, 606-8501, Japan*

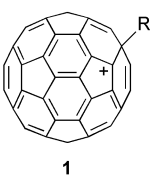
Received (in Cambridge, UK) 16th October 2002, Accepted 7th November 2002
First published as an Advance Article on the web 20th November 2002

Thermodynamic stabilities of alkylated C_{60} cations (RC_{60}^+) were determined based on the activation free energies of S_N1 solvolysis of the title compounds, indicating that these cations have stabilities comparable to that of the *tert*-butyl cation.

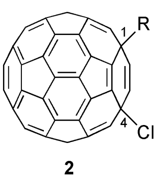
Recent reports of the successful preparation of functionalized C_{60} cations as long-lived ions[1–3] have opened up new aspects of fullerene chemistry. We recently reported that monoalkylated C_{60} cations **1b** and **1d** can be generated by ionization of the corresponding fullerenol precursors in CF_3SO_3H.[1] The high stability of the ions was demonstrated by the fact that they can be kept over weeks without change even at ambient temperature. The high stability of $Ar_5C_{60}^+$ in $CHCl_3$[2] and the isolation of HC_{60}^+ in the form of a carborane anion salt,[3] has also been reported. The demonstrated stability of the functionalized C_{60} cations under non-nucleophilic conditions led us to quantitatively evaluate their thermodynamic stabilities. The kinetics of S_N1 solvolyses, activation parameters of which reflect the properties of the intermediate carbocation relative to those of the starting molecule, have been widely applied for the investigations of the properties of carbocations. In this paper we report on the kinetics of S_N1 solvolysis reactions of 1-alkyl-4-chloro-1,4-dihydrofullerenes **2a–d**, which provides a measure of the thermodynamic stabilities of monoalkylated C_{60} cations **1a–d**.

The substrates for the solvolyses, **2a–d**, were prepared by the electrophilic addition of CH_2Cl_2, $CHCl_3$, CCl_4, and $Cl_2CHCHCl_2$, respectively, to C_{60} using $AlCl_3$ as a catalyst. While the addition of the latter three chlorides gave only 1,4-adducts **2b–d**, the reaction with CH_2Cl_2 gave a mixture (approximately 1:1) of 1,2- (**3a**) and 1,4-adducts (**2a**).[4] These isomers could be separated by gel permeation chromatography, but they isomerized slowly, by first-order kinetics, to give an equilibrium mixture (Table 1). An accelerated isomerization that occurred in a polar solvent $C_6D_5NO_2$ suggests that the reaction proceeds *via* a transition state with a considerable ionic character.

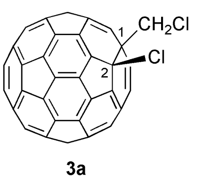
For the solvolysis of **2**, highly polar solvents (*i.e.* with a high solvent ionizing power *Y*,[5] typically hydroxylic solvents) that are normally used for mechanistic studies of solvolysis are not suitable because of the low solubilities of the compounds. This problem was solved by using a mixed solvent system composed of anisole, in which C_{60} derivatives are moderately soluble, and highly ionizing 2,2,2-trifluoroethanol (TFE) in 9:1 volume ratio. Keeping solutions of **2a–d** at 25 or 50 °C in this mixed solvent resulted in conversion to solvent substitution products **4** and **5** in over 80% total yields (Scheme 1).[6]



1



2



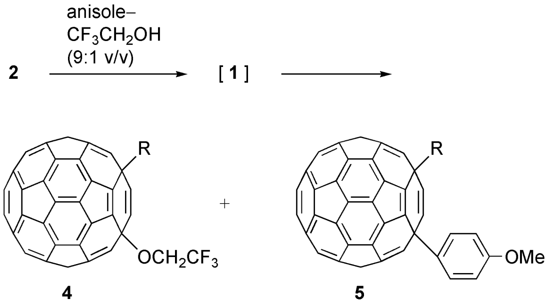
3a

a R = CH_2Cl, **b** R = $CHCl_2$, **c** R = CCl_3, **d** R = CCl_2CH_2Cl

Table 1 Rate constants and equilibrium constants for the interconversion of **2a** and **3a** at 25.0 °C[a]

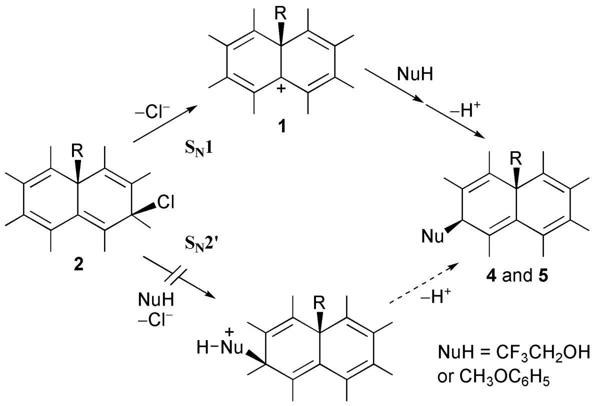
Solvent	Dielectric constant[b]	$k_{2a\rightarrow 3a}$/ 10^{-6} s^{-1}	K[c]
1,2-$Cl_2C_6D_4$	9.9	1.94	0.98
$C_6D_5NO_2$	34.8	4.23	0.90

[a] Initial concentration, 2.3–4.2 × 10^{-3} M. Measured in the presence of 2,6-lutidine (1.5–2.8 equiv.) to exclude the effect of trace amounts of acidic impurities. [b] Values for the undeuteriated solvent. [c] K = $[\mathbf{3a}]_{eq}/[\mathbf{2a}]_{eq}$



Scheme 1 Solvolysis of **2** in anisole–trifluoroethanol.

No reaction was observed in the absence of TFE (*i.e.* in pure anisole). This fact is interpreted as indicating that substitution does not occur by an S_N2' type mechanism (Scheme 2), which has been proposed to explain the high reactivity of poly-



Scheme 2 Proposed mechanism for the solvolysis of **2**. A part of C_{60} core is shown.

---

† Electronic supplementary information (ESI) available: selected spectral data for newly synthesized compounds. See http://www.rsc.org/suppdata/cc/b2/b210126b/

DOI: 10.1039/b210126b

fluorinated C_{60} toward hydrolysis.[7] In this mechanism, the formation of **4** and **5** by the direct nucleophilic attack at an allylic position by TFE and anisole, respectively, and concomitant elimination of the chloride ion would be expected. Rather, the low nucleophilicity of the solvent and the absence of any reaction in pure anisole suggests that the solvolysis proceeds by an S_N1 mechanism, where **4** and **5** are formed *via* a common carbocationic intermediate **1**, generated with assistance by TFE.

For product identification, **4a–d** were synthesized by the $AgBF_4$ promoted ionization of **2** in TFE–PhCN or by quenching cation **1**, generated from fullerenol 1,4-$RC_{60}OH$[1] in CF_3SO_3H, with TFE. Compounds **5a–d** were synthesized by the $AlCl_3$ or $AgBF_4$ catalyzed electrophilic substitution of anisole with **2**. By using $AgBF_4$, it is possible to generate cation **2** under non-acidic conditions, providing a useful method for derivatization *via* a fullerenyl cation precursor with a variety of acid-sensitive nucleophiles.

Whereas NMR studies of cation **1b** and **1d** clearly indicated that most of the positive charge is located on C-2,[1] the solvolysis and Lewis-acid promoted substitution gave 1,4-adducts. The selective formation of this regioisomer can be attributed to the blocking of C-2 by the adjacent group R (see below).

In the kinetic study, the progress of the solvolyses of **2b** and **2d** was monitored by measurement of the ^1H NMR peak areas. The rates of reaction of **2a** and **2c** were measured by changes in HPLC (Buckyprep) peak areas.[8] In all reactions the decay of the substrate followed first-order kinetics. The rate constants (k_1) at 25 and 50 °C provided the activation parameters listed in Table 2. The possible slow isomerization of **2a** to **3a** during solvolysis would not affect the observed rate constant for **2a**, since the two isomers undergo solvolysis at essentially the same rate (**3a** underwent solvolysis with a rate constant $k_1 = 1.10 \times 10^{-4}\ s^{-1}$ at 50 °C), and the rates were determined based on the decay of the total amount of **2a** and **3a**.[9] Kinetic measurements of the solvolysis of *t*-BuCl in the same solvent at 50 and 75 °C gave an extrapolated value of $1.08 \times 10^{-7}\ s^{-1}$ for k_1 at 25 °C, which corresponds to a Y value of -1.93. This indicates that this mixed solvent has an ionizing power approximately equal to that of 99 vol% aqueous ethanol.[10]

All the reactions in Table 2 showed large negative entropies of activation ($\Delta S^\ddagger$). The magnitude of $\Delta S^\ddagger$ observed for *t*-BuCl is typical of the solvolysis of alkyl chlorides[11] and is considered to be largely due to solvation at the transition state, especially to the leaving chloride ion. An additional 14–19 cal $mol^{-1}\ K^{-1}$ lowering of $\Delta S^\ddagger$ values for the reactions of **2a–d** can be attributed to the decrease in conformational freedom due to the coordination of chlorine atom(s) in group R to the developing cationic center in the transition state. This is consistent with the observation for **1b** and **1d**, generated in CF_3SO_3H, that the ^{13}C NMR signal of the cationic carbon (C-2) is significantly high-field shifted, owing to the partial through-space delocalization of the positive charge to the chlorine atom(s) in group R.[12]

Table 2 Rate constants and activation parameters for the solvolysis of **2a–d** and *t*-BuCl in anisole–2,2,2-trifluoroethanol (9 : 1 v/v)[a]

Substrate	T/°C	$k_1{}^b/10^{-6}\ s^{-1}$	$\Delta H^\ddagger$/kcal mol^{-1}	$\Delta S^\ddagger$/cal $mol^{-1}\ K^{-1}$	$\Delta G^\ddagger_{25°C}$/ kcal mol^{-1}
2a	25.0	21.7[c]	11.6	−41	23.8
	50.0	107[c]			
2b	25.0	14.6	10.6	−45	24.0
	50.0	62.6			
2c	25.0	2.81	11.7	−45	25.0
	50.0	14.0			
2d	25.0	2.89	11.4	−46	25.0
	50.0	13.9			
t-BuCl	25.0	0.108[d]	18.8	−27	26.9
	50.0	1.37			
	75.0	12.0			

[a] Initial concentration, 0.15–1.4 × 10^{-3} M. 2,6-Lutidine (1.3–6.3 equiv.) was added as a buffer in all runs. [b] Experimental error, ±5%. [c] Decay of the sum of the amounts of **2a** and **3a**. [d] Extrapolated from data obtained at higher temperatures.

The free energies of activation ($\Delta G^\ddagger$) observed for **2a–d** are only slightly lower than the $\Delta G^\ddagger$ for *t*-BuCl. This indicates that the alkylated C_{60} cations **1a–d** have stabilities close to that of the *tert*-butyl cation. This is rather surprising, considering the well-known, electronegative nature of the C_{60} cage.[13] It should be noted that the kinetic data for **2a–d** include the contribution of the change in molecular strain by rehybridization of the reaction center from sp^3 to sp^2. This might lead to an underestimation of the cation stabilities to a small extent, since such a change would develop a strain in the cationic sp^2 carbon due to deviation from planarity.[14]

In conclusion, the present study provides the first quantitative evaluation of the thermodynamic stabilities of alkylated C_{60} cations based on kinetic data for the solvolysis of the corresponding chlorides. The results indicate that the stabilities of these ions are comparable to that of simple tertiary alkyl cations.[15]

This work was supported by the Sumitomo Foundation, the Kurata Foundation, and a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Notes and references

1 T. Kitagawa, H. Sakamoto and K. Takeuchi, *J. Am. Chem. Soc.*, 1999, **121**, 4298.

2 A. G. Avent, P. R. Birkett, H. W. Kroto, R. Taylor and R. M. Walton, *Chem. Commun.*, 1998, 2153; P. R. Birkett, M. Bühl, A. Khong, M. Saunders and R. Taylor, *J. Chem. Soc., Perkin Trans. 2*, 1999, 2037.

3 C. A. Reed, K.-C. Kim, R. D. Bolskar and L. J. Mueller, *Science*, 2000, **289**, 101; L. J. Mueller, D. W. Eriott, K.-C. Kim, C. A. Reed and P. D. Boyd, *J. Am. Chem. Soc.*, 2002, **124**, 9360.

4 The synthesis and characterization of **2b** and **2d** have been described in ref. 1. Compounds **2a**, **2c** and **3a** were synthesized in similar manners.

5 The solvent ionizing power Y is defined by $Y = \log (k/k_0)$, where k and k_0 are the rate constants of solvolysis of *tert*-butyl chloride at 25 °C in a given solvent and in 80 vol% aqueous ethanol, respectively; E. Grunwald and S. Winstein, *J. Am. Chem. Soc.*, 1948, **70**, 846.

6 Under similar conditions (in benzene–ROH, R=Me or *i*-Pr, reflux), $C_{60}Cl_6$ has been reported to give 1,4-$(MeO)_2C_{60}$ and 1,4-$(i\text{-}PrO)_2C_{60}$ in 11 and 30%, respectively; A. G. Avent, P. R. Birkett, A. D. Darwish, S. Houlton, R. Taylor, K. S. T. Thomson and X.-W. Wei, *J. Chem. Soc., Perkin Trans. 2*, 2001, 782.

7 R. Taylor, J. H. Holloway, E. G. Hope, A. G. Avent, G. J. Langley, T. J. Dennis, J. P. Hare, H. W. Kroto and D. R. M. Walton, *J. Chem. Soc., Chem. Commun.*, 1992, 665; R. Taylor, *Synlett*, 2000, 776.

8 HPLC analysis of the solvolysis reaction mixture was carried out in Buckyprep–toluene. As a standard, a known amount of C_{70} was added before sample injection.

9 The two isomers were not monitored separately because of their nearly identical HPLC retention times.

10 A. H. Fainberg and S. Winstein, *J. Am. Chem. Soc.*, 1956, **78**, 2770.

11 Y. Ohga, M. Munakata, T. Kitagawa, T. Kinoshita, K. Takeuchi, Y. Oishi and H. Fujimoto, *J. Org. Chem.*, 1994, **59**, 4056.

12 Based on PM3 calculations we proposed that cations **1b** and **1d** have chlorine-bridged, chloronium ion like structures (ref. 1). DFT calculations at the B3LYP/3-21G level, however, indicated that the CH_2Cl group in the lowest energy structure of **1a** is bound to the C_{60} core with a staggered conformation in which the chlorine atom has a *gauche* orientation. Details of the theoretical results will be reported separately.

13 T. Kitagawa and K. Takeuchi, *Bull. Chem. Soc. Jpn.*, 2001, **74**, 785; C. A. Reed and R. D. Bolskar, *Chem. Rev.*, 2000, **100**, 1075; P. J. Fagan, P. J. Krusic, D. H. Evans, S. A. Lerke and E. Johnston, *J. Am. Chem. Soc.*, 1992, **114**, 9697.

14 F. Diederich and C. Thilgen, *Science*, 1996, **271**, 317; R. C. Haddon, *Science*, 1993, **261**, 1545; A. Hirsch, *The Chemistry of the Fullerenes*, Thieme, Stuttgart, 1994, ch. 9.

15 The pK_{R^+} values of **1a–d** also indicated the similarity in stability between these cations and the *tert*-butyl cation. The result will be reported in due course.