Regioselective Superacid-Catalyzed Electrocyclization of Diphenylmethyl Cations to Fluorenes, Phenanthrols and Benzofurans

Naohiro Yoshida,[a] Tomohiko Ohwada*[b]

[a] Faculty of Pharmaceutical Sciences, Nagoya City University, 3–1 Tanabe-dori, Mizuho-ku, Nagoya 467-8603, Japan

[b] Graduate School of Pharmaceutical Sciences, The University of Tokyo, 7–3-1 Hongo, Bunkyo-ku, Tokyo 113–0033, Japan
Fax +81(3)58414730; E-mail: ohwada@mol.f.u-tokyo.ac.jp

Received 27 March 2001; revised 16 April 2001

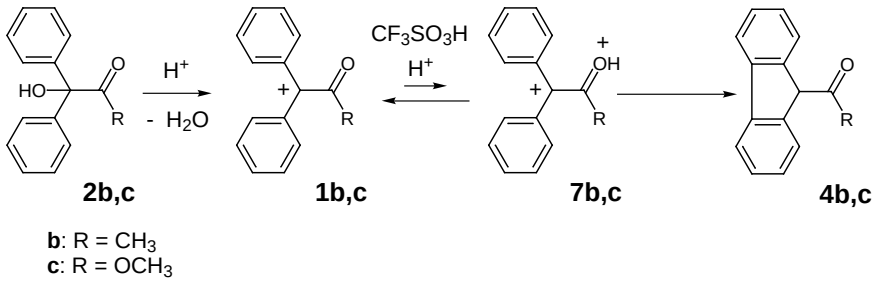
Abstract: Cationic electrocyclization of α-benzoyldiphenylmethanols in the presence of superacid provides fluorenes, phenanthrols and benzofurans in good to moderate yields. A single substitution leads to regioselective cationic electrocyclizations.

Key words: carbocations, electrocyclizations, regioselectivity, superacid, diphenylmethyl cations

Diphenylmethyl cations **1** and related diarylmethyl cations substituted with electron-withdrawing groups constitute a typical class of destabilized cations, i.e. carbocations bearing electron-withdrawing groups directly attached to the carbenium ion center.[1] The prototype diphenylmethyl cations **1** (Scheme 1) bearing electron-withdrawing substituents (RC=O) have been generated in the presence of acids,[2] or by flash-laser photolysis,[3] and characterized as discrete stable ions. The cations **1** undergo three modes of electrocyclization reactions (see Scheme 2): (1) cyclization to form benzofurans **3**, (2) cyclization to give fluorenes **4**, and (3) cyclization to give phenanthrols **5**. The first isolation of the relevant carbocation, the di-*p*-anisyl(4-methoxybenzoyl)methyl cation (**1a**), as a stable crystalline antimony pentafluoride salt, was reported by Takeuchi et al., who showed that heating the salt **1a** in a neutral solvent (1,2-dichloroethane, 50 °C, 8 h), gave the benzofuran **3a** in 94% yield (Scheme 3).[4,5] In contrast to this heteroatom cyclization process, the acetyl, acid, ester and amide analogs underwent electrocyclic coupling of the two aromatic rings, leading to fluorene derivatives. Thus, α-acetyldiphenylmethanol (**2b**) gave 9-acetylfluorene (**4b**),[6] whereas α-methoxycarbonyldiphenylmethanol (**2c**) gave 9-methoxycarbonylfluorene (**4c**) (Scheme 1).[2,7,8]

The chemical behavior of the monocations **1**, generated under neutral and strongly acidic conditions were also reported from this laboratory,[8,9] and were divergent from those described.[2,6,10,11] α-Benzoyldiphenylmethanol (**2d**, $R_1 = R_2 = H$, Scheme 2), a precursor of the unsubstituted cation **1d** (Scheme 4), reacted in trifluoromethanesulfonic acid (TFSA) at –48 °C to afford the fluorene **4d**, along with the phenanthrene derivative 9-phenylphenanthr-10-ol (**5d**) (Scheme 2). No benzofurans **3** were obtained in TFSA. This superacid-catalyzed fluorene cyclization of **2d** was also reported by Olah and Wu in the same acid,[12] although the yields were a little divergent. The same authors also reported the formation of 9-phenanthrol (79% yield) by TFSA-catalyzed cyclization of benzoin.[12]

The monocations **1c** and **1d** could be generated as stable entities at –50 °C by the reaction of the α-chloro ketones **6c** and **6d** with silver salts (Scheme 4).[8a] However, no fluorene, phenanthrol or benzofuran was formed under these neutral conditions. When the stable cation was added to TFSA at –48 °C, fluorene and the phenanthrol were produced (Scheme 2). This led to the proposals that the fluorenes **4** and phenanthrols **5** do not arise directly from the monocation **1**, and that the real intermediate is the dication **7** (Scheme 1), formed by protonation of the α-carbonyl group by TFSA. The involvement of the dicationic intermediate **7** was supported by kinetic studies of the acidity-dependent reactions, and by theoretical evaluation of energetics.[9]

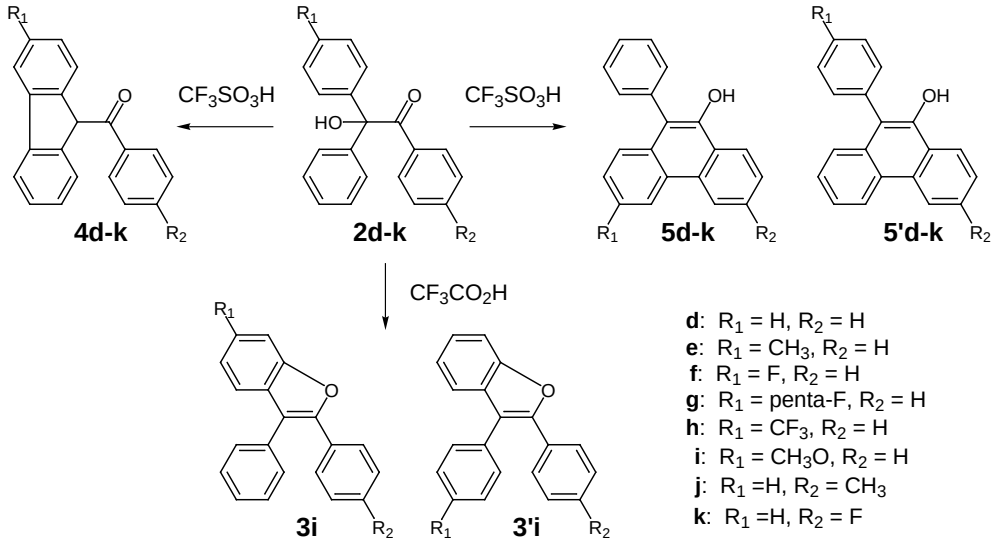


Scheme 1

In this context, α-benzoyldiphenylmethanols **2d–k** can produce fluorene, phenanthrol and benzofuran by acid-

Synthesis 2001, No. 10, 30 07 2001. Article Identifier:
1437-210X,E;2001,0,10,1487,1494,ftx,en;F02901SS.pdf.

ISSN 0039-7881

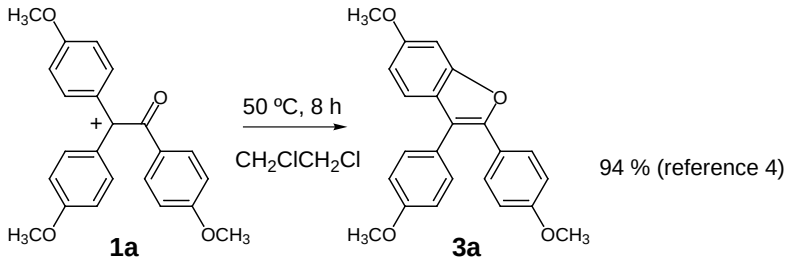


Scheme 2

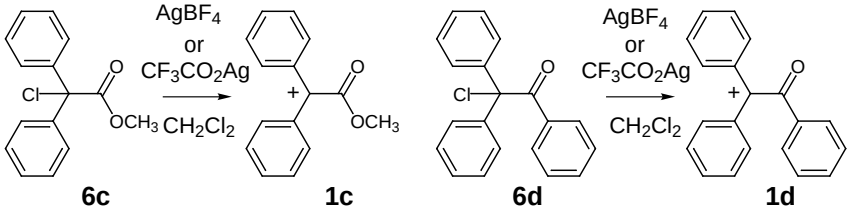
catalyzed electrocyclization through cationic intermediates (Scheme 2). The former two cyclizations represent an acid-catalyzed electrocyclization wherein two aromatic rings participate, and the latter cyclization represents a heteroatom cyclization, all these being of synthetic interest.[2b] There has been no systematic study of the ring-closing regiochemistry of cationic electrocyclization wherein several modes of cyclization are possible. Herein we deal with the substituent effects on the modes of the relevant electrocyclization reactions in order to reveal the synthetic potential of cationic electrocyclizations in which benzene rings participate.

The α-benzoyldiphenylmethanols **2d**–**k** (except **2g**, see experimental) can be readily prepared through the addition of Grignard reagents to *O*-trimethylsilylated cyanohydrins **9** of substituted benzophenones **8**, followed by acidic hydrolysis of the intermediate imines (Scheme 5).[13]

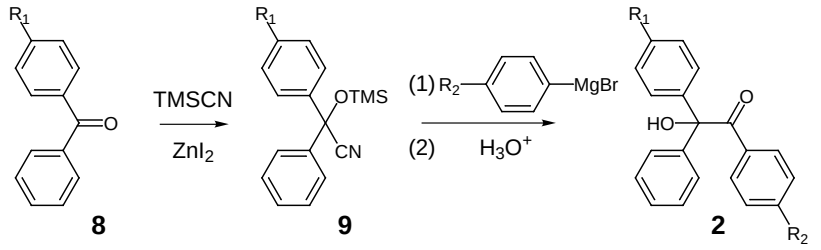
The acid-catalyzed cyclizations of α-benzoyldiphenylmethanols **2d**–**k** were studied, and yields and reaction conditions are summarized in the Table. In the case of the parent α-benzoyldiphenylmethanol (**2d**), superacid-catalyzed cyclization favored the formation of the fluorene **4d** (76%) over that of 9-phenylphenanthr-10-ol (**5d**) (9%).[8] Therefore the ratio of the yields of fluorene/phenanthrol (ratio **4**:**5** in the Table) was 8.4. This can be understood in terms of feasibility of formation of 5-membered ring over 6-membered ring.[14] A single substituent on the benzene ring can significantly modify the cyclization preference (Table). Methyl substitution at one of the benzene rings of the diphenylmethanol moiety as in **2e** affords a mixture of fluorene **4e** and phenanthrol **5e**, the former being favored



Scheme 3



Scheme 4



Scheme 5

over the latter. The ratio of the yields of fluorene/phenanthrol (6.3) decreased as compared with that of **2d** (8.4). Thus, the methyl substituenet changed the modes of the cyclizations to some extent.

On the other hand, pentafluoro substitution as in **2g**[15] can lead to exclusive formation of the phenanthrol derivative **5'g**. This is a reasonable outcome because the fluorene cyclization was inhibited due to the perfluoro substitution. However, substitution of a single fluorine atom on the benzene ring as in **2f** can change the cyclization preference: **2f** favored the formation of phenanthrol (**5'f**, 45% yield) over fluorene (**4f**, 35% yield) (ratio **4**/**5** = 0.78). Generally in the case of the phenanthrene cyclizations, two regio-isomers are possible, **5** and **5'** (Scheme 2). In the cases of **2f** and **2g**, a single isomer of the phenanthrols **5'f** and **5'g**, respectively, was predominantly formed while the methyl analog **2e** favored the phenanthrol structure **5e**. In the case of trifluoromethyl group as the R_1 substituent, the TFSA-catalyzed cyclization of **2h** at –45 °C for 30 minutes gave the phenanthrol **5'h** exclusively in 44% yield. No isomer of the phenanthrol **5h** or fluorene **4h** was formed. When the acid catalyst is trifluoroacetic acid (TFA), a much weaker acid than TFSA, no cyclized product was formed from **2h** (Table). Instead, α-benzoylphenyl(*p*-trifluoromethylphenyl)methyl trifluoroacetate was obtained in 27% yield, together with the recovery (47%) of the starting alcohol **2h**. The former product can be formed by nucleophilic attack of trifluoroacetate anion to the corresponding carbocation **1** (see Scheme 1). This result is consistent with the previous proposals that the fluorenes **4** and phenanthrols **5** do not arise from the monocations **1**, and that the cyclizations require superacid catalysis.[8,9]

Substitution of a methoxy group at the R_1 position also has a significant effect on the cyclizations. The substrate **2i** exclusively affords the benzofuran derivative **3i** (Scheme 2). A single substitution of a methoxy group is sufficent to activate the benzofuran cyclization (cf. **1a** in Scheme 3). In the case of the benzofuran cyclization, two regioisomers are also possible. In this case a single isomer, **3i** rather than **3'i**, was predominantly formed. The benzofuran cyclization of **2i** can also be catalyzed by

Table Acid-Catalyzed Electrocyclizations of α-Benzoyldiphenylmethanols

Substrate	R_1	R_2	Acid	Temp. (°C)[a]	Time (h)	Yield[b]			Ratio
						3	**4**	**5**	**4**/**5**[c]
2d[d]	H	H	TFSA	–48	0.5	0	76	9	8.4
2e	CH_3	H	TFSA	–48	3.0	0	63	10 (**5e**)	6.3
2f	F	H	TFSA	–48	2.5	0	35	45 (**5'f**)	0.78
2g	penta-F	H	TFSA	–48	1.5	0	0	41 (**5'g**)	–
2h	CF_3	H	TFSA	–48	0.5	0	0	44 (**5'h**)	–
2h[e]	CF_3	H	TFA	0	2.0	0	0	0	–
2i	CH_3O	H	TFSA	40	22.0	47 (**3i**)	0	0	–
2i	CH_3O	H	TFA	0	2.0	52 (**3i**)	0	0	–
2j	H	CH_3	TFSA	–48	8.0	0	69	14 (**5'j**)	4.9
2k	H	F	TFSA	–48	0.6	0	83	0	–

[a] ± 2 °C.
[b] Isolated yields.
[c] Ratio of the yields of fluorene (**4**)/phenanthrol (**5**).
[d] Reference.[8a]
[e] α-Benzoylphenyl(*p*-trifluoromethylphenyl)methyl trifluoroacetate (27%) and recovery (47%).

TFA. In TFA the cyclization reaction to benzofuran **3i** proceeded readily at 0 °C for 2 hours. Thus, as judged from the reaction conditions (long reaction time and high temperature in TFSA), the superacid catalyst (TFSA) retarded the benzofuran cyclization. This is consistent with the previous assessment of the involvement of the monocationic intermediate **1** of the benzofuran cyclization.[4,9]

Substitution of the benzene ring of the benzoyl moiety, i.e. influence of substituent R_2, was also studied. The methyl group at the R_2 position as in **2j** produced fluorene **4j** (69% yield) and phenanthrol **5j** (= **5'j**, in this case) (14% yield). The ratio of the yields of fluorene/phenanthrol (4.9) decreased as compared with that in the case of **2d** (8.4), suggesting encouragement of the phenanthrene cyclization by the CH_3 group. On the other hand, fluorine substitution at the R_2 position in **2k** suppressed the formation of phenanthrol, and the fluorene **4k** was exclusively formed (83%) (Table).

In summary, cationic electrocyclizations of the α-benzoyldiphenylmethanols in the presence of superacid provide fluorenes, phenanthrols and benzofurans in good to moderate yields. Although substituent effects on the cationic electrocyclization reactions have been poorly studied, the present work reveals a trend that relatively electron-rich benzene rings preferentially participate in the relevant cationic electrocyclizations. This tendency is crucial for the observed selectivities between fluorene/phenanthrol cyclizations (except in the case of **2e**), and between cyclized isomers (i.e. benzofurans **3i** and **3'i**, and phenanthrols **5** and **5'**). The present substitution effects therefore provide regioselective cationic electrocyclizations with synthetic potential.

The melting points were measured with a Yanaco Micro Melting Point Apparatus (MP-500D) and are uncorrected. ^{1}H NMR (400 MHz) spectra were measured on a JEOL Caliber-GX400 NMR spectrometer with TMS as an internal reference in $CDCl_3$ as the solvent, unless otherwise specified. Chemical shifts are shown in ppm. Coupling constants are given in Hertz. HRMS (EI^+) spectra were recorded on a Jeol JMS-SX 102A instrument. IR spectra were recorded as KBr suspension on a Nicolet Avatar 360 FT-IR spectrometer. Trifluoromethanesulfonic acid (TFSA) was purchased from Central Glass Co. (Japan), and was used after distillation under reduced pressure. The combustion analyses were carried out in the microanalytical laboratory of this faculty.

***O*-Trimethylsilylcyanohydrin of 4-Methylbenzophenone (9e)[13]**

To a solution of **8e** (2.00 g, 10.2 mmol) and a catalytic amount of ZnI_2 (163 mg, 0.51 mmol) in anhyd CH_2Cl_2 (40 mL) was added TMSCN (4.26 g, 4 equiv) at 0 °C under argon over 30 min. The mixture was stirred at 50 °C for 12 h. The residue, obtained after evaporation of the solvent, was diluted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give **9e** (2.701 g, 76%) as a pale yellow oil.

^{1}H NMR ($CDCl_3$): δ = 7.488 (2 H, dd, *J* = 8.25, 1.46 Hz), 7.377–7.323 (5 H, m), 7.153 (2 H, d, *J* = 8.07 Hz), 2.338 (3 H, s), 0.129 (9 H, s).

MS (EI^+): *m*/*z* = 295 (M^+).

α-Benzoylphenyl(*p*-tolyl)methanol (2e)[13]

To the Grignard reagent prepared from *p*-bromobenzene (4.207 g, 3 equiv) and Mg turnings (716 mg, 3.3 equiv) in anhyd Et_2O (7 mL) was added a solution of **9e** (2.701 g, 9.16 mmol) in anhyd Et_2O (4 mL) over 30 min and the reaction mixture was stirred at r.t. for 4 h. Aq 10% H_2SO_4 (200 mL) was added, the mixture stirred at 40 °C for 2 h and evaporated to give a residue consisting of a mixture of a ketol and an imine. In order to complete hydrolysis of the imine, a solution of the residue in EtOH (35 mL) was treated with 3 N aq HCl (1 mL) at 50 °C for 30 min. The residue, obtained after evaporation of the solvent, was diluted with $CHCl_3$, the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue, which was flash-chromatographed (EtOAc–hexane, 1:19) to give 1.655 g (61%) of ketol **2e** as a pale yellow oil.

^{1}H NMR ($CDCl_3$): δ = 7.719 (2 H, dd, *J* = 8.43, 1.28 Hz), 7.463–7.258 (9 H, m), 7.146 (2 H, d, *J* = 7.88 Hz), 4.936 (1 H, s), 2.344 (3 H, s).

MS (EI^+): *m*/*z* = 197 (M^+ – COPh).

Acid-Catalyzed Reaction of α-Benzoylphenyl(*p*-tolyl)methanol (2e)

To pre-cooled TFSA (58 mL, 500 equiv) at –48 °C (in a dry ice-MeCN bath) was added a solution of **2e** (400 mg, 1.32 mmol) in anhyd CH_2Cl_2 (3 mL) over 10 min. After stirring at –48 °C for 3 h, the mixture was poured into ice-water and extracted with $CHCl_3$. The organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 1:4 to 2:3) to give phenanthrol **5e** (39.1 mg, 10%) as a colorless oil and fluorene **4e** (237.2 mg, 63%) as a colorless solid.

Fluorene 4e

Colorless needles; mp 118.0–119.6 °C (recrystallized from CH_2Cl_2–hexane).

^{1}H NMR ($CDCl_3$): δ = 7.800 (1 H, d, *J* = 7.70 Hz), 7.744 (2 H, dd, *J* = 8.43, 1.10 Hz), 7.641 (1 H, s), 7.480 (1 H, dd, *J* = 7.52, 7.33 Hz), 7.402 (1 H, dd, *J* = 7.51, 7.33 Hz), 7.365–7.212 (7 H, m), 7.066 (1 H, dd, *J* = 7.70, 0.92 Hz), 5.538 (1 H, s), 2.441 (3 H, s).

MS (EI^+): *m*/*z* = 284 (M^+).

Anal. Calcd for $C_{21}H_{16}O \cdot H_2O$: C, 86.78; H, 5.79. Found: C, 86.65; H, 5.69.

Phenanthrol 5e

^{1}H NMR ($CDCl_3$): δ = 8.703 (1 H, d, *J* = 7.52 Hz), 8.462 (1 H, s), 8.371 (1 H, dd, *J* = 8.61, 1.47 Hz), 7.783–7.182 (9 H, m), 5.389 (1 H, s), 2.568 (3 H, s).

MS (EI^+): *m*/*z* = 284 (M^+).

HRMS (EI^+): *m*/*z* Calcd for $C_{21}H_{16}O$: 284.1202. Found: 284.1196.

***O*-Trimethylsilylcyanohydrin of 4-Fluorobenzophenone (9f)**

To a solution of **8f** (2.00 g, 10 mmol) and a catalytic amount of ZnI_2 (154 mg, 0.48 mmol) in anhyd CH_2Cl_2 (32 mL) was added TMSCN (4.048 g, 4 equiv) at 0 °C over 60 min. The mixture was stirred at 50 °C for 24 h. The residue, obtained after evaporation of the solvent, was diluted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give **9f** (2.706 g, 93%) as a colorless oil.

^{1}H NMR ($CDCl_3$): δ = 7.519–7.439 (4 H, m), 7.394–7.313 (3 H, m), 7.042 (2 H, t, *J* = 8.62 Hz), 0.137 (9 H, s).

MS (EI^+): *m*/*z* = 299 (M^+).

α-Benzoyl(4-fluorophenyl)phenylmethanol (2f)

To the Grignard reagent prepared from bromobenzene (4.564 g, 3 equiv) and Mg turnings (777 mg, 3.3 equiv) in anhyd Et_2O (12 mL)

was added a solution of **9f** (2.706 g, 9.7 mmol) in anhyd Et_2O (4 mL) over 20 min. The mixture was stirred at r.t. for 6 h and added to aq 10% H_2SO_4 (200 mL) and stirred at r.t. for 18 h. The mixture was extracted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent, was dissolved in EtOH (35 mL), and the resultant solution was treated with 3 N aq HCl (3 mL) at 50 °C for 5 h. The solvent was evaporated to give a residue which was flash-chromatographed (EtOAc–hexane, 1:9) to give **2f** (1.791 g, 60%) as colorless needles; mp 78.4–79.4 °C (recrystallized from CH_2Cl_2–hexane).

^{1}H NMR ($CDCl_3$): δ = 7.695 (2 H, dd, *J* = 8.43, 1.28 Hz), 7.484–7.278 (10 H, m), 7.023 (2H, t, *J* = 8.98 Hz), 4.976 (1 H, s).

MS (EI^+): *m*/*z* = 201 (M^+ – COPh).

Anal. Calcd for $C_{20}H_{15}FO_2$: C, 78.42; H, 4.94. Found: C, 78.24; H, 4.96.

Acid-Catalyzed Reaction of α-Benzoyl(4-fluorophenyl)-phenylmethanol (2f)

To pre-cooled TFSA (28.8 mL, 500 equiv) at –48 °C (in a dry ice-MeCN bath) was added a solution of **2f** (200 mg, 0.65 mmol) over 10 min. After stirring at –48 °C for 2.5 h, the mixture was poured into ice-water (300 mL), extracted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 3:7) to give phenanthrol **5'f** (85 mg, 45%) as a pink solid and fluorene **4f** (65 mg, 34%) as a colorless solid.

Fluorene 5'f

Colorless solid; mp 149.1–150.0 °C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 7.789 (2 H, d, *J* = 7.70 Hz), 7.760 (2 H, dd, *J* = 8.43, 1.28 Hz), 7.534–7.269 (8 H, m), 6.907 (1 H, ddd, *J* = 9.16, 8.43, 2.38 Hz), 5.589 (1 H, s).

HRMS (EI^+): *m*/*z* Calcd for $C_{20}H_{13}FO$: 288.0947. Found: 288.0950.

Anal. Calcd for $C_{20}H_{13}FO{\cdot}H_2O$: C, 78.42; H, 4.92. Found: C, 78.46; H, 4.93.

Phenanthrol 5'f

Pink plates; mp 159.3–164.0 °C (recrystallized from $CHCl_3$–hexane).

^{1}H NMR ($CDCl_3$): δ = 8.721 (1 H, dd, *J* = 8.25, 0.73 Hz), 8.682 (1 H, dd, *J* = 8.07, 0.72 Hz), 8.386 (1 H, dd, *J* = 7.52, 1.47 Hz), 7.753–7.285 (9 H, m), 5.359 (1 H, s).

MS (EI^+): *m*/*z* = 288 (M^+).

Anal. Calcd for $C_{20}H_{13}FO$: C, 83.32; H, 4.54. Found: C, 83.03; H, 4.59.

α-Benzoyl(pentafluorophenyl)phenylmethanol (2g)[15]

To a solution of pentafluorobenzene (2.0 g, 11.9 mmol) in Et_2O (6 mL) was added a solution of BuLi in hexane (7.8 mL, 1.52 mmol/mL, 1 equiv) at –55 °C over 20 min under argon. The mixture was stirred at –55 °C for 2 h, and then cooled to –78 °C. To the resultant solution was added a solution of benzil (2.5 g, 1 equiv) in THF (3 mL) over 10 min and the mixture was stirred for 2 h at –78 °C. The cooling bath was removed to warm the mixture to r.t. The mixture was stirred for 1 h, poured into 3 N aq HCl (200 mL), and extracted with $CHCl_3$. The organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed (EtOAc–hexane, 1:99) to give **2g** (2.2 g, 49%) as a colorless powder; mp 106.9–108.2 °C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): 7.828 (2 H, d, *J* = 7.70 Hz), 7.643–7.331 (8 H, m), 5.300 (1 H, s).

MS (EI^+): *m*/*z* = 273 (M^+ – COPh).

Anal. Calcd for $C_{15}H_{11}F_3O_2{\cdot}0.8H_2O$: C, 62.31; H, 3.09. Found: C, 62.25; H, 3.11.

Acid-Catalyzed Reaction of α-Benzoyl(pentafluoro-phenyl)phenylmethanol (2g)

To pre-cooled TFSA (23.4 mL, 500 equiv) at –48 °C (in a dry ice-MeCN bath) was added **2g** (200 mg, 0.53 mmol) over 5 min. After stirring at –48 °C for 1 h, the mixture was poured into ice-water (400 mL), extracted with $CHCl_3$, the $CHCl_3$ layer washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 3:7) to give phenanthrol **5'g** (67 mg, 41%) as a solid.

Phenanthrol 5'g

Off-white powder; mp 140.0–144.2 °C (recrystallized from hexane–CH_2Cl_2).

^{1}H NMR ($CDCl_3$): δ = 8.755 (1 H, d, *J* = 8.43 Hz), 8.703 (1 H, d, *J* = 8.06 Hz), 8.309 (1 H, d, *J* = 7.88 Hz), 7.795 (1 H, t, *J* = 7.32 Hz), 7.716 (1 H, t, *J* = 7.52 Hz), 7.578 (1 H, t, *J* = 7.15 Hz), 7.522 (1 H, t, *J* = 7.70 Hz), 5.233 (1 H, s).

MS (EI^+): *m*/*z* = 360 (M^+).

HRMS (EI^+): *m*/*z* Calcd for $C_{20}H_9F_5O$: 360.0554. Found: 360.0573.

***O*-Trimethylsilylcyanohydrin of 4-Trifluoromethylbenzo-phenone (9h)**

To a solution of **8h** (3.00 g, 12 mmol) and a catalytic amount of ZnI_2 (191 mg, 0.6 mmol) in CH_2Cl_2 (40 mL) was added TMSCN (2.38 g, 2 equiv) at 0 °C over 30 min. The mixture was stirred at 40 °C for 24 h. The residue, obtained after evaporation of the solvent, was diluted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give **9h** in quantitative yield as a yellow oil.

^{1}H NMR ($CDCl_3$): δ = 7.628 (4 H, s), 7.490 (2 H, d, *J* = 6.60 Hz), 7.375 (3 H, d, *J* = 7.52 Hz), 0.156 (9 H, s).

MS (EI^+): *m*/*z* = 349 (M^+).

α-Benzoylphenyl(4-trifluoromethylphenyl)methanol (2h)

To the Grignard reagent prepared from bromobenzene (4.706 g, 3 equiv) and Mg turnings (801 mg, 3.3 equiv) in anhyd Et_2O (14 mL) was added a solution of **9h** (3.491 g, 10 mmol) in anhyd Et_2O (4 mL) over 30 min. The mixture was stirred at r.t. for 4 h. The mixture was added to 10% aq H_2SO_4 (200 mL), and stirred at r.t. for 11 h. The mixture was extracted with $CHCl_3$, and the organic layer was washed with brine, and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent was dissolved in EtOH (35 mL), and the resultant solution was treated with 3 N aq HCl (8 mL) at 40 °C for 3 h. The solvent was evaporated to give a residue, which was diluted with $CHCl_3$. The organic layer was washed with brine and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent, was flash-chromatographed (EtOAc–hexane, 1:9) to give **2h** (3.0824 g, 86%) as a yellow oil which solidified; colorless solid; mp 64.9–69.0 °C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 7.702 (2 H, d, *J* =7.70 Hz), 7.585 (4 H, dd, *J* = 12.28, 8.80 Hz), 7.483 (1 H, t, *J* = 7.33 Hz,), 7.375 (5 H, s), 7.372 (2 H, t, *J* = 7.88 Hz), 4.970 (1 H, s).

MS (EI^+): *m*/*z* = 175 (M^+ – COPh).

Anal. Calcd for $C_{21}H_{15}F_3O_2$: C, 70.78; H, 4.24. Found: C, 70.58; H, 4.53.

TFSA-Catalyzed Reaction of α-Benzoylphenyl(4-trifluoro-methylphenyl)methanol (2h)

To pre-cooled TFSA (27.8 mL, 500 equiv) at –48 °C (in a dry ice-MeCN bath) was added **2h** (200 mg, 0.56 mmol) over 10 min. After stirring at –48 °C for 30 min, the mixture was poured into ice-water

(300 mL), extracted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue, which was flash-chromatographed ($CHCl_3$–hexane, 3:7) to give phenanthrol **5'h** (83.3 mg, 44%) as a solid.

Phenanthrol 5'h

Pale yellow powder; mp 170.0–171.1°C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 8.728 (2 H, d, *J* = 8.25 Hz), 8.691 (1 H, d, *J* = 8.25 Hz), 8.395 (2 H, t, *J* = 7.88 Hz), 7.902 (2 H, d, *J* = 7.88 Hz), 7.762–7.291 (9 H, m), 5.28 (1 H, s).

MS (EI$^+$): *m*/*z* = 338 (M^+).

HRMS (EI$^+$): *m*/*z* Calcd for $C_{21}H_{13}F_3O$: 338.0907. Found: 338.0916.

TFA-Catalyzed Reaction of α-Benzoylphenyl(4-trifluoromethylphenyl)methanol (2h)

To pre-cooled TFA (10.7 mL, 500 equiv) at –15°C (in a dry ice-CCl_4 bath) was added **2h** (100 mg, 0.28 mmol) over 10 min. After stirring at –15°C for 1 h and then at 0°C for 2 h, the mixture was poured into ice-water (300 mL). The mixture was extracted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 1:9) to give α-benzoylphenyl(4-trifluoromethylphenyl)methyl trifluoroacetate (33.6 mg, 27%) as a colorless oil and the starting material **2h** (46.5 mg, 47% recovery).

α-Benzoylphenyl(4-trifluoromethylphenyl)methyl Trifluoromethylacetate

^{1}H NMR ($CDCl_3$): δ = 7.738 (2 H, d, *J* = 7.70 Hz), 7.683 (2 H, d, *J* = 8.43 Hz), 7.637 (2 H, d, *J* = 7.70 Hz), 7.565 (2 H, d, *J* = 6.96 Hz), 7.515–7.399 (4 H, m), 7.345 (2 H, t, *J* = 7.70 Hz).

MS (EI$^+$): *m*/*z* = 339 ($M^+ - CF_3CO_2$), 105 (PhCO).

IR (KBr suspension): ν = 1794 (C=O of CF_3CO_2), 1695 cm^{-1} (C=O of benzoyl).

***O*-Trimethylsilylcyanohydrin of 4-Methoxybenzophenone (9i)**

To a solution containing **8i** (2.00 g, 9.4 mmol) and a catalytic amount of ZnI_2 (150 mg, 0.47 mmol) in anhyd CH_2Cl_2 (31 mL) was added TMSCN (3.73 g, 4 equiv) at 0°C over 15 min. The mixture was stirred at 40°C for 12 h. The residue, obtained after evaporation of the solvent, was diluted with $CHCl_3$. The organic layer was washed with brine, dried (Na_2SO_4) and the solvent was evaporated to give **9i** (2.790 g, 95%) as a yellow oil.

^{1}H NMR ($CDCl_3$): δ = 7.483 (2 H, ddd, *J* = 8.06. 2.10, 1.65 Hz), 7.391 (2 H, dd, *J* = 8.98, 2.20 Hz), 7.355–7.329 (3 H, m), 6.866 (2 H, dd, *J* = 8.17, 2.20 Hz), 0.129 (9 H, s).

MS (EI$^+$): *m*/*z* = 311 (M^+).

α-Benzoyl(4-methoxyphenyl)phenylmethanol (2i)

To the Grignard reagent prepared from bromobenzene (4.22 g, 3 equiv) and Mg turnings (718 mg, 3.3 equiv) in anhyd Et_2O (7 mL) was added a solution of **9i** (2.79 g, 9 mmol) in anhyd Et_2O (4 mL) over 30 min. The mixture was stirred at r.t. for 4 h and added to 10% aq H_2SO_4 (200 mL) and stirred at r.t. for 18 h. The mixture was extracted with $CHCl_3$, and the organic layer was washed with brine, and dried (Na_2SO_4). The residue obtained after evaporation of the solvent was dissolved in EtOH (35 mL), and the resultant solution was treated with 3 N aq HCl (5 mL) at 50°C for 12 h. The solvent was evaporated to give a residue, which was diluted with $CHCl_3$ and the organic layer was washed with brine, and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent, was flash-chromatographed (EtOAc–hexane, 1:9) to give **2i** (550 mg, 19%) as a yellow oil.

^{1}H NMR ($CDCl_3$): δ = 7.714 (2 H, dd, *J* = 8.43, 1.28 Hz), 7.448–7.228 (10 H, m), 6.865 (2 H, dd, *J* = 6.78, 2.20 Hz), 4.985 (1 H, s), 3.804 (3 H, s).

MS (EI$^+$): *m*/*z* = 253 (M^+ – COPh).

TFSA-Catalyzed Reaction of α-Benzoyl(4-methoxyphenyl)-phenylmethanol (2i)

To pre-cooled TFSA (27.6 mL, 500 equiv) at –48°C (in a dry ice-MeCN bath) was added a solution of **2i** (200 mg, 0.63 mmol) in CH_2Cl_2 (3 mL) over 10 min. After stirring at 24°C even for 10 h, the reaction was very slow. After gentle heating at 40°C for 22 h, the mixture was poured into ice-water. It was extracted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The organic solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 1:4 to 2:3) to give benzofuran **3i** (88 mg, 46%) as a colorless solid.

Benzofuran 3i

Colorless powder; mp 126.0–126.9°C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 7.619 (2 H, dd, *J* = 6.72, 1.65 Hz), 7.513–7.239 (9 H, m), 7.099 (1 H, d, *J* = 2.20 Hz), 6.876 (1 H, dd, *J* = 8.62, 2.20 Hz), 3.890 (3 H, s).

MS (EI$^+$): *m*/*z* 300 (M^+).

Anal. Calcd for $C_{21}H_{16}O_2$: C, 83.98; H, 5.37. Found: C, 83.79; H, 5.54.

TFA-Catalyzed Reaction of α-Benzoyl(4-methoxyphenyl)-phenylmethanol (2i)

To pre-cooled TFA (9 mL, 500 equiv) at –15°C (in a dry ice-CCl_4 bath) was added a solution of **2i** (75.0 mg, 0.24 mmol) in CH_2Cl_2 (3 mL) over 10 min. After stirring at 0°C for 2 h, the mixture was poured into ice-water. It was extracted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The organic solvent was evaporated to give a residue, which was flash-chromatographed ($CHCl_3$–hexane, 1:4) to give benzofuran **3i** (37.0 mg, 52%) as a colorless solid. This product was identical with that obtained above.

***O*-Trimethylsilylcyanohydrin of Benzophenone 9j (= 9k)**

To a solution of benzophenone (**8j** = **8k**; 2.00 g, 11 mmol) and a catalytic amount of ZnI_2 (175 mg, 0.55 mmol, 0.05 equiv) in anhyd CH_2Cl_2 (37 mL) was added TMSCN (4.36 g, 4 equiv) at 0°C over 0.5 h and the mixture was stirred at 40°C for 17 h. The residue, obtained after evaporation of the solvent, was diluted with $CHCl_3$, and the organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give **9j** (= **9k**) (3.02 g, 97%) as a colorless oil.

^{1}H NMR ($CDCl_3$): δ = 7.497 (4 H, ddd, *J* = 6.87, 2.20, 1.65 Hz), 7.376–7.294 (6 H, m), 0.135 (9 H, s).

MS (EI$^+$): *m*/*z* = 281 (M^+).

IR (KBr suspension): ν = 2326 cm^{-1} (CN).

α-(*p*-Methylbenzoyl)diphenylmethanol (2j)

To the Grignard reagent prepared from *p*-bromotoluene (5.634 g, 3 equiv) and Mg turnings (880 mg, 3.3 equiv) in anhyd Et_2O (8 mL) was added a solution of **9j** (3.226 g, 11.5 mmol) in anhyd Et_2O (4 mL) over 15 min. The mixture was stirred at r.t. for 4 h and added to aq 10% H_2SO_4 (200 mL) and stirred at 40°C for 13 h. It was then extracted with $CHCl_3$, the organic layer washed with brine, and dried (Na_2SO_4). The residue, obtained after evaporation of the organic solvent was dissolved in EtOH (35 mL), and the resultant solution was treated with 3 N aq HCl (8 mL) at 40°C for 2.5 h. The solvent was evaporated to give a residue, which was diluted with $CHCl_3$, and the organic layer was washed with brine, and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent,

was flash-chromatographed (EtOAc–hexane, 1:19) to give **2j** (2.5146 g, 75%) as a yellow oil which solidified; colorless solid; mp 64.5–65.5 °C (recrystallizaed from hexane).

^{1}H NMR ($CDCl_3$): δ = 7.635 (2 H, d, *J* = 8.06 Hz), 7.424–7.324 (10 H, m), 7.079 (2 H, d, *J* = 7.88 Hz), 5.188 (1 H, s), 3.799 (3 H, s).

MS (EI$^+$): *m*/*z* = 183 (M^+ – $COPhCH_3$).

Anal. Calcd for $C_{21}H_{18}O_2$: C, 83.42; H, 6.00. Found: C, 83.50; H, 6.11.

Acid-Catalyzed Reaction of α-(4-Methylbenzoyl)diphenylmethanol (2j)

To pre-cooled TFSA (58.5 mL, 500 equiv) at –48 °C (in a dry ice-MeCN bath) was added **2j** (400 mg, 1.33 mmol) over 10 min. After stirring at –48 °C for 1 h, the mixture was poured into ice-water (300 mL) and extracted with $CHCl_3$. The organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 1:4 to 1:1) to give phenanthrol **5j** (51.6 mg, 14%) as a colorless oil (solidfied) and fluorene **4j** (260.5 mg, 69%) as a yellow solid.

Phenanthrol 5j

Colorless powder; mp 93.5–94.3 °C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 8.667 (1 H, d, *J* = 8.25 Hz), 8.506 (1 H, s), 8.274 (2 H, d, *J* = 8.25 Hz), 7.623 (2 H, d, *J* = 7.15 Hz), 7.559–7.364 (7 H, m), 5.425 (1 H, s), 2.659 (3 H, s).

MS (EI$^+$): *m*/*z* = 284 (M^+).

HRMS (EI$^+$): *m*/*z* Calcd for $C_{21}H_{16}O$: 284.1202. Found: 284.1194.

Fluorene 4j

Colorless needles; mp 126.9–128.5 °C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 7.842 (2 H, d, *J* = 7.52 Hz), 7.659 (2 H, d, *J* = 8.25 Hz), 7.427 (2 H, t, *J* = 7.52 Hz), 7.390 (2 H, d, *J* = 7.33 Hz), 7.265 (2 H, t, *J* = 7.51 Hz), 7.165 (2 H, d, *J* = 8.07 Hz), 5.599 (1 H, s), 2.364 (3 H, s).

MS (EI$^+$): *m*/*z* 284 (M^+).

Anal. Calcd for $C_{21}H_{16}O·0.48H_2O$: C, 86.07; H, 5.83. Found: C, 86.07; H, 5.54.

α-(4-Fluorobenzoyl)diphenylmethanol (2k)

To the Grignard reagent prepared from 1-bromo-4-fluorobenzene (5.765 g, 3 equiv) and Mg turnings (880 mg, 3.3 equiv) in anhyd Et_2O (8 mL) was added a solution of **9j** (= **9k**) (3.020 g, 10. 8 mmol) in anhyd Et_2O (5 mL) over 5 min. The mixture was stirred at r.t. for 5 h, then added to aq 10% H_2SO_4 (200 mL), and stirred at 40 °C for 24 h. The mixture was extracted with $CHCl_3$, the organic layer was washed with brine and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent was dissolved in EtOH (35 mL), and the solution was treated with 3 N aq HCl (8 mL) at 40 °C for 9 h. The solvent was evaporated to give a residue, which was diluted with $CHCl_3$. The organic layer was washed with brine and dried (Na_2SO_4). The residue, obtained after evaporation of the solvent, was flash-chromatographed (EtOAc–hexane, 1:39) to give **2k** (1.698 g, 65%) as a yellow solid; colorless powder; mp 82.9–83.1 °C (recrystallized from hexane–CH_2Cl_2).

^{1}H NMR ($CDCl_3$): δ = 7.707 (2 H, d, *J* = 7.70 Hz), 7.557–7.438 (6 H, m), 7.311 (2 H, t, *J* = 7.70 Hz), 4.776 (1 H, s).

Anal. Calcd for $C_{20}H_{15}FO_2$: C, 70.42; H, 4.94. Found: C, 70.19; H, 4.97.

Acid-Catalyzed Reaction of α-(4-Fluorobenzoyl)diphenylmethanol (2k)

To pre-cooled TFSA (57.8 mL, 500 equiv) at –48 °C (in a dry ice-MeCN bath) was added **2k** (400 mg, 1.3 mmol) over 6 min. After stirring at –48 °C for 50 min, the mixture was poured into ice-water (300 mL) and extracted with $CHCl_3$. The organic layer was washed with brine and dried (Na_2SO_4). The solvent was evaporated to give a residue which was flash-chromatographed ($CHCl_3$–hexane, 7:15 to 1:1 to 3:2) to give fluorene **4k** (313.7 mg, 83%) as a solid.

Fluorene 4k

Colorless needles; mp 126.0–126.7 °C (recrystallized from hexane).

^{1}H NMR ($CDCl_3$): δ = 7.860 (2 H, d, *J* = 7.70 Hz), 7.667 (2 H, dd, *J* = 9.62, 6.78 Hz), 7.467–7.283 (6 H, m), 6.979 (2 H, t, *J* = 8.61 Hz), 5.509 (1 H, s).

MS (EI$^+$): *m*/*z* = 288 (M^+).

Anal. Calcd for $C_{20}H_{13}FO$: C, 83.32; H, 4.54. Found: C, 83.04; H, 4.65.

Acknowledgement

Part of the work was financially supported by Takeda Science Foundation (Osaka, Japan).

References

(1) (a) Creary, X. *Chem. Rev.* **1991**, *91*, 1625. (b) Creary, X.; Hopkinson, A. C.; Lee-Ruff, E. *Advances in Carbocation Chemistry*, Vol. 1; Creary, X., Ed.; JAI Press: Greenwich, CT, **1989**, 45. (c) Gassman, P. G.; Tidwell, T. T. *Acc. Chem. Res.* **1983**, *16*, 279. (d) Tidwell, T. T. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 20.

(2) (a) Dao, L. H.; Maleki, M.; Hopkinson, A. C.; Lee-Ruff, E. *J. Am. Chem. Soc.* **1986**, *108*, 5237. (b) Hopkinson, A. C.; Lee-Ruff, E.; Maleki, M. *Synthesis* **1986**, 366.

(3) Johnston, L. J.; Kwong, P.; Shelemay, A.; Lee-Ruff, E. *J. Am. Chem. Soc.* **1993**, *115*, 1664.

(4) Takeuchi, K.; Kitagawa, T.; Okamato, K. *J. Chem. Soc., Chem. Commun.* **1983**, 7.

(5) Photochemical cyclizations of methoxy-substituted benzoin esters (e.g., 4'-methoxybenzoin acetate) to give benzofurans (2-phenyl-6-methoxybenzofuran) was reported by Sheehan, J. C.; Wilson, R. M.; Oxford, A. W. *J. Am. Chem. Soc.* **1971**, *93*, 7222.

(6) It was reported that α-acetyldiphenylmethanol (**2b**, R = CH_3) and α-benzoyldiphenylmethanol (**2d**, $R_1 = R_2$ = H) cyclized in H_2SO_4–$CHCl_3$ by an electrocyclization mechanism between the benzene ring and the carbonyl group, resulting in the formation of the corresponding benzofurans,[2,10] although the formation of the fluorene derivative **4d** from **2d** has also been reported under similar conditions.[11]

(7) (a) Vorlander, D.; Pritzsche, A. *Ber. Dtsch. Chem. Ges.* **1913**, *46*, 1793. (b) Britzrzycki, A.; Herbst, C. *Ber. Dtsch. Chem. Ges.* **1903**, *36*, 145. (c) Dobeneck, H. V.; Kiefer, R. *Liebigs Ann. Chem.* **1965**, *684*, 115. (d) Arnold, R. T.; Parham, W. E.; Dodson, R. M. *J. Am. Chem. Soc.* **1949**, *71*, 2439. (e) Hopkinson, A. C.; Khazanie, P. G.; Dao, L. H. *J. Chem. Soc., Perkin Trans. 2* **1979**, 1395. (f) Delacre, M. *Bull. Soc. Chim. Fr.* **1918**, *23*, 229.

(8) (a) Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1988**, *110*, 1862. (b) Ohwada, T.; Shudo, K. *J. Org. Chem.* **1989**, *54*, 5227.

(9) Ohwada, T.; Suzuki, T.; Shudo, K. *J. Am. Chem. Soc.* **1998**, *120*, 4629.

(10) Hopkinson, A. C.; Dao, L. H.; Duperrouzel, P.; Maleki, M.; Lee-Ruff, E. *J. Chem. Soc., Chem. Commun.* **1983**, 727.

(11) Maleki, M.; Hopkinson, A. C.; Lee-Ruff, E. *Tetrahedron Lett.* **1983**, *24*, 4911.

(12) (a) Olah, G. A.; Wu, A.-H. *J. Org. Chem.* **1991**, *56*, 2531 . (b) For a review of superelectrophiles, see: Olah, G. A. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 767. (c) See also: Olah, G. A.; Klumpp, D. A.; Nlyer, G.; Wang, Q. *Synthesis* **1996**, 321.
(13) (a) Krepski, L. R.; Heilmann, S. M.; Rasmussen, J. K. *Tetrahedron Lett.* **1983**, *24*, 4075. (b) Gassman, P. G.; Talley, J. J. *Tetrahedron Lett.* **1978**, 3773.
(14) Johnson, C. D. *Acc. Chem. Res.* **1993**, *26*, 476.
(15) Chambers, R. D.; Clark, M. *J. Chem. Soc., Perkin Trans. 1* **1972**, 2469.