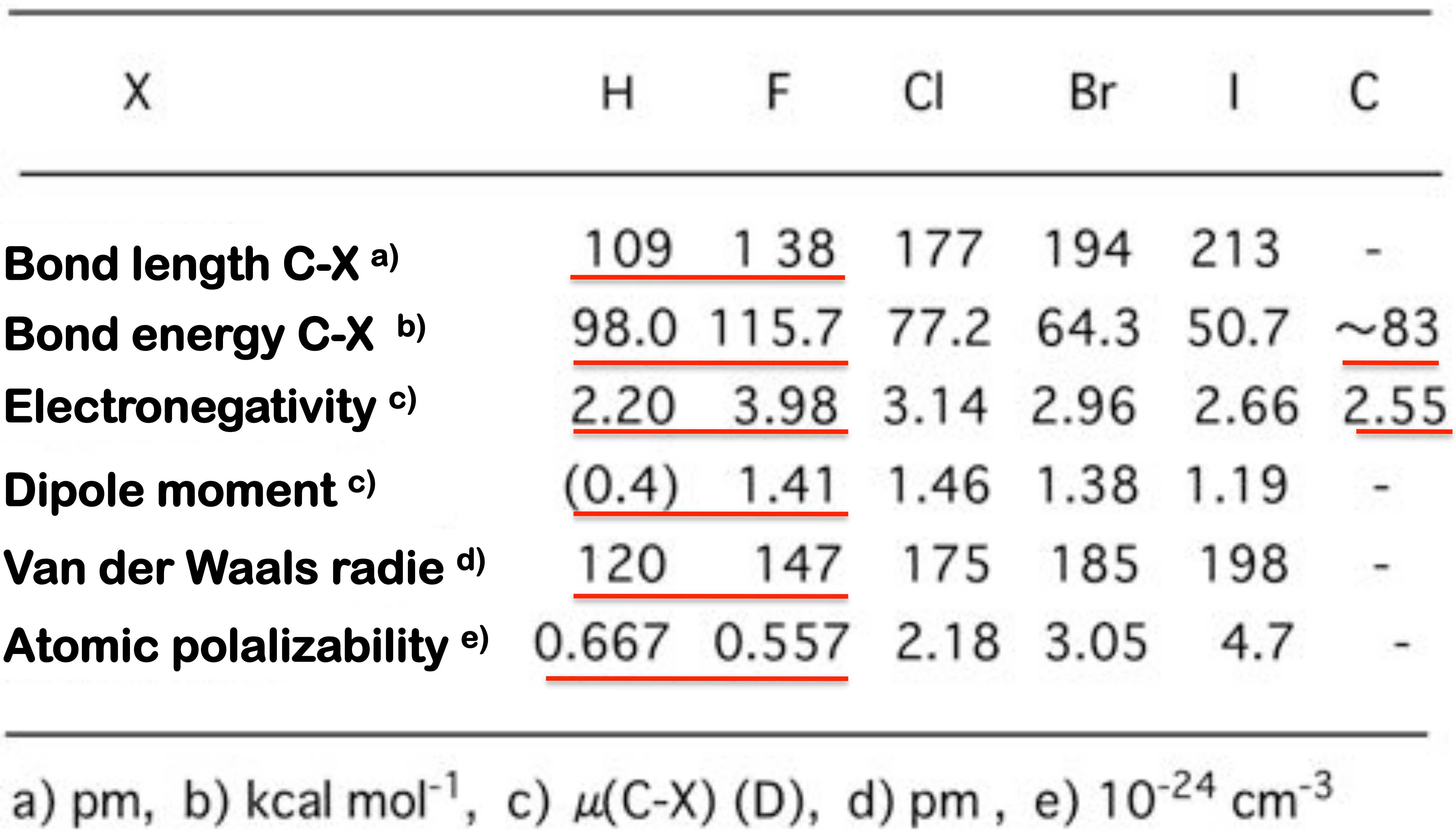
研究例：

1. 有機化学におけるフッ素効果とは？（続き）
2. 含フッ素弱配位性アニオンとは？
3. 有機フッ素分子の気相酸性度とは？
4. 含フッ素超強酸およびその誘導体によって促進される有機反応に関する研究
    1) 超強炭素酸触媒反応
    2)フェニルカチオン中間体の安定化機構
    3)芳香族フッ化物の分子内縮合環化反応の機構

Table. Comparison of several properties of C-X bonds

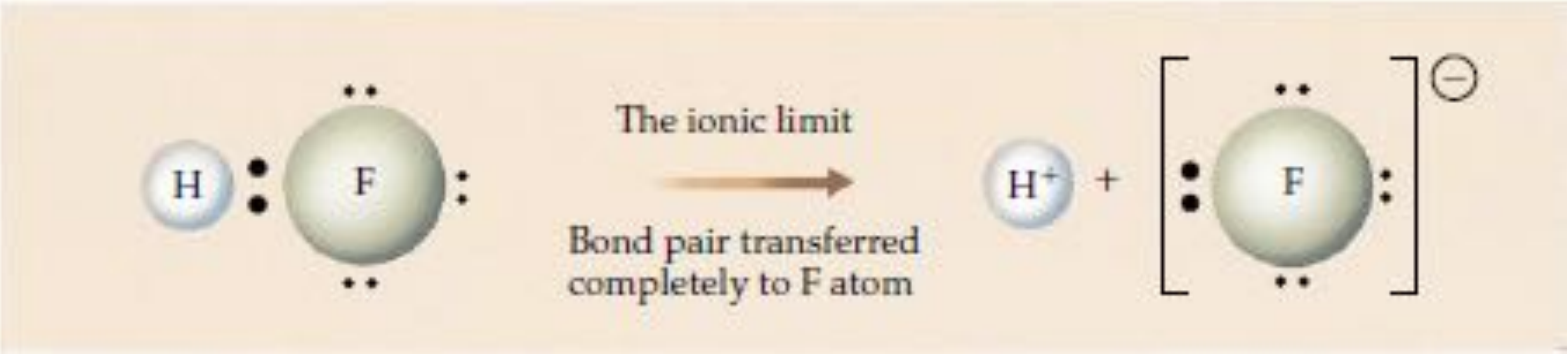


X	H	F	Cl	Br	I	C
Bond length C-X a)	109	138	177	194	213	-
Bond energy C-X b)	98.0	115.7	77.2	64.3	50.7	~83
Electronegativity c)	2.20	3.98	3.14	2.96	2.66	2.55
Dipole moment c)	(0.4)	1.41	1.46	1.38	1.19	-
Van der Waals radie d)	120	147	175	185	198	-
Atomic polalizability e)	0.667	0.557	2.18	3.05	4.7	-

a) pm, b) kcal mol^{-1}, c) μ(C-X) (D), d) pm , e) 10^{-24} cm^{-3}

Dielectric const. C_6F_{14} (1.69) vs C_6H_{14} (1.89) vs C_3F_7-C_3H_7 (5.99)

Ion Dissociation of Acid Molecule



Acid Dissociation Constant(*K*a) in Aqueous Phase

$$\text{A-H} + H_2O \overset{K}{\rightleftharpoons} A^- + H_3O^+$$

(excess amount) oxonium Ion

$$K_a = K \times [H_2O] = [A^-] \times [H_3O^+] / [\text{A-H}]$$

$$pK_a = -\log Ka$$

pKa Values of Organic Compounds

CH_3-H (sp^3-carbon)	48
CH_2=CH-H (sp^2-carbon)	44
C_6H_5-H (sp^2-carbon)	43
$C_6H_5CH_2$-H	41
(conjugative stabilization)	
NH_2-H	38
CF_3-H (HFC-23)	30.5
(inductive fluorine stabilization)	
CF_3CF_2-H (HFC-125)	28.2
HC≡C-H (sp-carbon)	25
$(CF_3)_3$C-H	21.0
(hyperconjugative fluorine stabilization)	
CH_3COCH_2-H	20
(conjugative stabilization)	
HO-H	15.7
(inductive stabilization)	

H-CH $(COCH_3)_2$	13
(conjugative stabilization)	
H-CH_2NO_2	10.2
(conjugative and inductive)	
C_6H_5O-H	10
(conjugative and inductive)	
CH_3COO-H	4.8
(conjugative and inductive)	
HCOO-H	3.8
(conjugative and inductive)	
H-CH$(NO_2)_2$	3.6
CCl_3COO-H	0.7
(conjugative and inductive)	
CF_3COO-H	0.5
(conjugative and inductive)	
H_2SO_4	-3.0
(conjugative and inductive)	

super acids

Solvent Effect on Acidity

$$CH_3O^- + Ph_2CH_2 \overset{K}{\rightleftharpoons} CH_3OH + Ph_2CH^-$$

Solvent	K
H_2O	10^{-17}
	↕
gas-phase	10^{11}

Solvent effect on conjugate base anion stability

$$HA + S \overset{K}{\rightleftharpoons} A^- + HS^+$$

HA: acid

A^- : conjugate base

S : solvent

	pKa	
	H_2O	(DMSO)
CH_4	48	(56)
$PhCH_3$	41	(43)
Ph_2CH_2	33.5	(32.2)
Ph_3CH	31.5	(30.6)
H_2O	15.7	(31.2)
MeOH	15.5	(27.9)

Δ18 (Δ 4.3)

Gas-Phase Acidities of Neutral Brønsted Acids

JACS, 116, 3047 (1994)

fruitful collaboration of four groups of physical organic chemistry in Estonia, France, Spain, and USA with three groups of synthetic organic fluorine chemistry in Russia, Ukraine, and USA.

Gas phase acidity: $\Delta G^0_{ac}(\mathrm{HA})$

$$\mathrm{H\text{-}A(g)} \overset{K}{\rightleftharpoons} \mathrm{A^-(g) + H^+(g)} \qquad \Delta G^0_{ac}(\mathrm{HA}) = -RT\ln K$$

$\Delta G^0_{ac}(\mathrm{HA})$ (kcal/mol)

CH_4	(408.5)	$CF_3SO_2NH_2$	(321.3)
NH_3	(396.1)	HI	(309.2)
H_2O	(384.1)	H_2SO4	(302.2)
$PhCH_3$	(373.7)	CF_3SO_2OH	(299.5)
$CH_3SO_2CH_3$	(358.2)	$(CF_3SO_2)_2NH$	(291.8)
$C_6F_5CH_3$	(354.7)	$(CF_3SO_2)_3CH$	(289.0)
$CF_3SO_2CH_3$	(339.8)	$(C_4F_9SO_2)_2NH$	(284.1)

super acids

Chemistry of Weakly Coordinating Anions

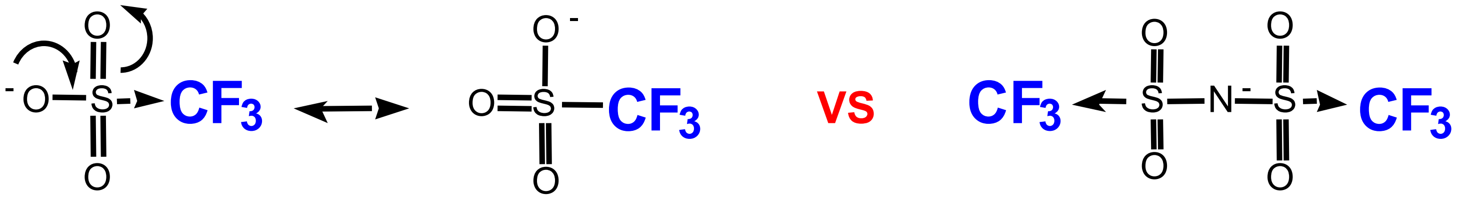
$$M - X\,(M^{+}X^{-}) \rightleftharpoons M^{+} + X^{-} \xrightleftharpoons{YX_3} M^{+} + X\text{-}YX_3^{-}$$

(Lewis acid-base complex)

M^+ : proton, metal ions

X^-: $OSO_2CF_3^-$, $N(SO_2CF_3)_2^-$, $C(SO_2CF_3)_3^-$

$N(SO_2OCH(CF_3)_2)_2^-$, $C(SO_2OCH_2CF_3)_3^-$



$X\text{-}YX_3^-$ "ate" complex anion

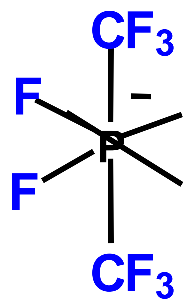
small anions:

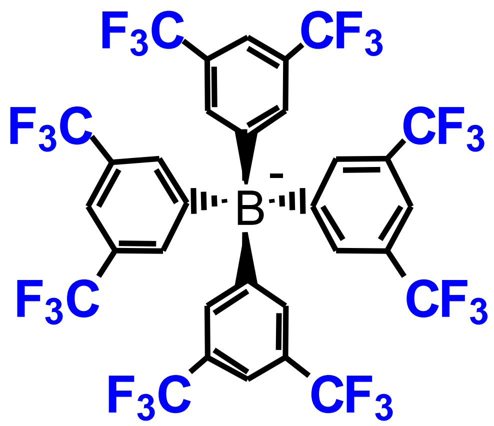
ClO_4^- , PF_6^-, BF_4^-, SbF_6^-

large anions:

$B(C_6H_3(CF_3)_2)_4^-$ (TFPB)

$B(C_6F_5)_4^-$ (TPFPB)





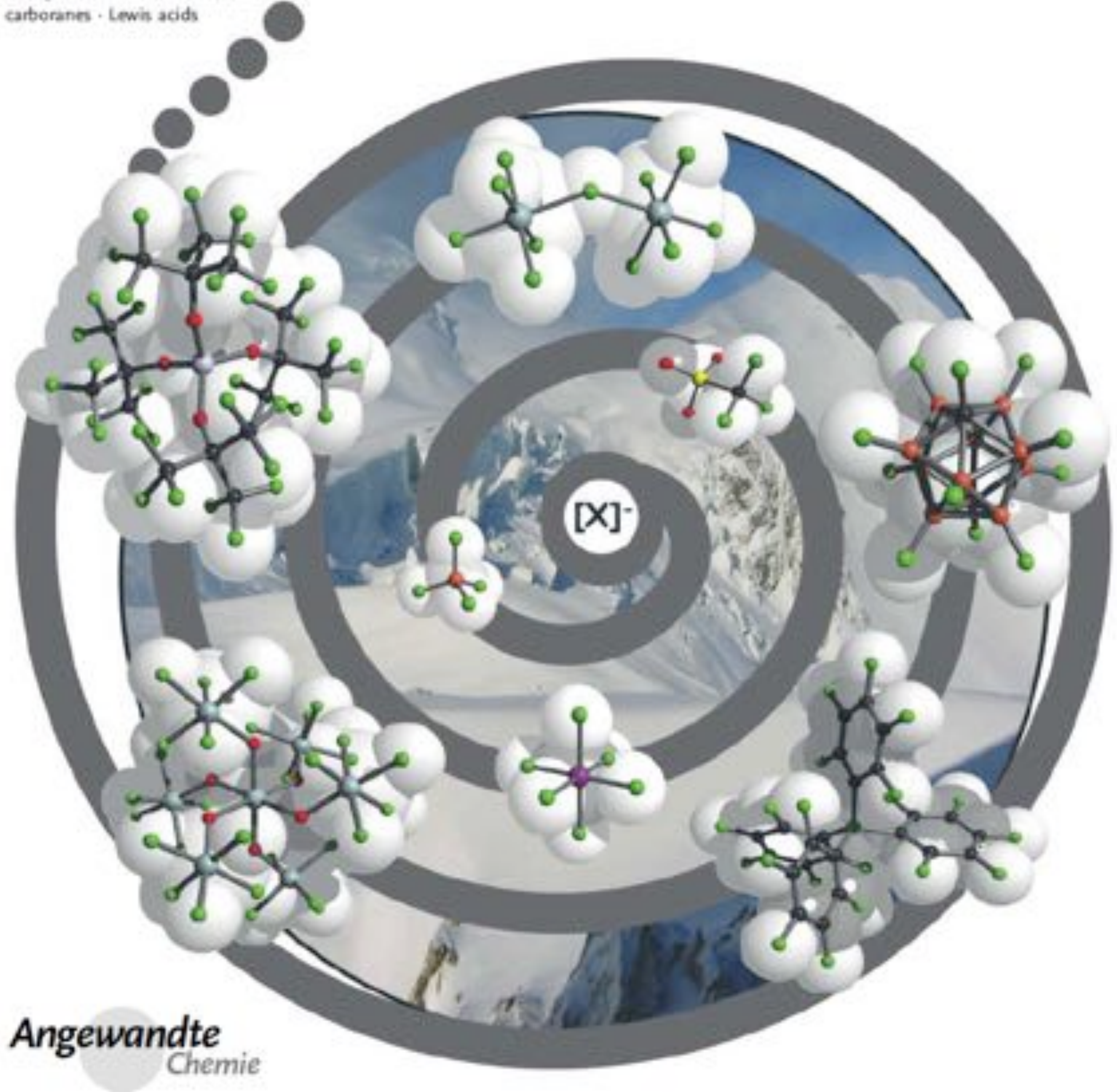
TFPB

Weakly Coordinating Anions

Noncoordinating Anions—Fact or Fiction? A Survey of Likely Candidates

I. Krossing and I. Raabe, Angew. Chem. Int. Ed. 43, 2066-2090(2004)

Keywords:
alkoxymetallates · aluminates · anions · carboranes · Lewis acids



Angewandte
Chemie

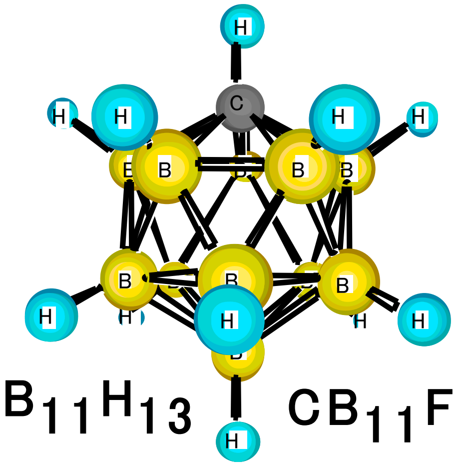
Order of Anion Stability:
Gas Phase Acidities of Conjugate Acids(kcal/mol) : ΔG^0_{ac}(HA)

CH_3COO^- > Cl^- > Br^- > NO_3^- > $CF_3CO_2^-$ > $CF_3SO_3^-$ > ClO_4^- >

341.1 328.1 318.3 317.8 316.3 299.5 *294.6*

$(CF_3SO_2)_2N^-$ > BF_4^- > PF_6^- > $AlCl_4^-$ > SbF_6^-

291.8 *287.7* *276.6* *257.4* *255.5*

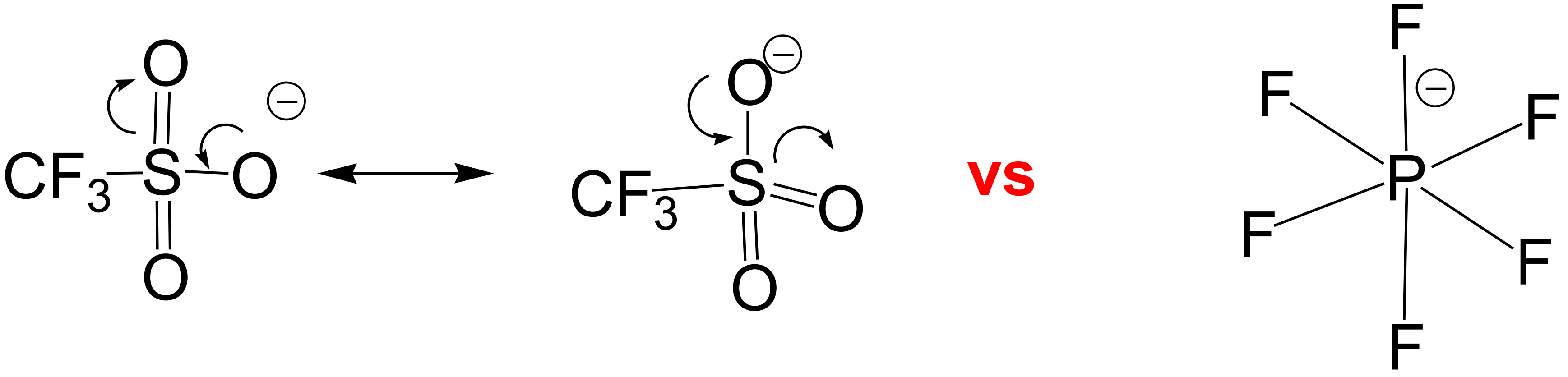


$CB_{11}H_{13}$ $CB_{11}F_{12}H$

265.5 *215.0*

→ more stable **WCAs**

WCAs: Weakly Coordinating Anions



The Structure of the Strongest Brønsted Acid: The Carborane Acid $H(CHB_{11}Cl_{11})$

Evgenii S. Stoyanov, Stephan P. Hoffmann, Mark Juhasz, and Christopher A. Reed*

J. AM. CHEM. SOC. 2006, *128*, 3160−3161

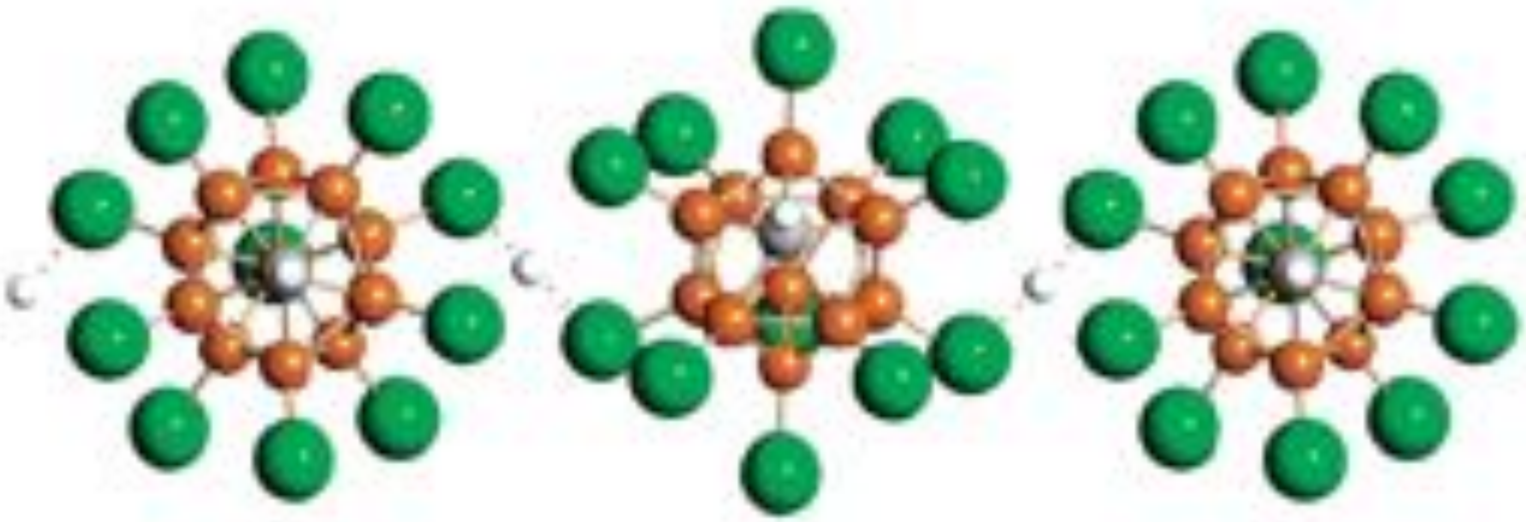


Figure 5. Perspective view of the proton-bridged X-ray crystal structure of $H(CHB_{11}Cl_{11})$ looking down the C−H bonds of the carborane anions (green = Cl, orange = B, gray = C, white = H).

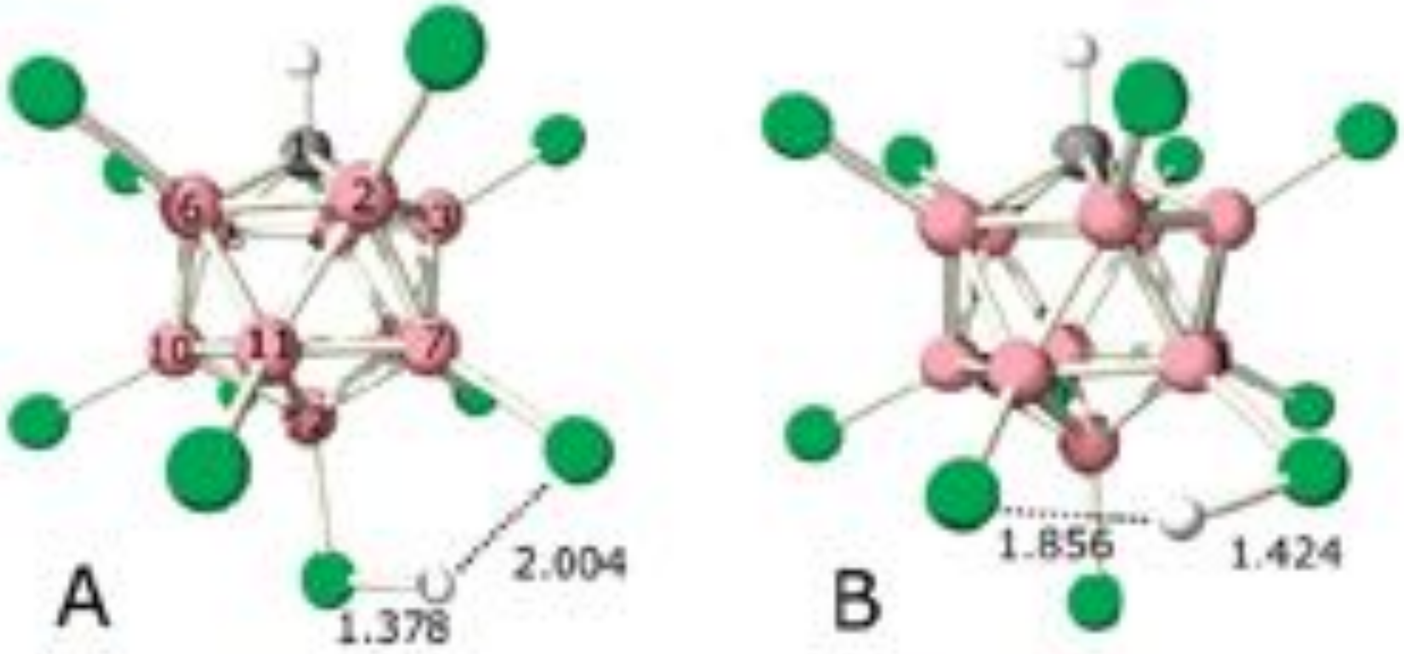
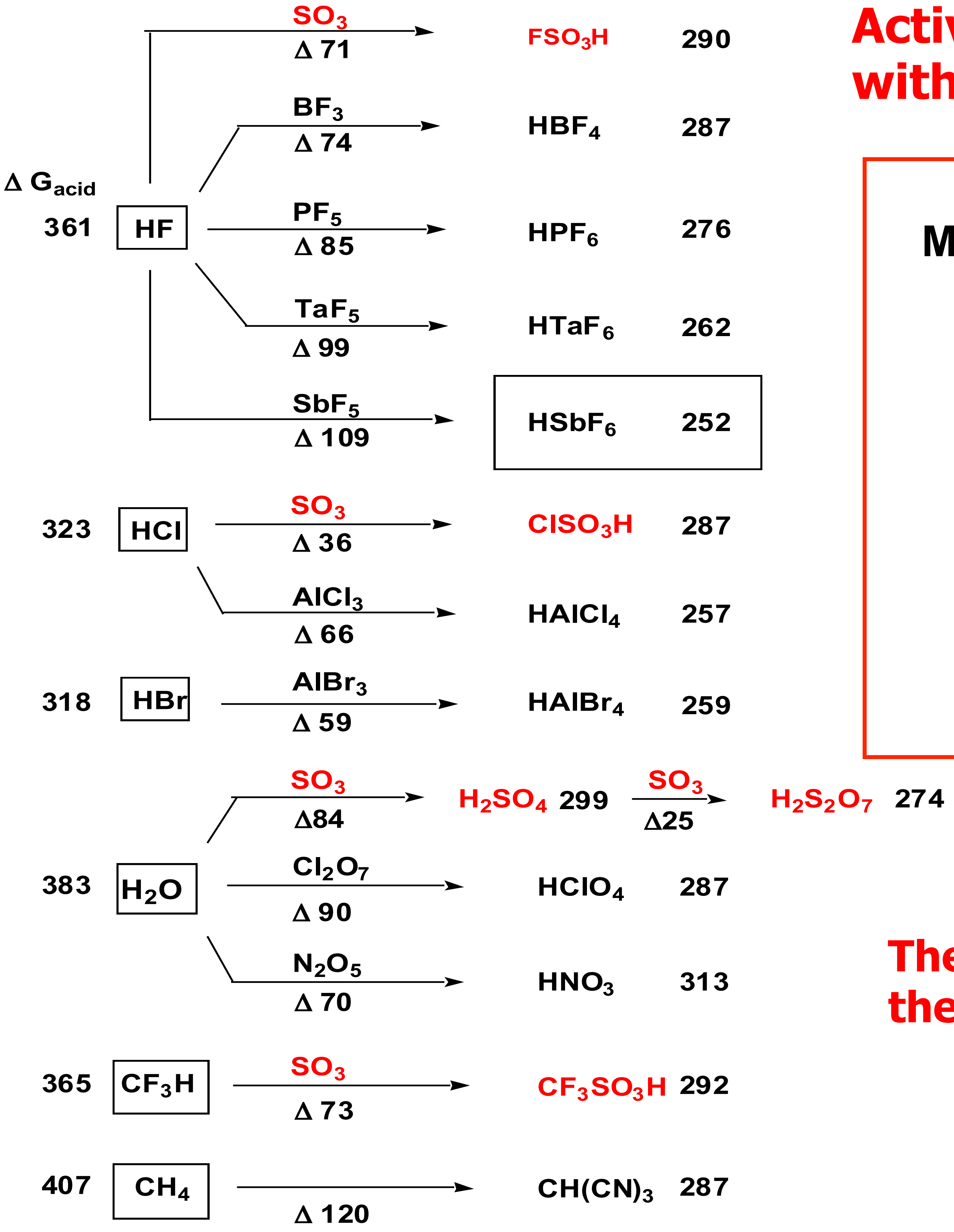


Figure 2. Carborane atom numbering scheme and DFT calculated structures of the 7,12 isomer (A) and the 7,8 isomer (B) of $H(CB_{11}Cl_{11})$ at the B3LYP/6-311+G(d,p) level. H−Cl distances in Å.

Activation of Proton Acids complexed with Lewis Acids



ΔG_{acid}

$$361\ \boxed{HF} \xrightarrow[\Delta 71]{SO_3} FSO_3H\ \ 290$$

$$\boxed{HF} \xrightarrow[\Delta 74]{BF_3} HBF_4\ \ 287$$

$$\boxed{HF} \xrightarrow[\Delta 85]{PF_5} HPF_6\ \ 276$$

$$\boxed{HF} \xrightarrow[\Delta 99]{TaF_5} HTaF_6\ \ 262$$

$$\boxed{HF} \xrightarrow[\Delta 109]{SbF_5} \boxed{HSbF_6\ \ 252}$$

$$323\ \boxed{HCl} \xrightarrow[\Delta 36]{SO_3} ClSO_3H\ \ 287$$

$$\boxed{HCl} \xrightarrow[\Delta 66]{AlCl_3} HAlCl_4\ \ 257$$

$$318\ \boxed{HBr} \xrightarrow[\Delta 59]{AlBr_3} HAlBr_4\ \ 259$$

$$383\ \boxed{H_2O} \xrightarrow[\Delta 84]{SO_3} H_2SO_4\ \ 299 \xrightarrow[\Delta 25]{SO_3} H_2S_2O_7\ \ 274$$

$$\boxed{H_2O} \xrightarrow[\Delta 90]{Cl_2O_7} HClO_4\ \ 287$$

$$\boxed{H_2O} \xrightarrow[\Delta 70]{N_2O_5} HNO_3\ \ 313$$

$$365\ \boxed{CF_3H} \xrightarrow[\Delta 73]{SO_3} CF_3SO_3H\ \ 292$$

$$407\ \boxed{CH_4} \xrightarrow[\Delta 120]{} CH(CN)_3\ \ 287$$

DFT B3LYP/6-311+G*

$$M - X(M^+X^-) \rightleftharpoons M^+ + X^-$$

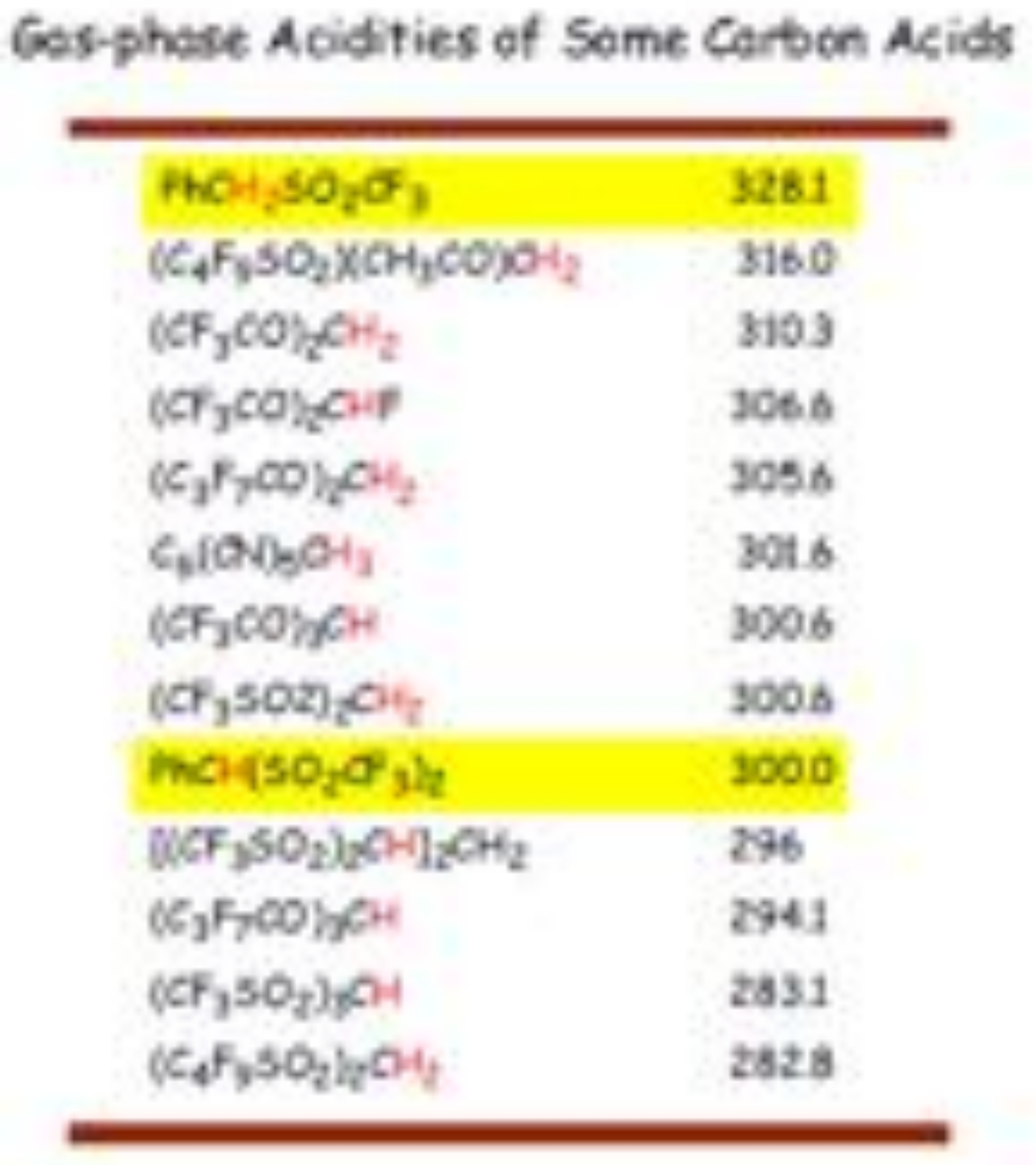
$$\xrightleftharpoons{YX_3} M^+ + X\text{-}YX_3^-$$

ate complex anion

(Lewis acid-base complex)

There is no experimental reports on the gas-phase acidities of HPF_6 and HBF_4.

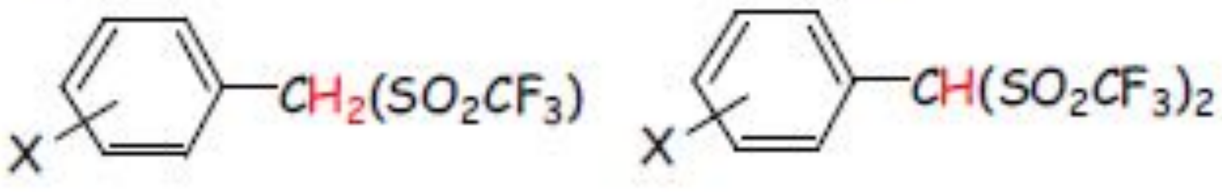
JACS, 122, 51114(2000)



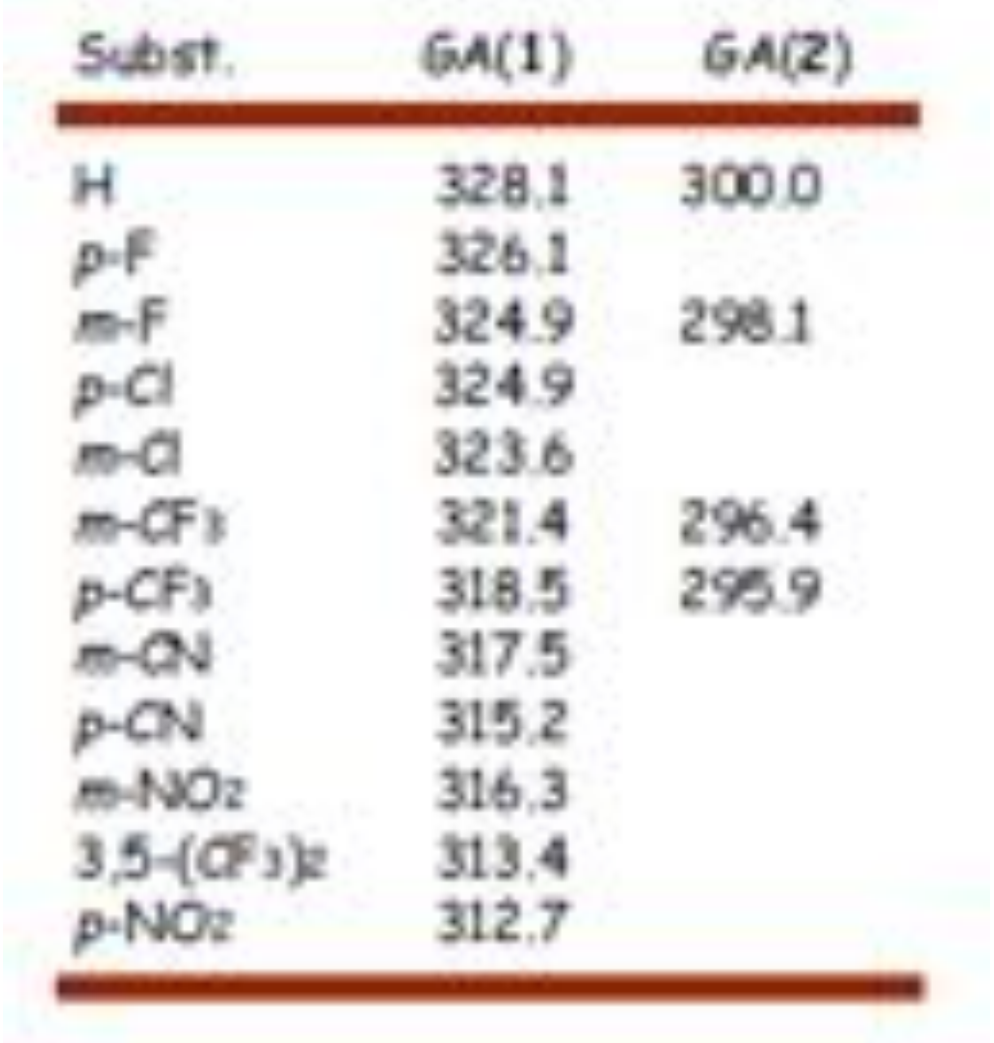
Gas-phase Acidities of Some Carbon Acids

$PhCH_2SO_2CF_3$	328.1
$(C_4F_9SO_2)(CH_3CO)CH_2$	316.0
$(CF_3CO)_2CH_2$	310.3
$(CF_3CO)_2CHF$	306.6
$(C_3F_7CO)_2CH_2$	305.6
$C_6(CN)_5CH_3$	301.6
$(CF_3CO)_3CH$	300.6
$(CF_3SO2)_2CH_2$	300.6
$PhCH(SO_2CF_3)_2$	300.0
$[(CF_3SO_2)_2CH]_2CH_2$	296
$(C_3F_7CO)_3CH$	294.1
$(CF_3SO_2)_3CH$	283.1
$(C_4F_9SO_2)_2CH_2$	282.8

Substituent Effects on Acidity



(1) (2)

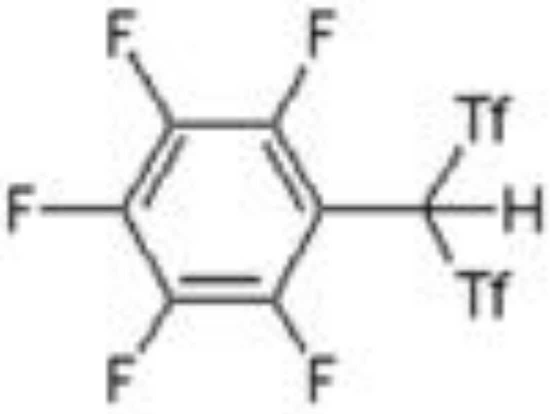


Subst.	GA(1)	GA(2)
H	328.1	300.0
p-F	326.1	
m-F	324.9	298.1
p-Cl	324.9	
m-Cl	323.6	
m-CF_3	321.4	296.4
p-CF_3	318.5	295.9
m-CN	317.5	
p-CN	315.2	
m-NO_2	316.3	
3,5-$(CF_3)_2$	313.4	
p-NO_2	312.7	

Cf. H_2SO_4 (302.2) , CF_3SO_2OH (299.5) , $(CF_3SO_2)_2NH$ (291.8)

Zhang, Mishima, Leito(2009), unpublished data

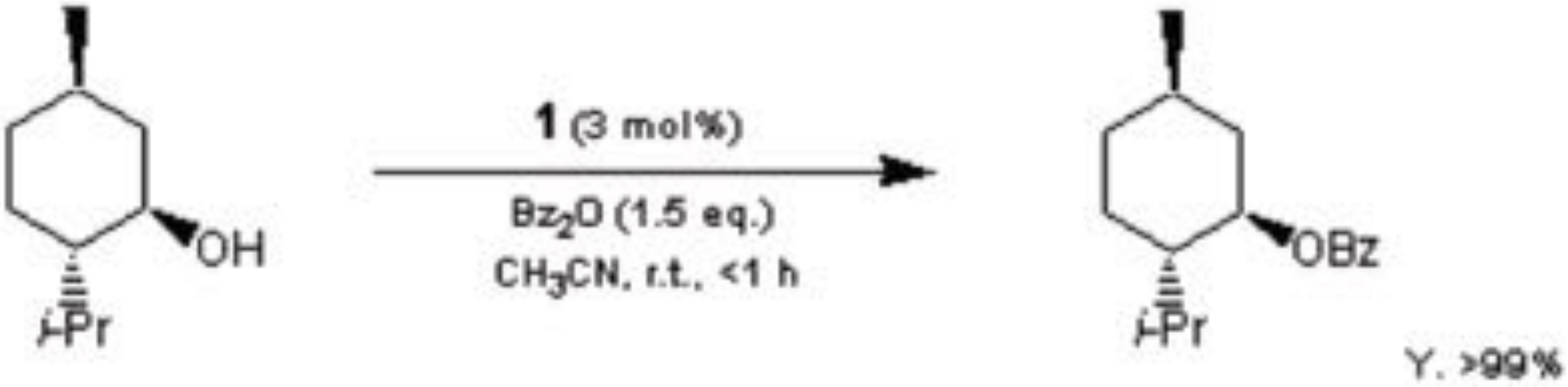
スーパーブレンステッド酸 / Super Brønsted Acid



1

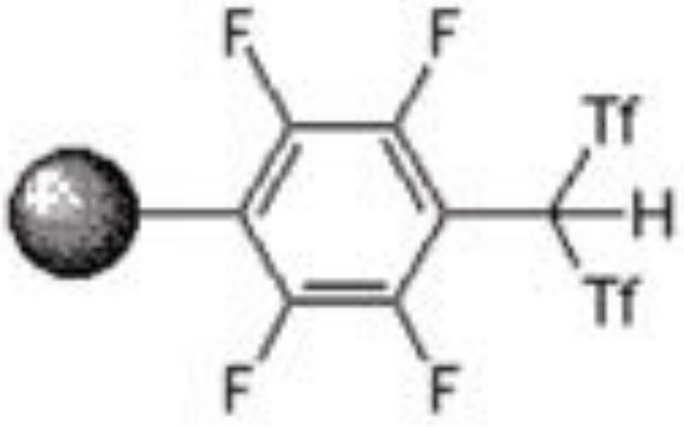
p*K*a=1.5 (in CD_3CO_2D)

1-[Bis(trifluoromethanesulfonyl)methyl]-2,3,4,5,6-pentafluorobenzene (1)



(-)-メントール

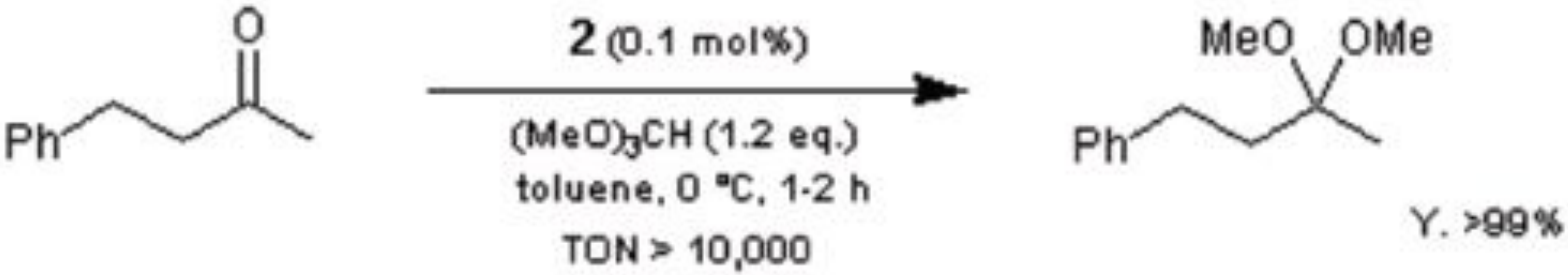
K. Ishihara, A. Hasegawa, H. Yamamoto, *Angew. Chem. Int. Ed.* **2001**, *40*, 4077.



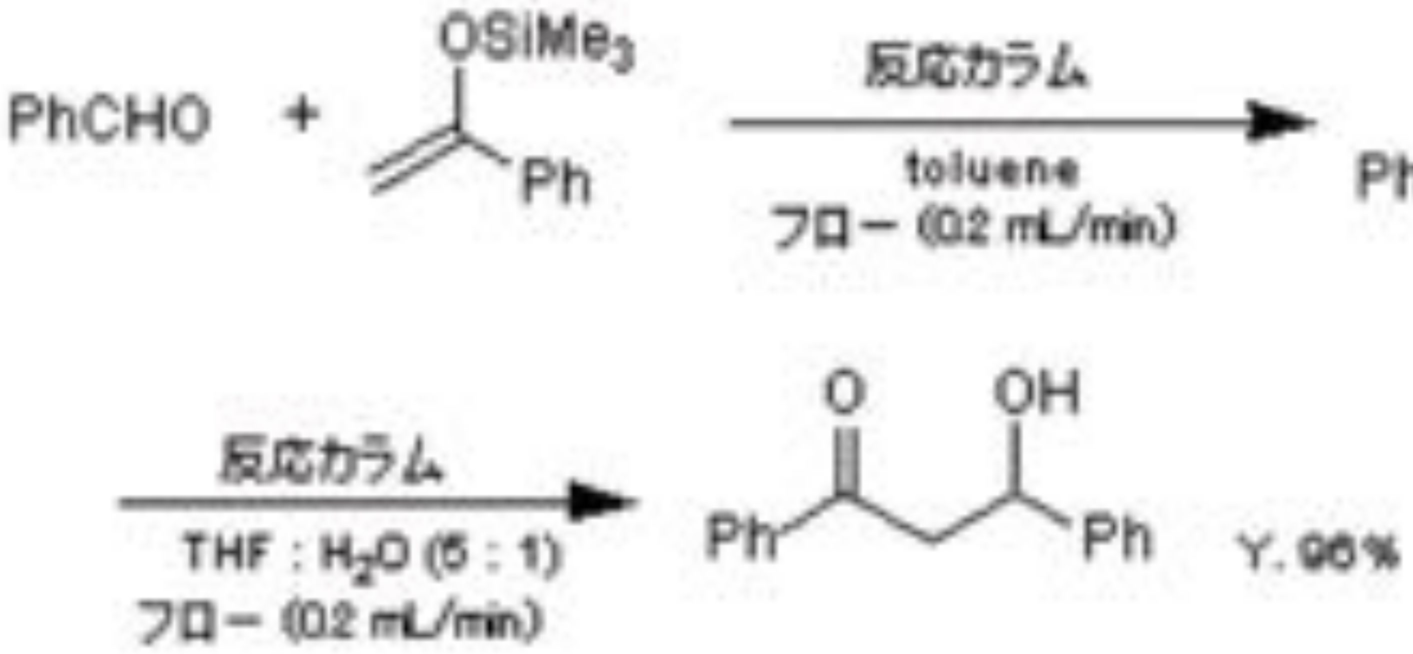
2

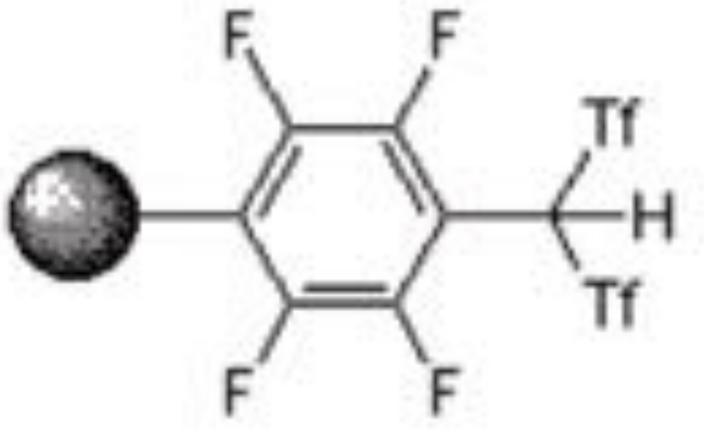
Bis(trifluoromethanesulfonyl)methyltetrafluorophenyl Polystyrene Resin (2)

ポリマー担持スーパーブレンステッド酸

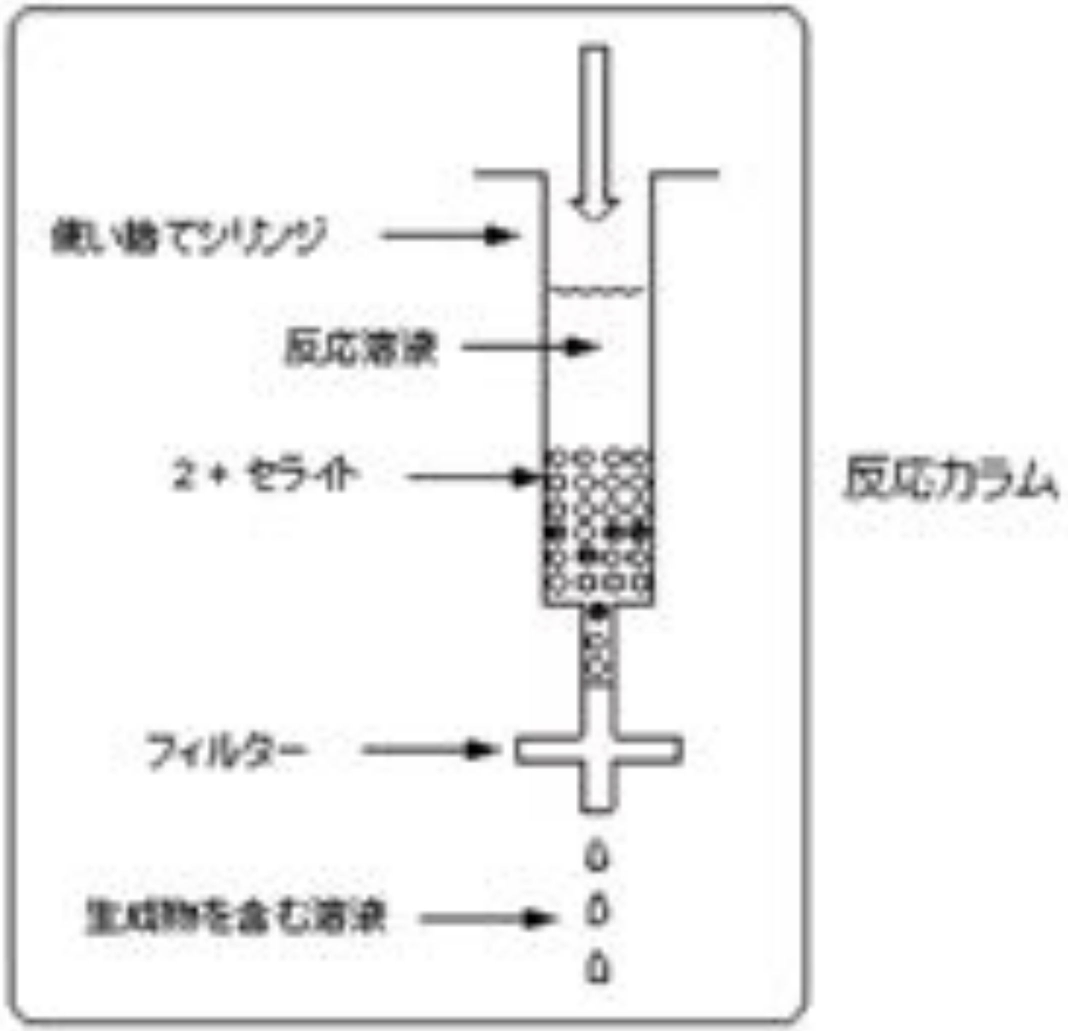


K. Ishihara, A. Hasegawa, H. Yamamoto, *Angew. Chem. Int. Ed.* **2001**, *40*, 4077.

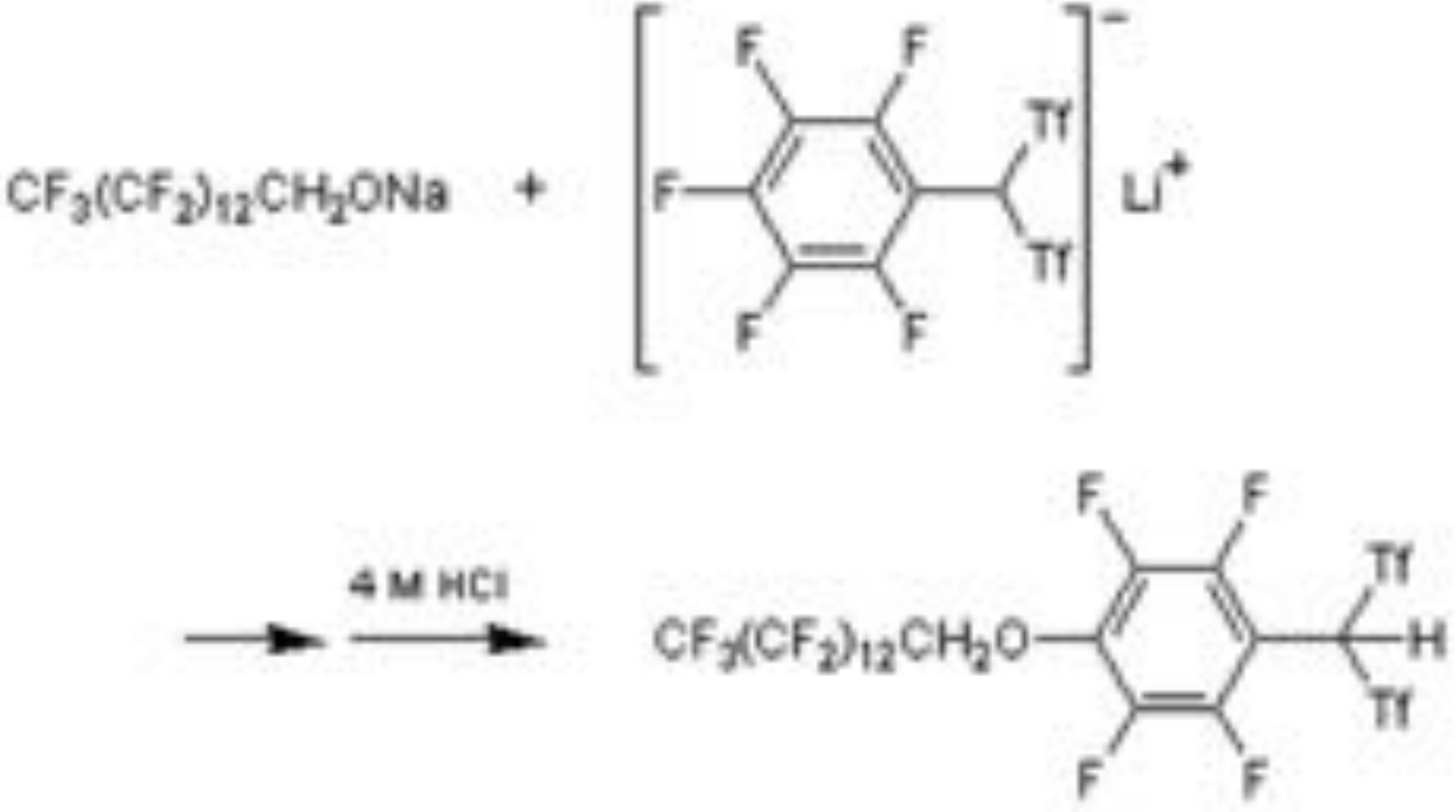




2



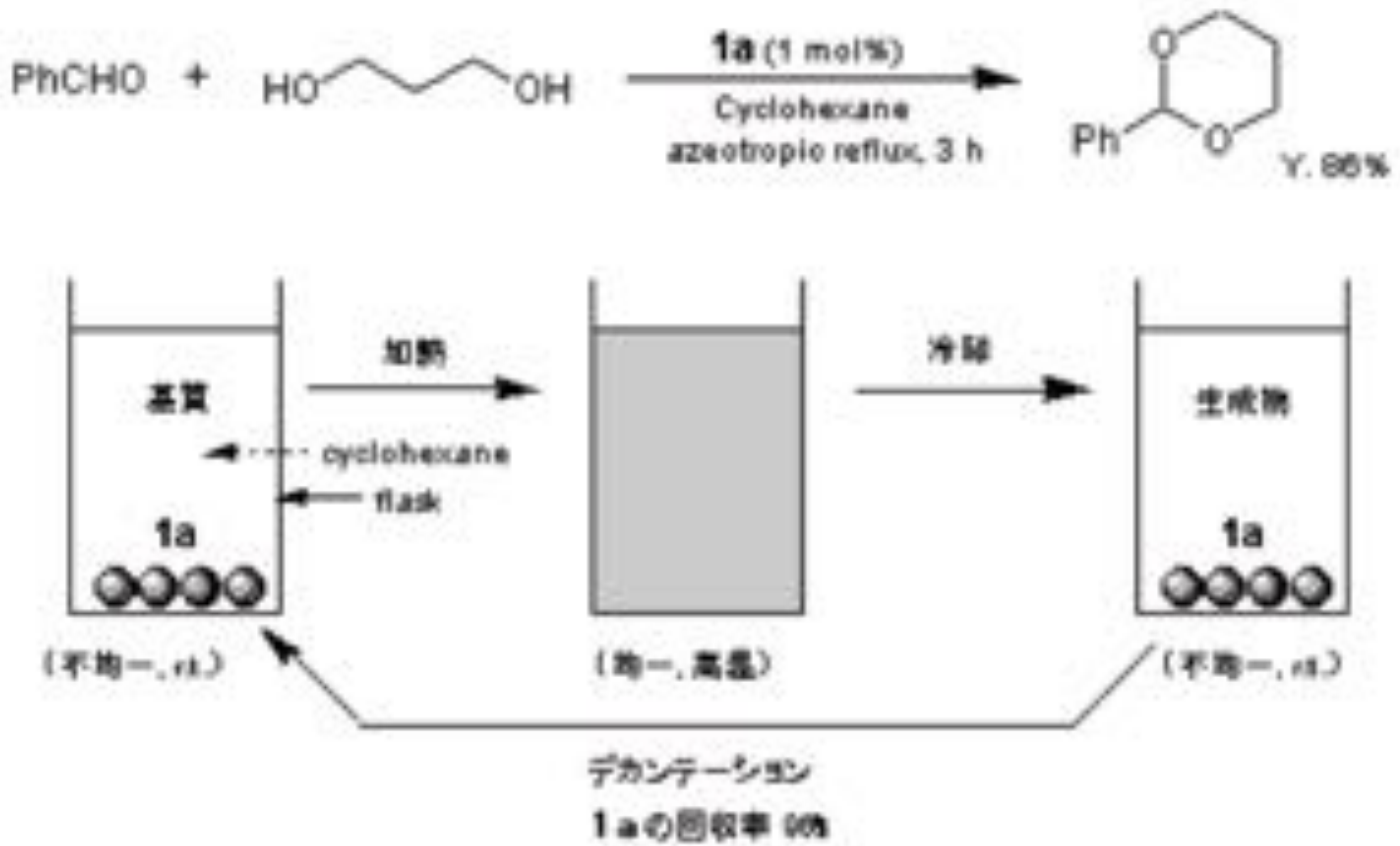
K. Ishihara, A. Hasegawa, H. Yamamoto, *Synlett* **2002**, 1296.



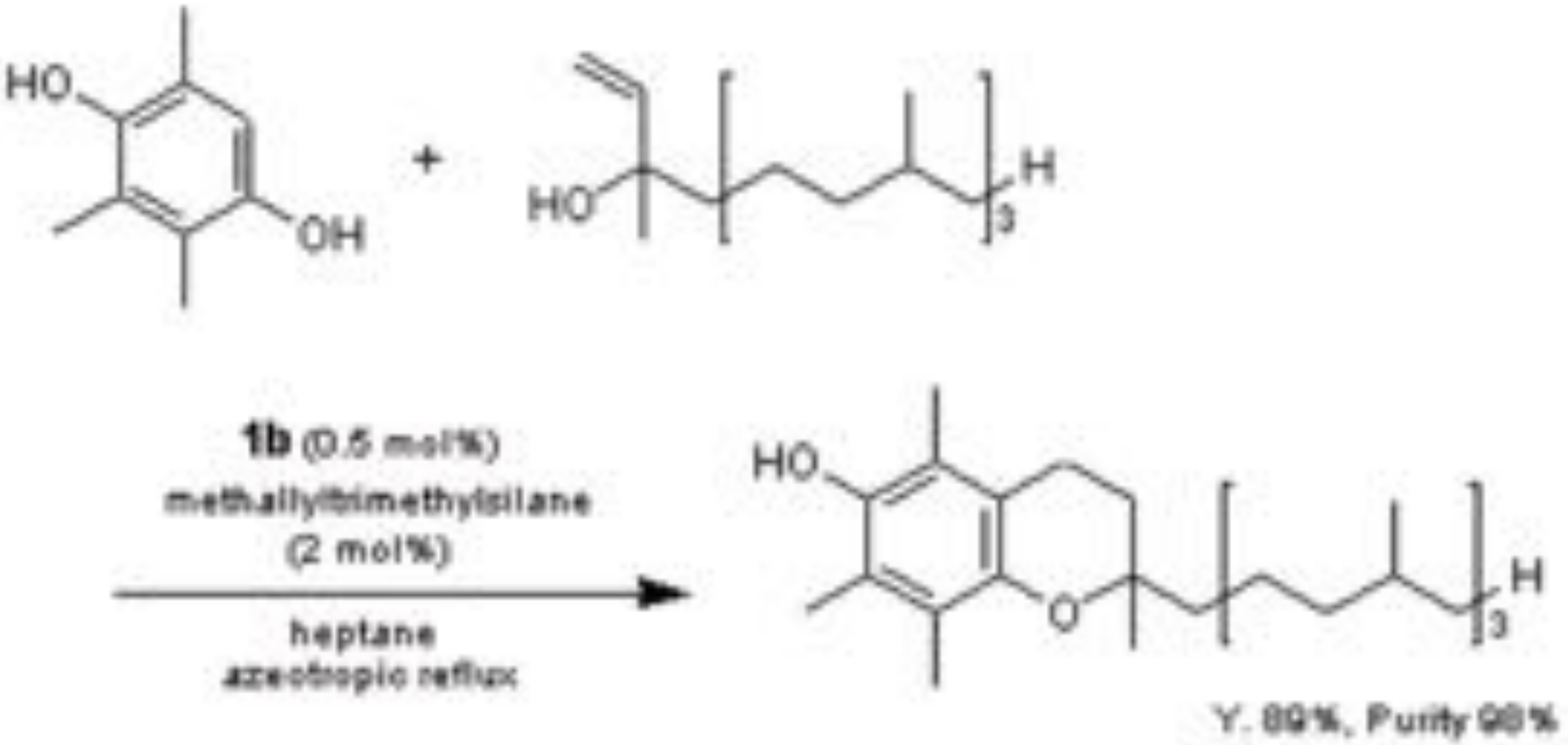
1a

フルオラスなスーパーブレンステッド酸触媒 **1a**

K. Ishihara, A. Hasegawa, H. Yamamoto, *Synlett* **2002**, 1299.



K. Ishihara, A. Hasegawa, H. Yamamoto, *Synlett* **2002**, 1299.



$[C_6F_5CTf_2]SiMe_3$ (**1b**)

$C_6F_5CHTf_2$ （**1**）

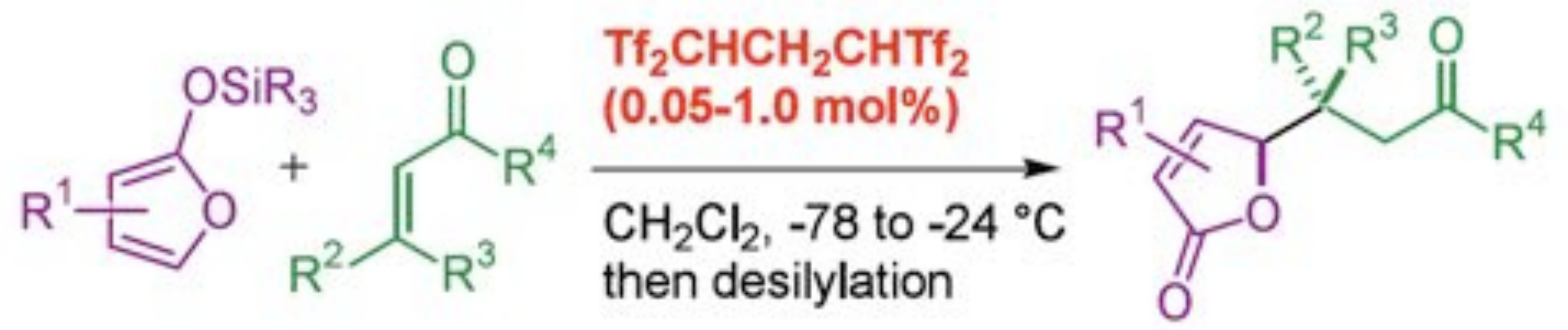
スーパールイス酸触媒

スーパーブレンステッド酸

1b > Tf_2NSiMe_3 > $TfOSiMe_3$ vs $TfOH$ > Tf_2NH > **1**

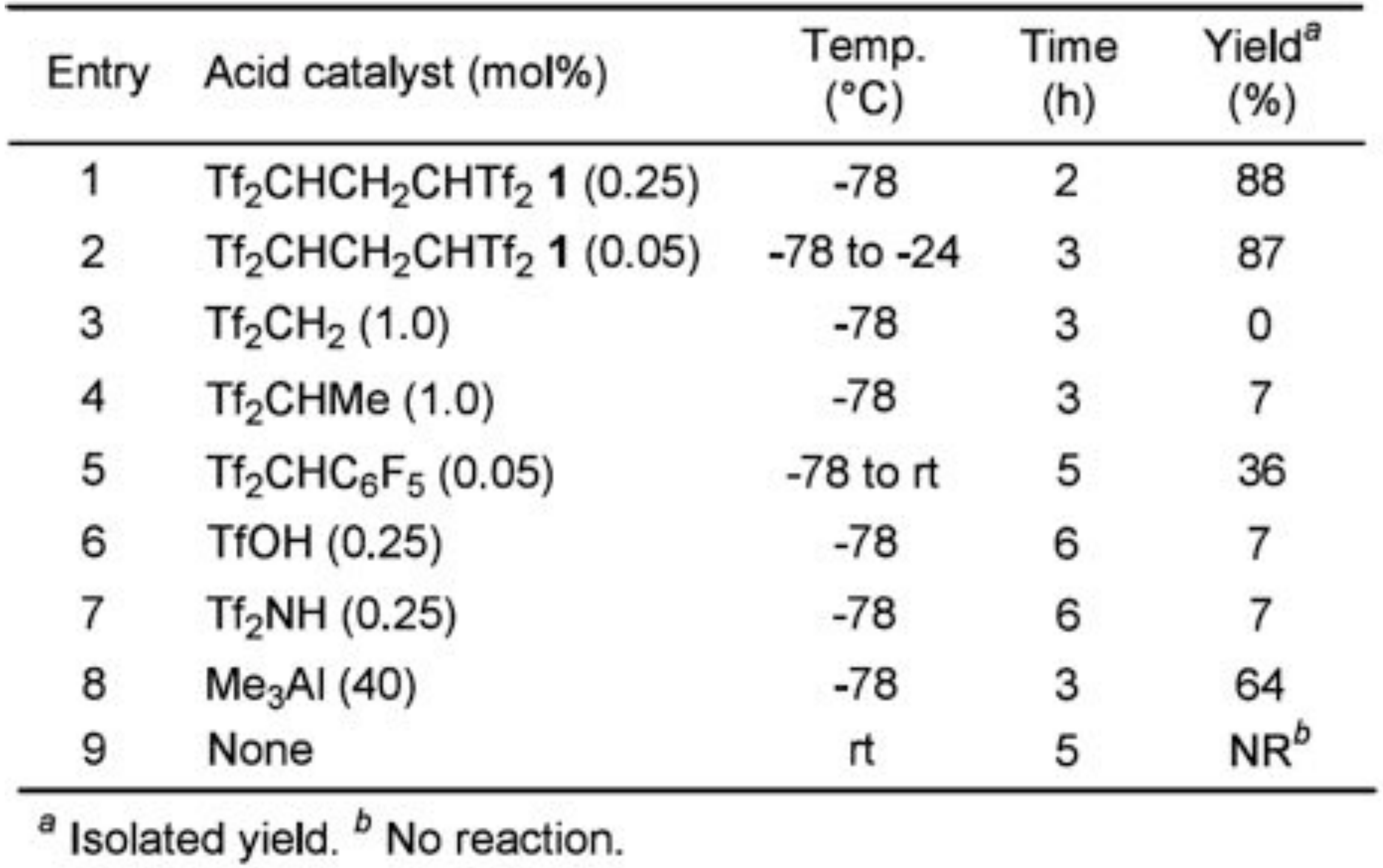
A. Hasegawa, K. Ishihara, H. Yamamoto, *Angew. Chem. Int. Ed*. **2003**, *42*, 5731.

Highly Effective Vinylogous Mukaiyama-Michael Reaction Catalyzed by Tetrakis(trifluoromethanesulfonyl)propane



Tf = SO_2CF_3

Significant low catalyst loading: up to 0.05 mol%
Stereoselective C-C bond formation between sterically hindered substrates

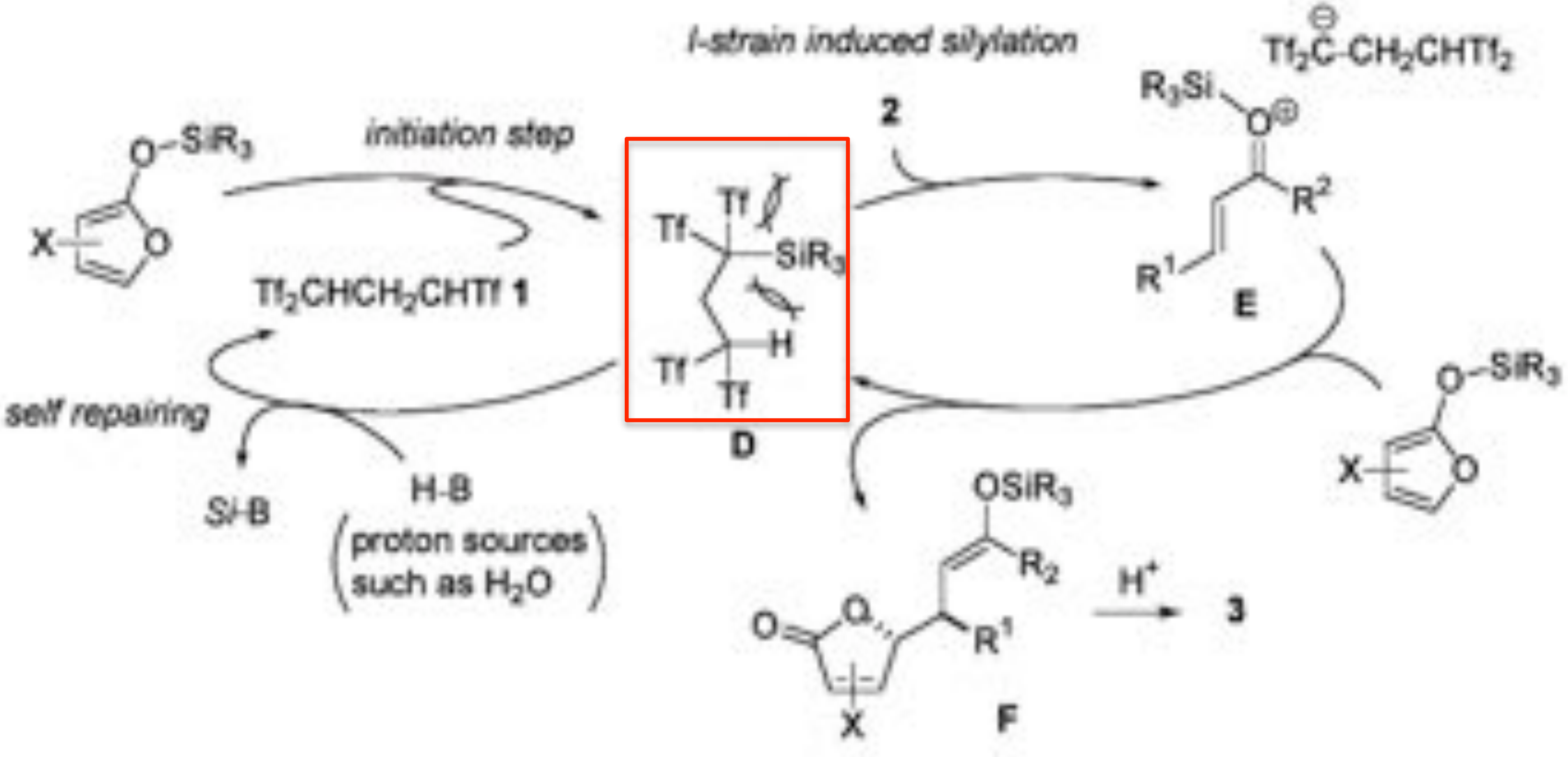


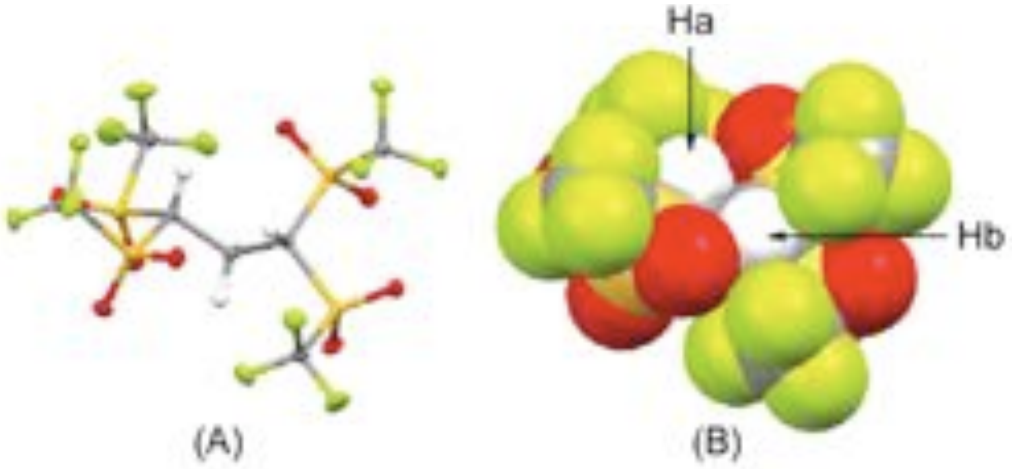
Entry	Acid catalyst (mol%)	Temp. (°C)	Time (h)	Yield[a] (%)
1	$Tf_2CHCH_2CHTf_2$ **1** (0.25)	-78	2	88
2	$Tf_2CHCH_2CHTf_2$ **1** (0.05)	-78 to -24	3	87
3	Tf_2CH_2 (1.0)	-78	3	0
4	Tf_2CHMe (1.0)	-78	3	7
5	$Tf_2CHC_6F_5$ (0.05)	-78 to rt	5	36
6	TfOH (0.25)	-78	6	7
7	Tf_2NH (0.25)	-78	6	7
8	Me_3Al (40)	-78	3	64
9	None	rt	5	NR[b]

[a] Isolated yield. [b] No reaction.

A. Takahashi, H. Yanai, M. Zhang, T. Sonoda, M. Mishima, T. Taguchi, *JOC*, **2010**, 75, 1259–1265

Proposed Catalyst Cycle of the Carbon Acid Catalyzed VMM Reaction





X-ray structure of carbon acid **1**

Steric Effect in Silylated Carbon Acid and/or HSAB Rule in Catalyzed VMM Reaction

１９７９年９月ー１９８０年８月
ETH Zuerich(スイス連邦工科大学)
Prof. Heinrich Zollinger

IUPAC物理有機化学国際会議
(ICPOC)の創設者
スイス日本友好協会会長

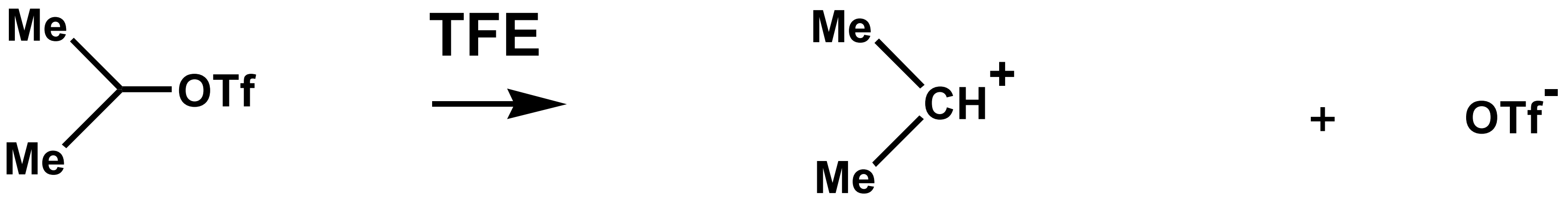
１９８０年１１月ー１９８１年８月
チュービンゲン大学（西ドイツ）
Dr. L. R. Subramanian,
Prof. Michael Hanack,
Prof. Hans-Ullrich Siehl

Application of Triflate Anions as Super-leaving Group for generating Aryl Cations and Benzyne

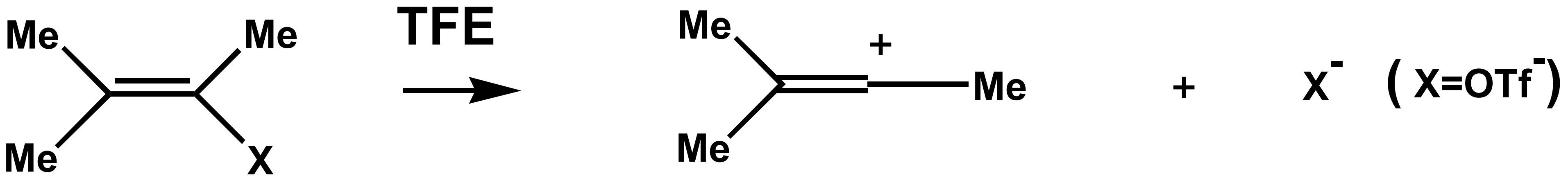
$$\boxed{\mathrm{R\text{-}X} \xrightarrow{S_N1} \mathrm{R}^+ + \mathrm{X}^-}$$

X^-	Cl^-	Br^-	OTs^-	OTf^-
k_{rel} :	1	2.5×10^2	2×10^5	2×10^{10}

OTf : OSO_2CF_3

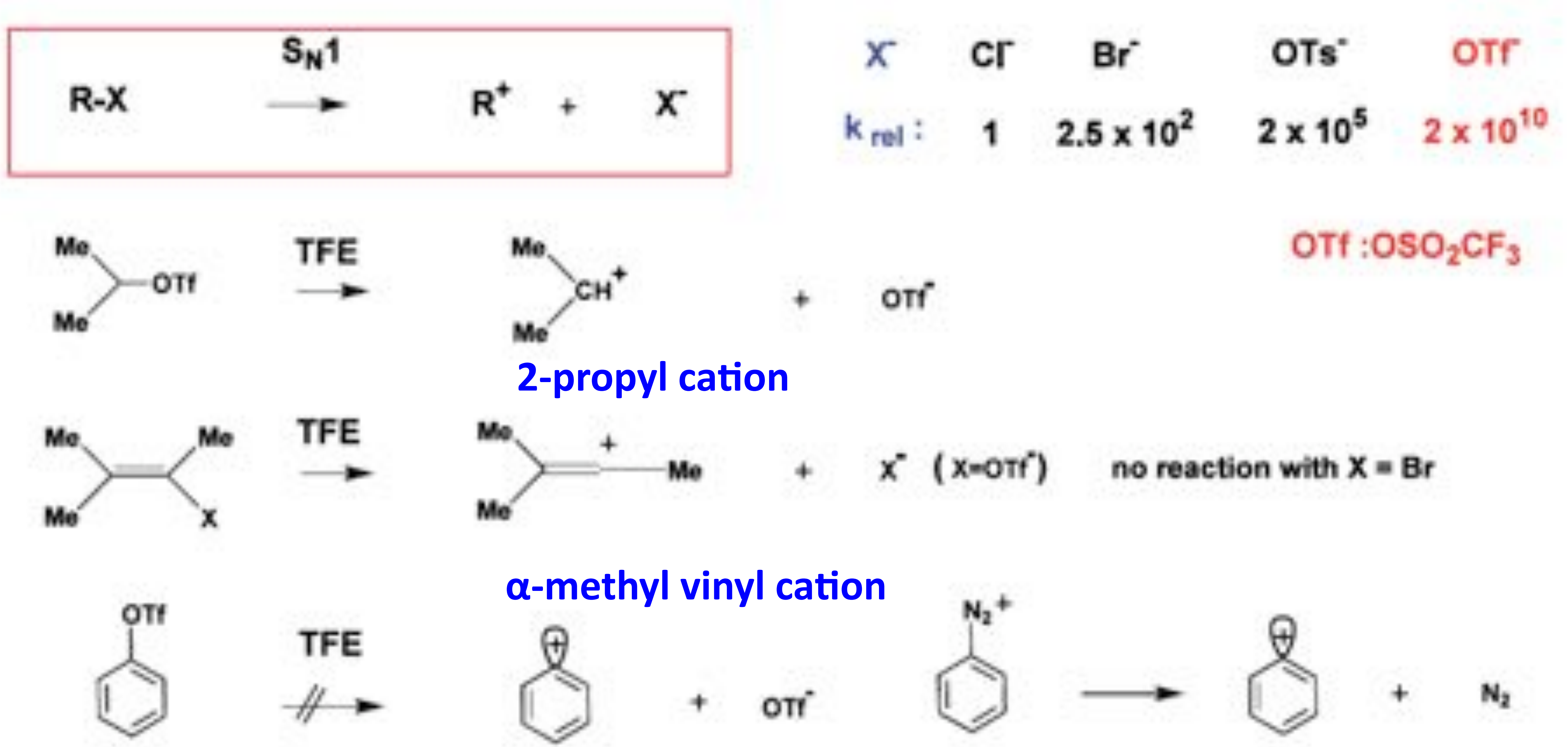


TFE = CF_3CH_2OH



no reaction with X = Br

Relative leaving ability of X^- anion in S_N1 solvolysis reactions



X^-	Cl^-	Br^-	OTs^-	OTf^-
k_{rel} :	1	2.5×10^2	2×10^5	2×10^{10}

OTf : OSO_2CF_3

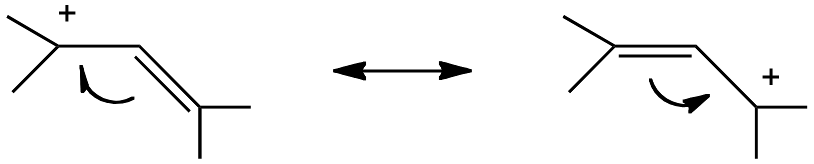
2-propyl cation

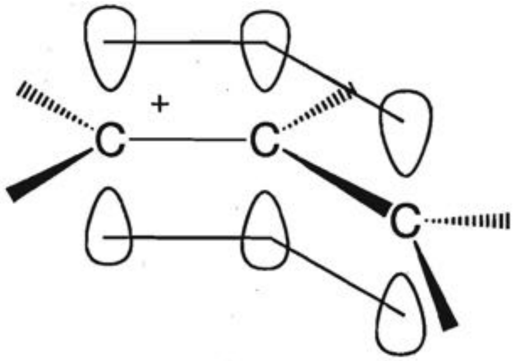
α-methyl vinyl cation

phenyl cation

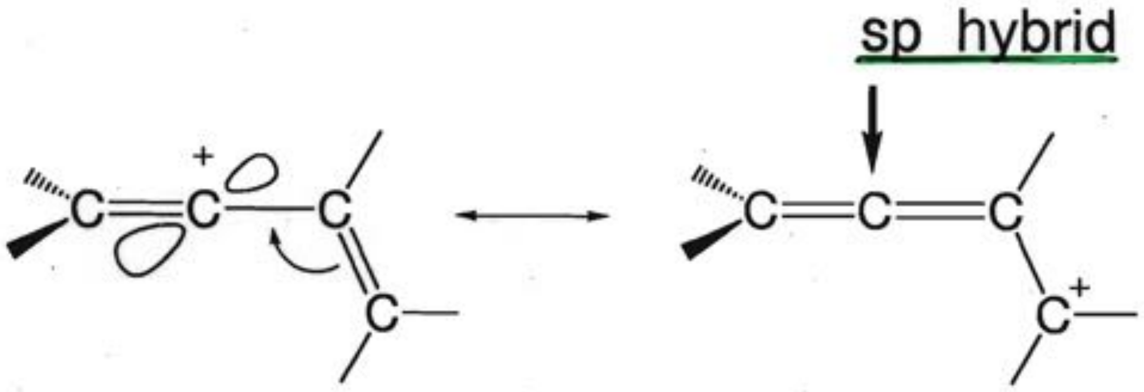
Relative leaving ability: k_{N2} / k_{OTf} = ??

Why is phenyl cation so unstable?



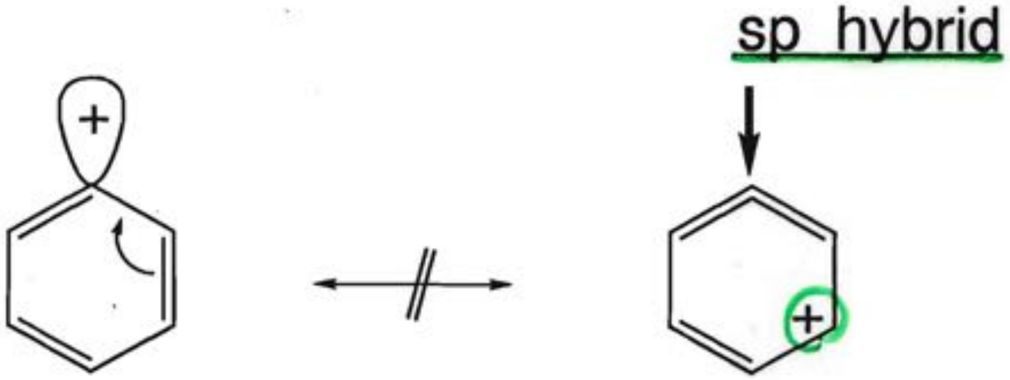


p-π conjugative stabilization in allyl cation



vinyl cation

p-π conjugative stabilization in vinyl cation with α-vinyl group

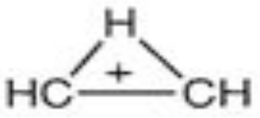
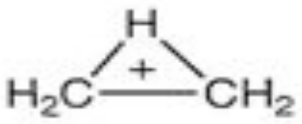


planar structure

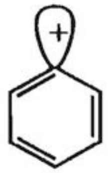
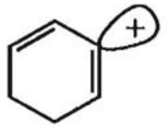
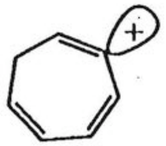
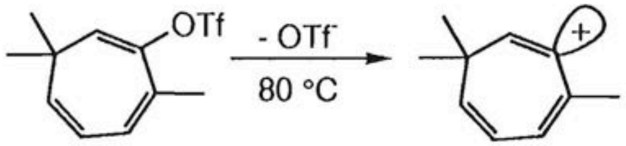
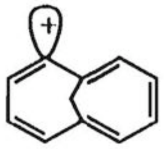
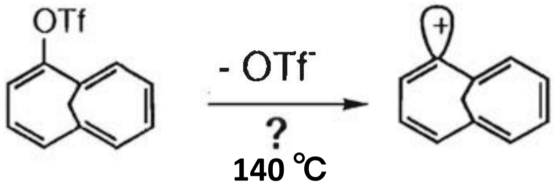
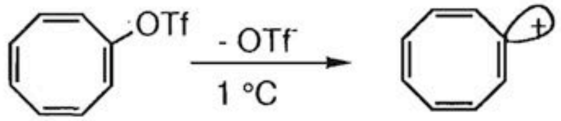
No p-π conjugative stabilization in phenyl cation

Relative stabilizing energies of carbocations

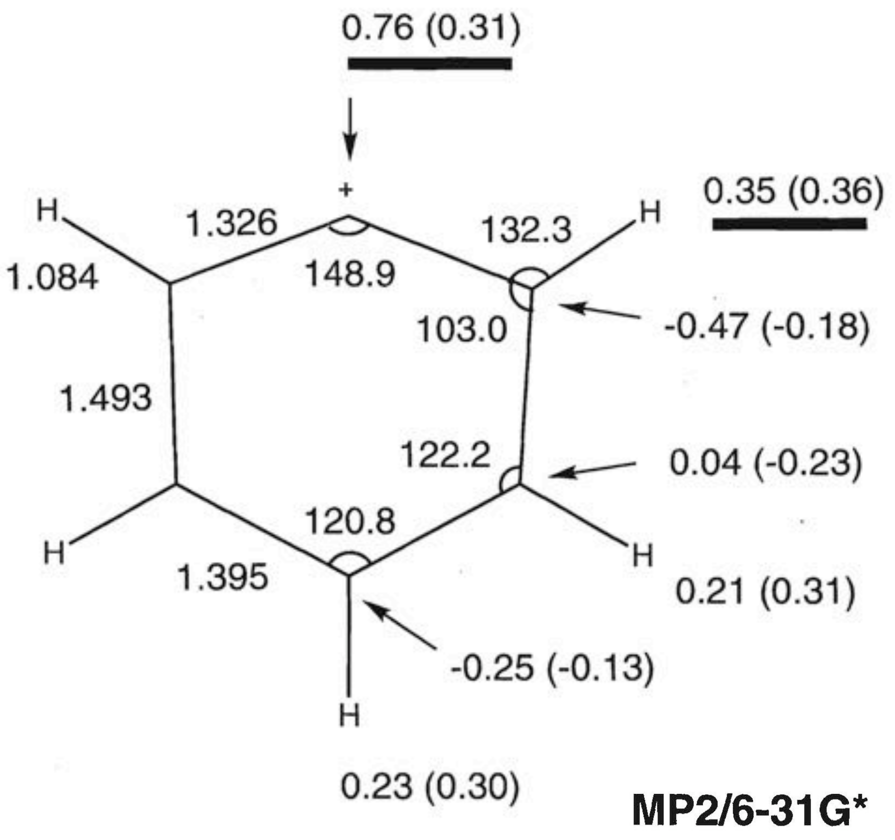
$$R^+ + C_6H_6 \xrightarrow{\Delta\Delta E} C_6H_5^+ + RH$$

R^+		Relative Stabilization Energy ($\Delta\Delta E$) MP2 / 6-31G* (kcal/mol)	Experimental (Gas Phase)
CH_3^+		-26.7	-29.5
$H_2C=C^+-H$	**vinyl cation**	-8.2	
		-3.5	-3.6
$C_6H_5^+$	**phenyl cation**	0	0
$CH_3-CH_2^+$		+7.7	
		+14.1	+13.9
$CH_2=C^+-CH_3$	**2-propeny cation**	+19.8	+19.4
$CH_3-C^+H-CH_3$	**2-propyl cation**	+32.2	+32.5

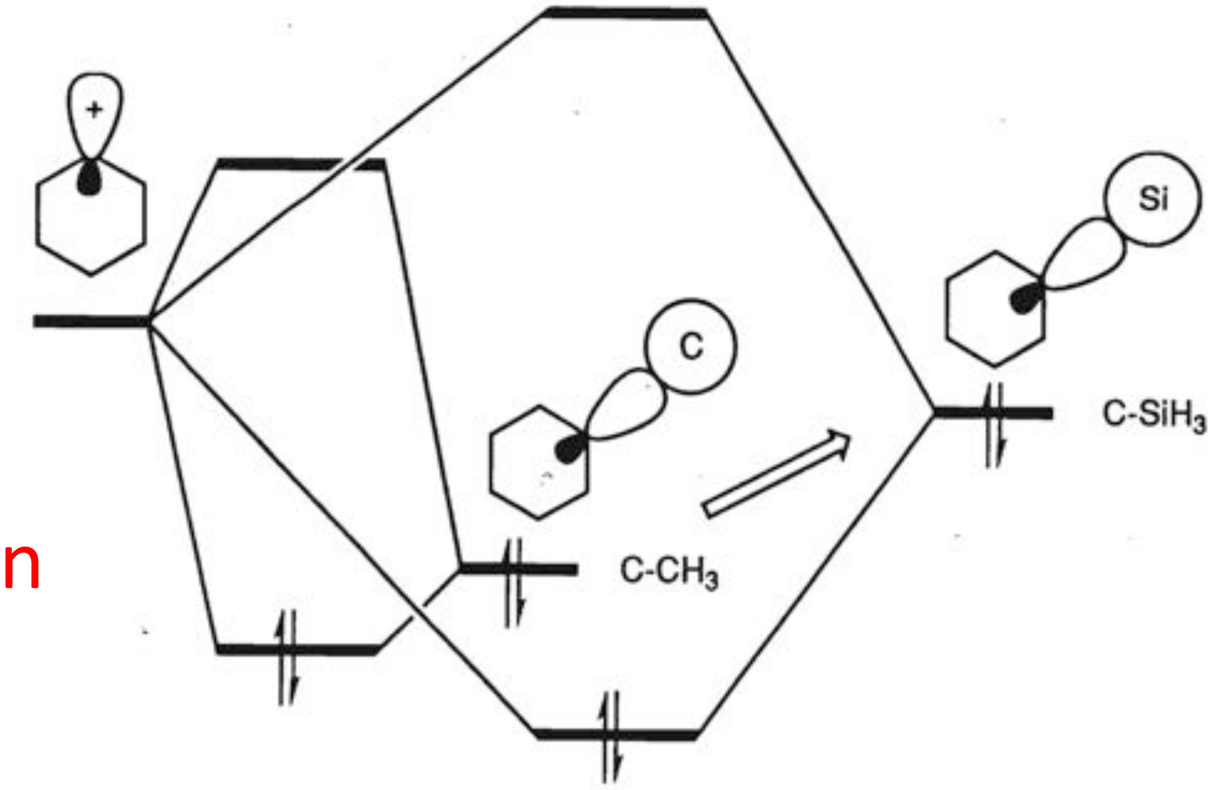
(+30)

R^+	ΔΔE (kcal/mok)(HF/6-31G)	solvoysis experiments	
	**phenyl cation** (-)		Streitwieser Schleyer Hanack Stang
	(-5.3)		
	(+19.7)		Hanack Subramanian
	(+30)		
	(+33.2)		Hanack Sonoda
	(+33.7)		Sonoda
	(+55.0)		Hanack

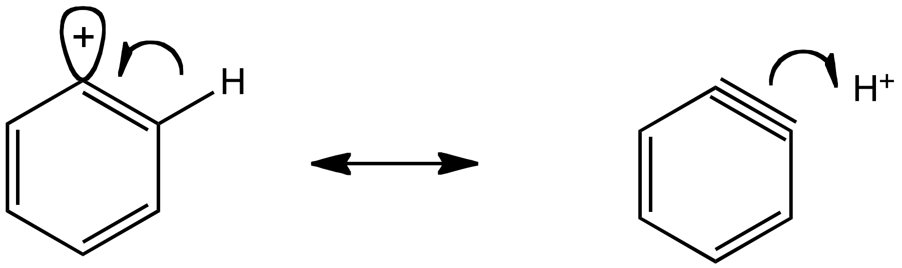
ESP positive charge in phenyl cation



Hyperconjugative stabilization in phenyl cation with ortho-silyl group



Hyperconjugation in phenyl cation

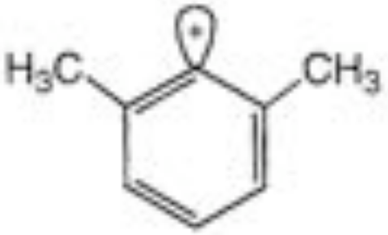


Phenyl cations highly stabilized with ortho-trimethly silyl groups

relative stabilizing energy: $\Delta\Delta E(Ar^+) = \Delta E(PhH) + \Delta E(Ar^+) - \Delta E(Ph^+) - \Delta E(ArH)$

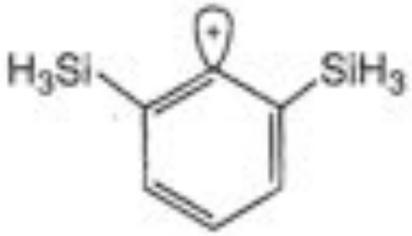
0

(0)



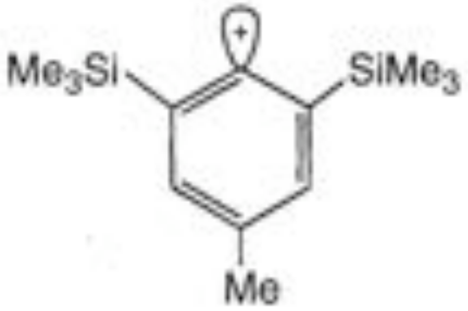
-13.0

(-12.1)



-22.0

(-24.1)

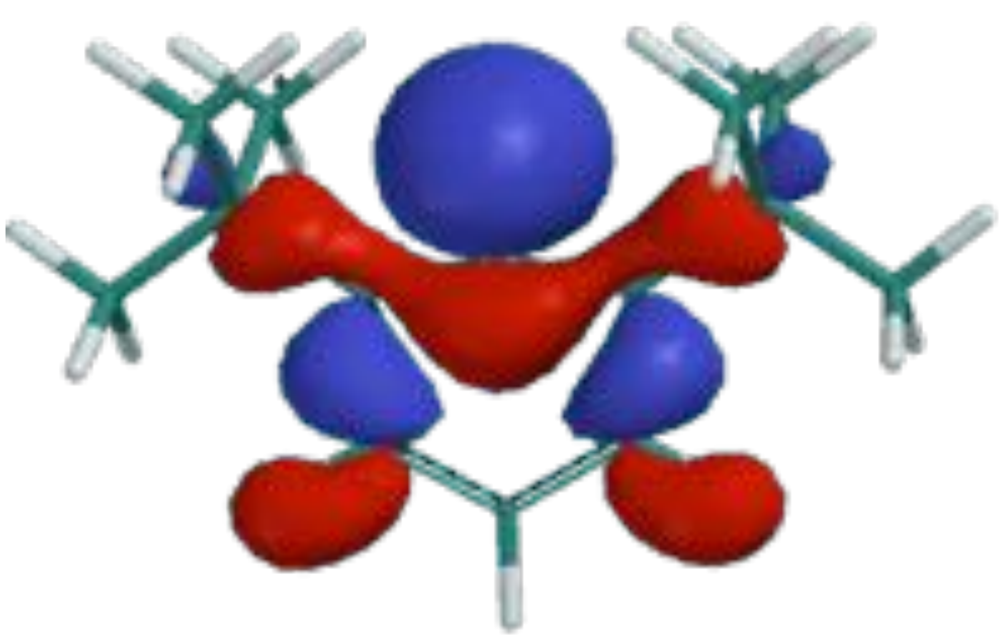


-39.1

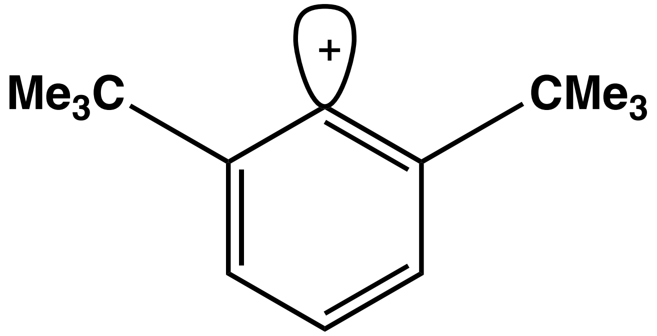
6-31G*

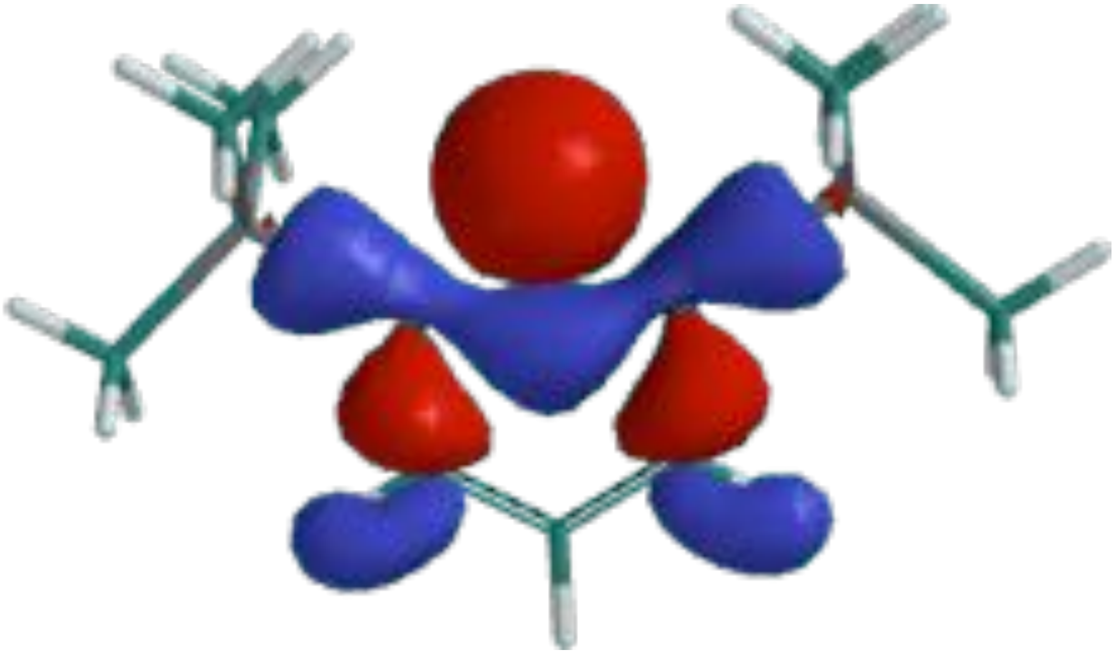
(MP2 / 6-31G*)

LUMO

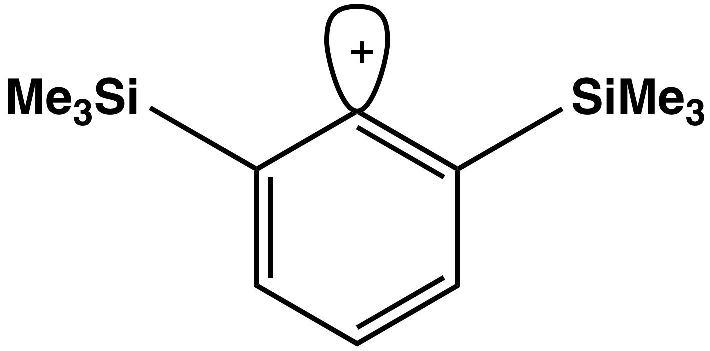


2,6-di-t-butylphenyl cation



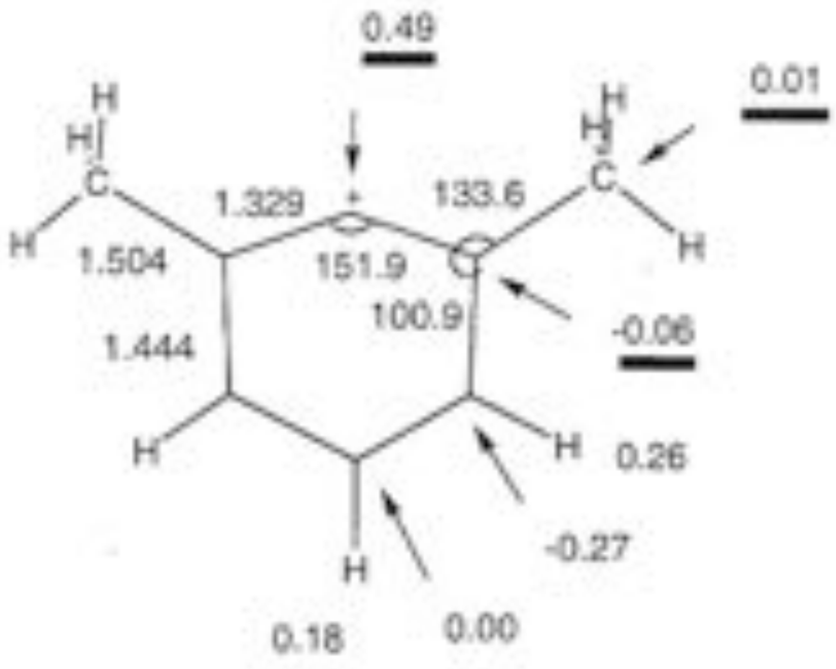


2,6-bis-trimethylsilylphenyl cation

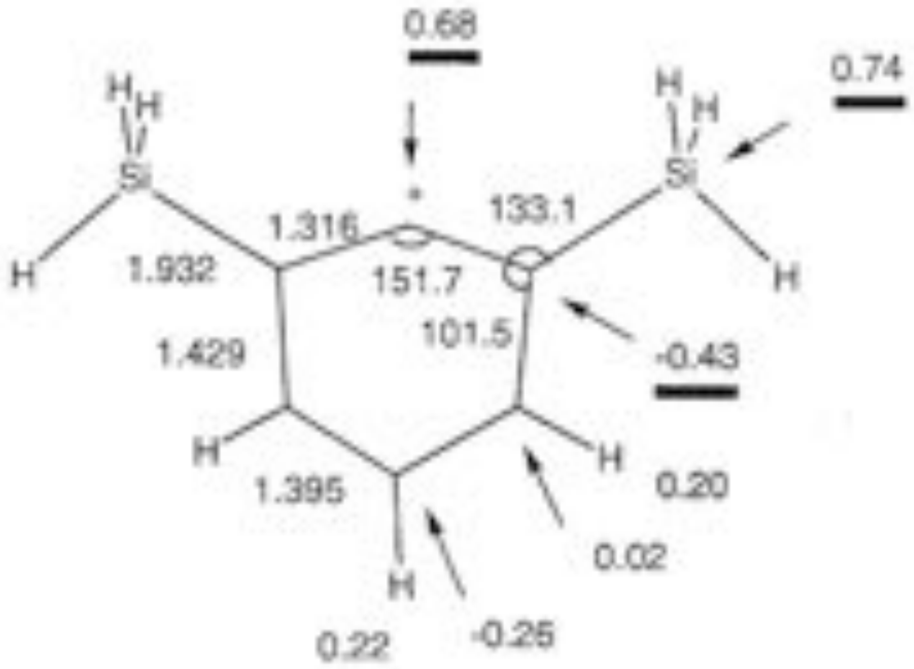


B3LYP/6-311+G**

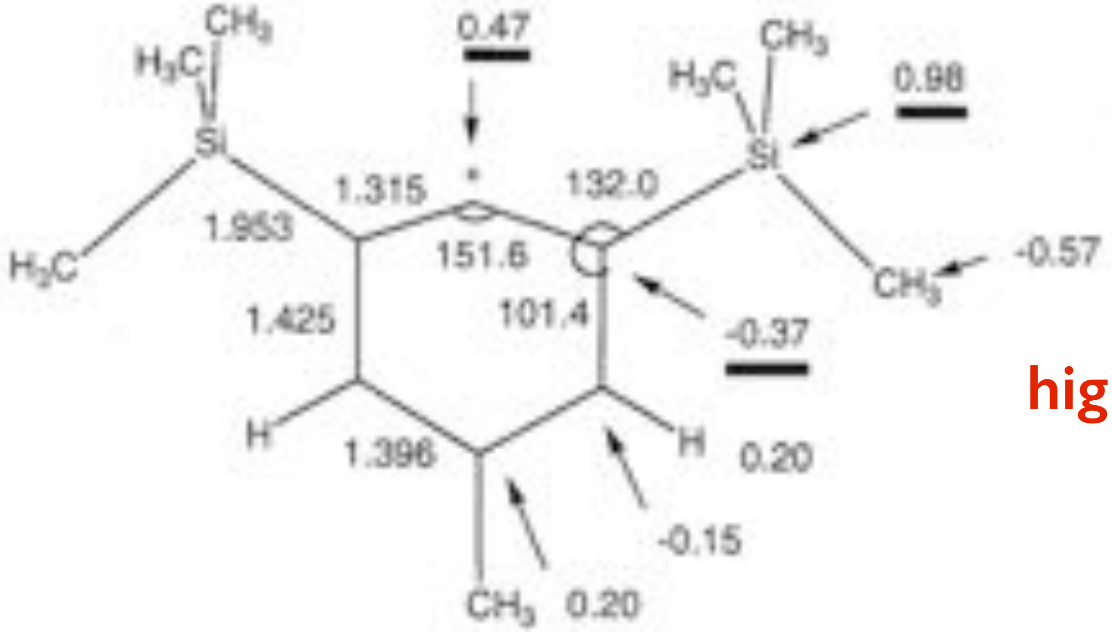
ElectroStaticPotential charge



2,6-dimethylphenyl cation



2,6-disilylphenyl cation

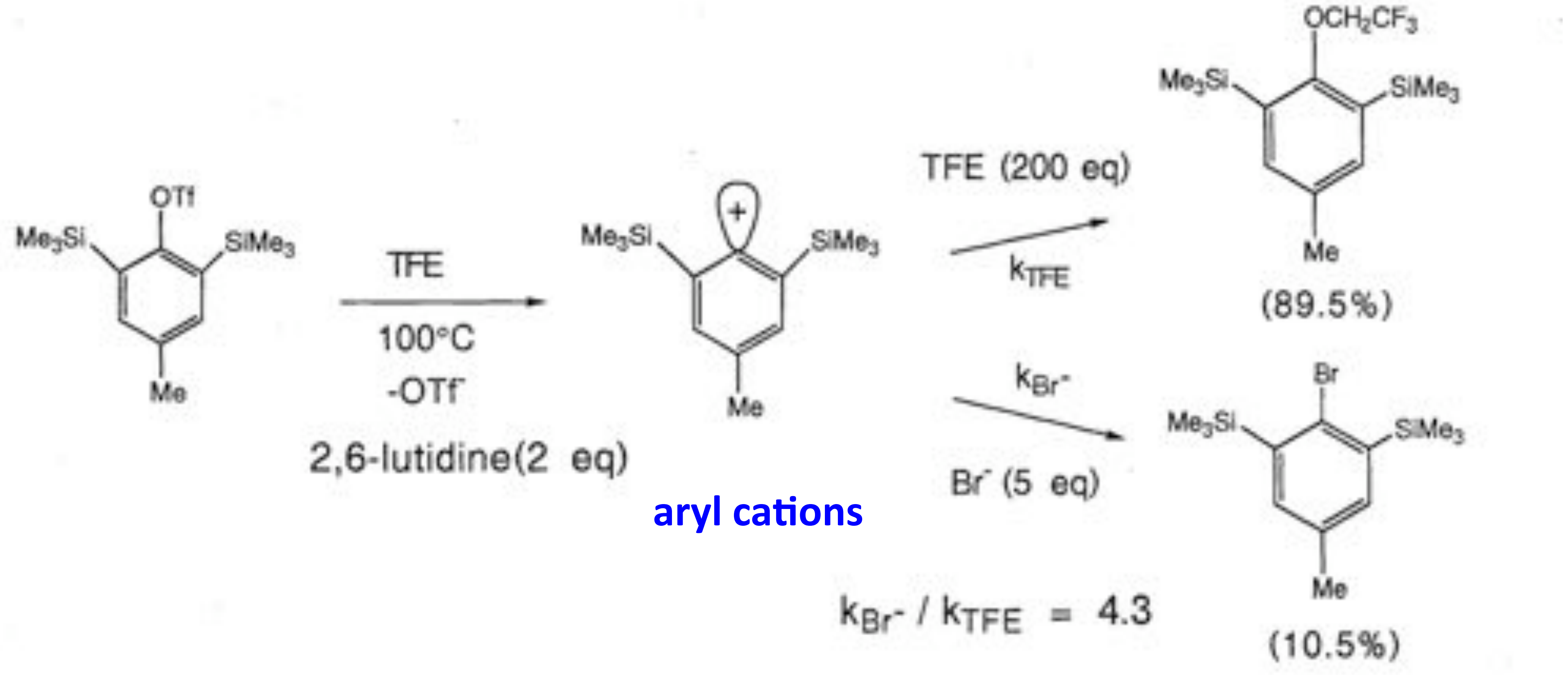


highly polarized Si-C bonds

MP2/6-31G*

2,6-bis-trimethylsilyl-4-methylphenyl cation

Low selectivity of aryl cations in TFE solvolysis of aryl triflate



aryl cations

$k_{Br^-} / k_{TFE} = 4.3$

$k_{Nu} / k_{TFE} = 7.7(I^-),\ 4.3(Br^-),\ 3.5(EtSH),\ 1.7(MeOH)$

(TFE = CF_3CH_2OH)

Yoshio Himeshima et al., J. Am. Chem. Soc., 107, 5286(1985)

C-F Activation of Fluorobenzene by Silylium Carboranes: Evidence for Incipient Phenyl Cation Reactivity

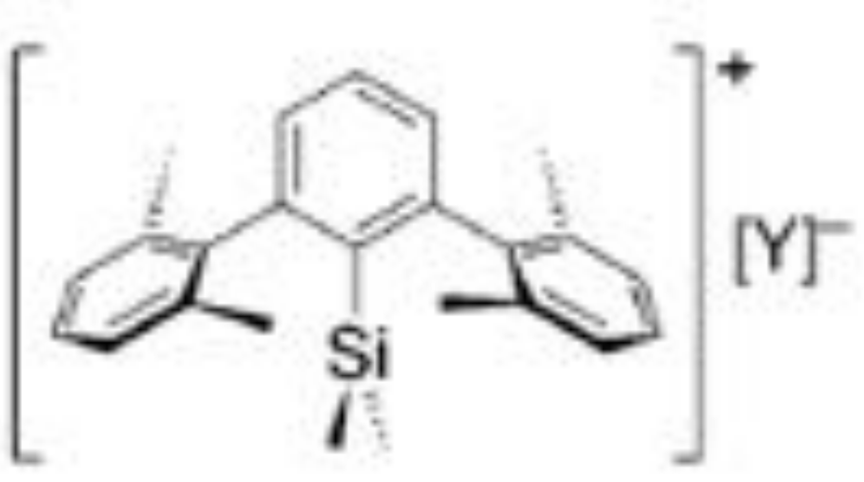
Simon Duttwyler, Christos Douvris, Nathanael L. P. Fackler, Fook S. Tham, Christopher A. Reed,* Kim K. Baldridge,* and Jay S. Siegel*

Angew. Chem. Int. Ed. 2010, 49, 1 - 5

Dedicated to Yitzhak Apeloig and Takaaki Sonoda

$[Et_3Si(X)]^+[Y]^-$

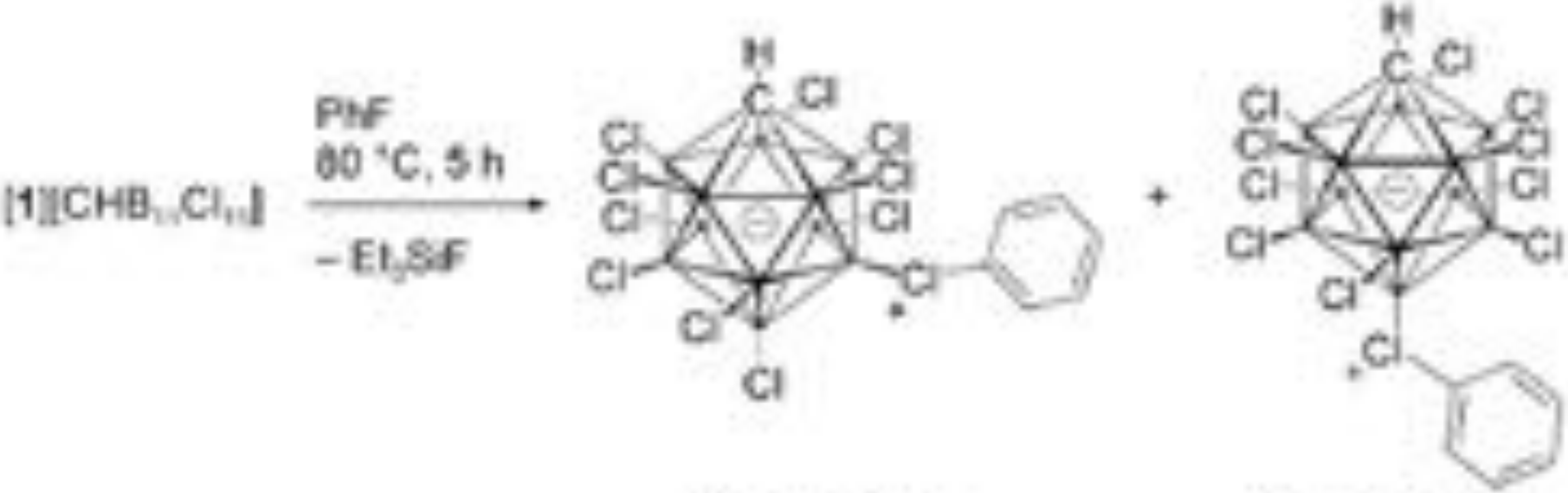
[**1**][Y]



[**2**][Y]

X = PhF or Et_3SiH

$[Y]^- = [CHB_{11}Cl_{11}]^-$



3a 7-isomer **3b** 12-isomer

1.3 : 1, 80 % combined yield

Scheme 1. C–F activation by 1^+ affording phenyl carboranes **3a,b**.

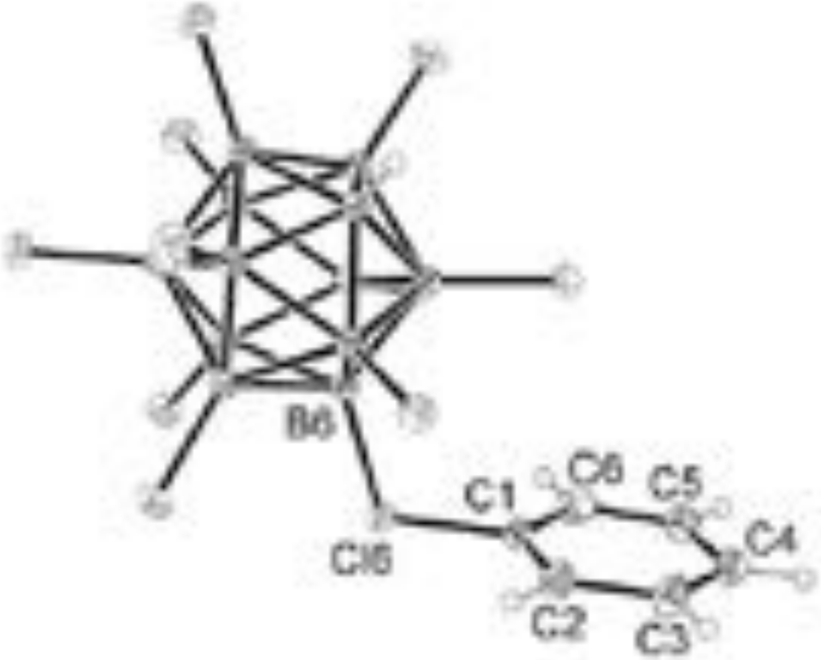
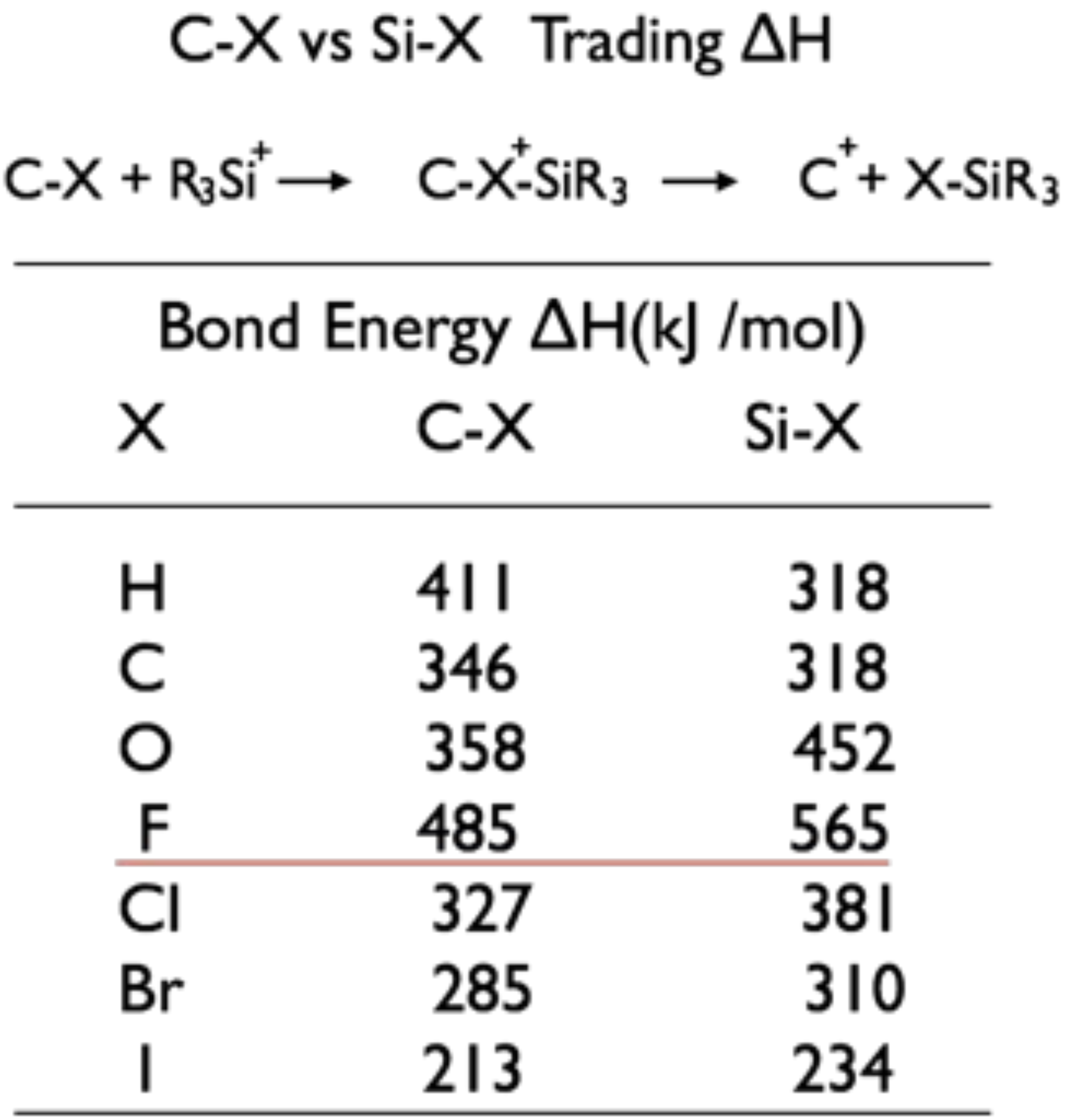


Figure 1. ORTEP plot of **3a** (thermal ellipsoids set at 50% probability).

C-F bond activation by fluorophilic silyl cations ion-paired with WCA



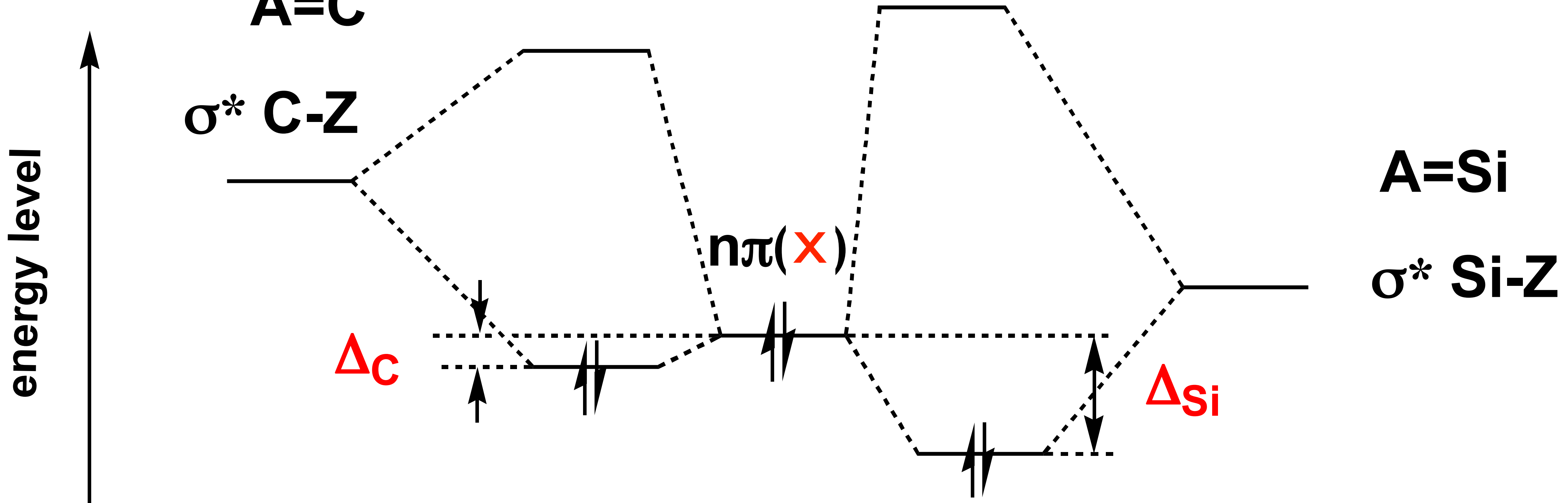
C-X vs Si-X Trading ΔH

$$\text{C-X} + \text{R}_3\text{Si}^+ \longrightarrow \text{C-}\overset{+}{\text{X}}\text{-SiR}_3 \longrightarrow \text{C}^+ + \text{X-SiR}_3$$

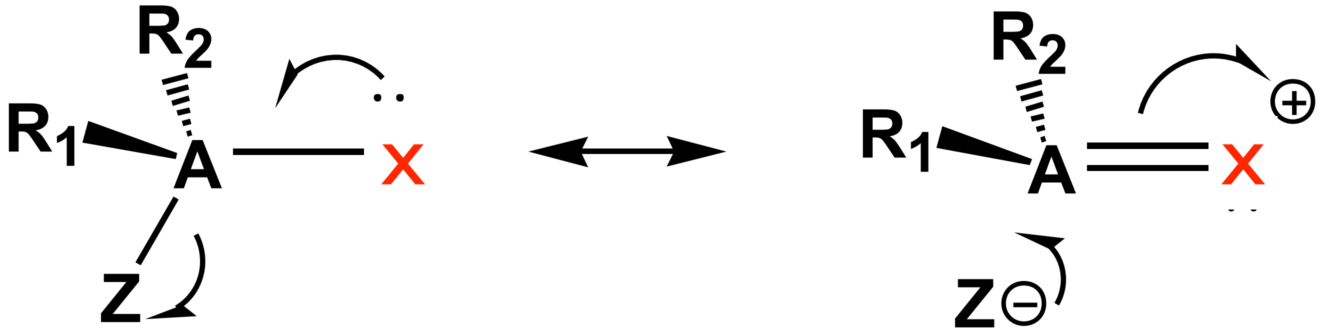
	Bond Energy ΔH(kJ /mol)	
X	C-X	Si-X
H	411	318
C	346	318
O	358	452
F	485	565
Cl	327	381
Br	285	310
I	213	234

Si-X bond is stronger than C-X bond

Si-X(herero atom) 結合はC-X結合よりも強い共有結合



$\Delta_C < \Delta_{Si}$



A = C or Si

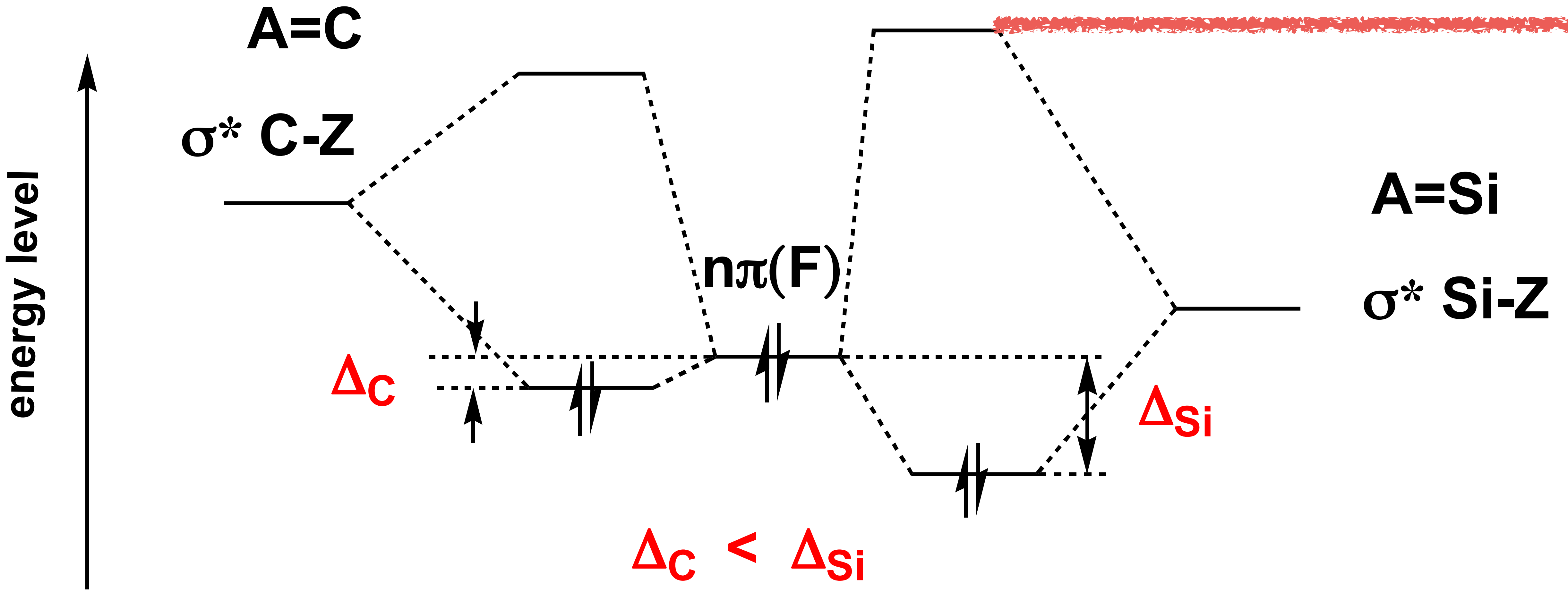
X : electron-donor

X: halogen, oxygen

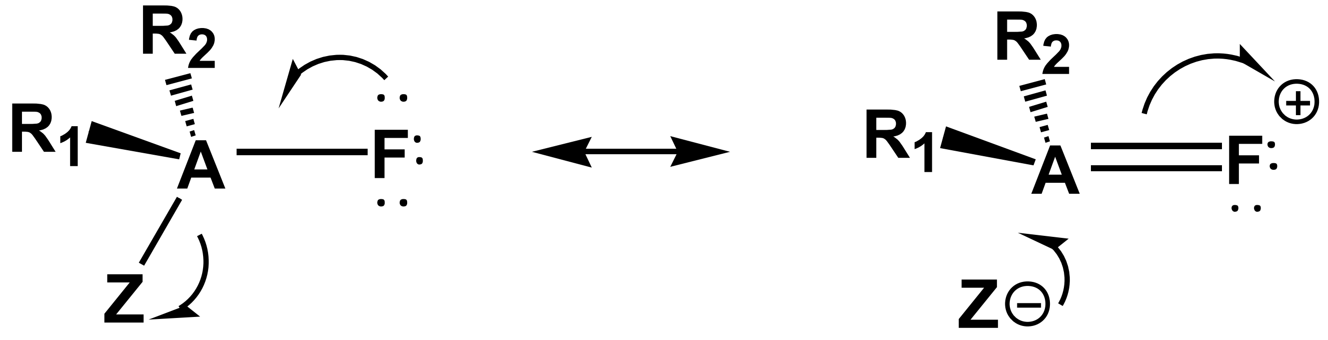
Si-F bond is stronger than C-F bond

due to positive (fluorine) hyperconjugative stabilization

Si-F結合は最も強い共有結合

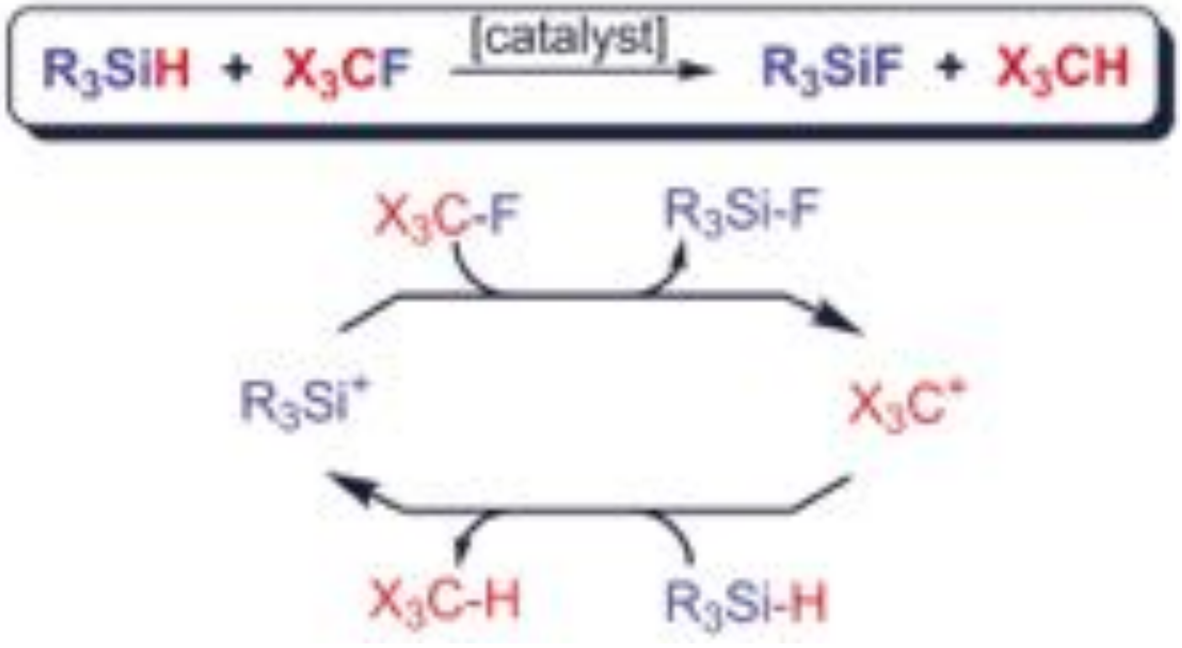


$\Delta_C < \Delta_{Si}$

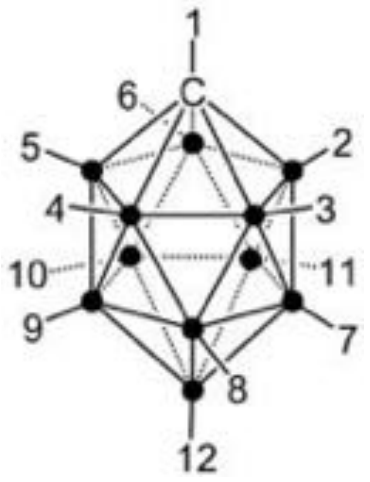


A = C or Si

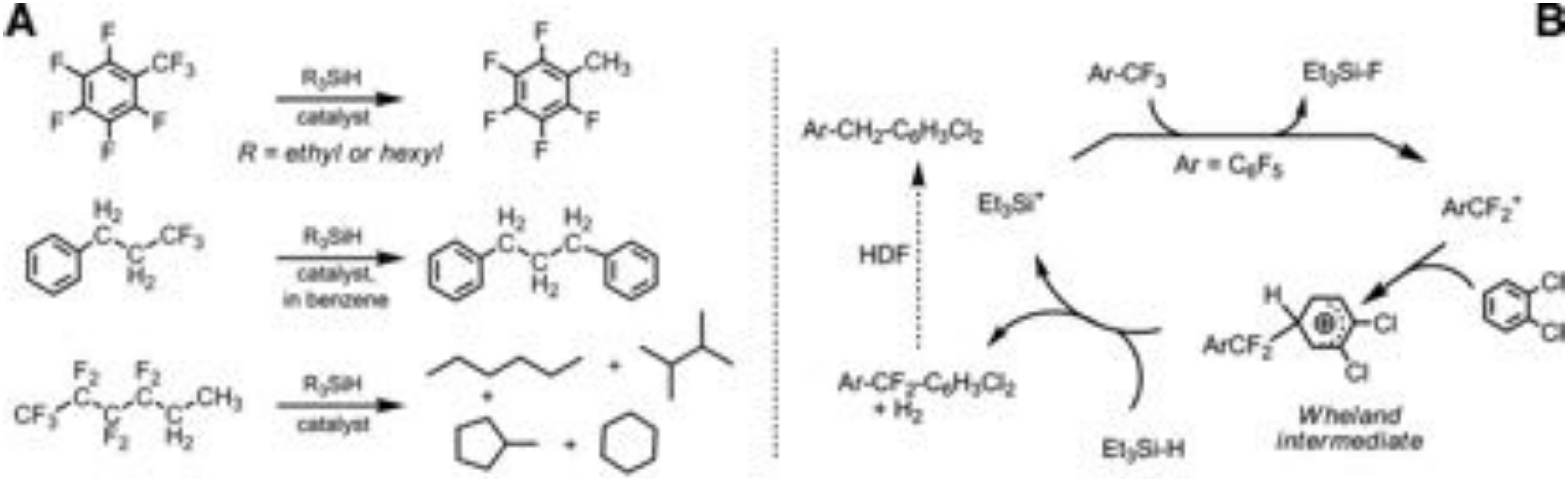
fluorine: electron-donor



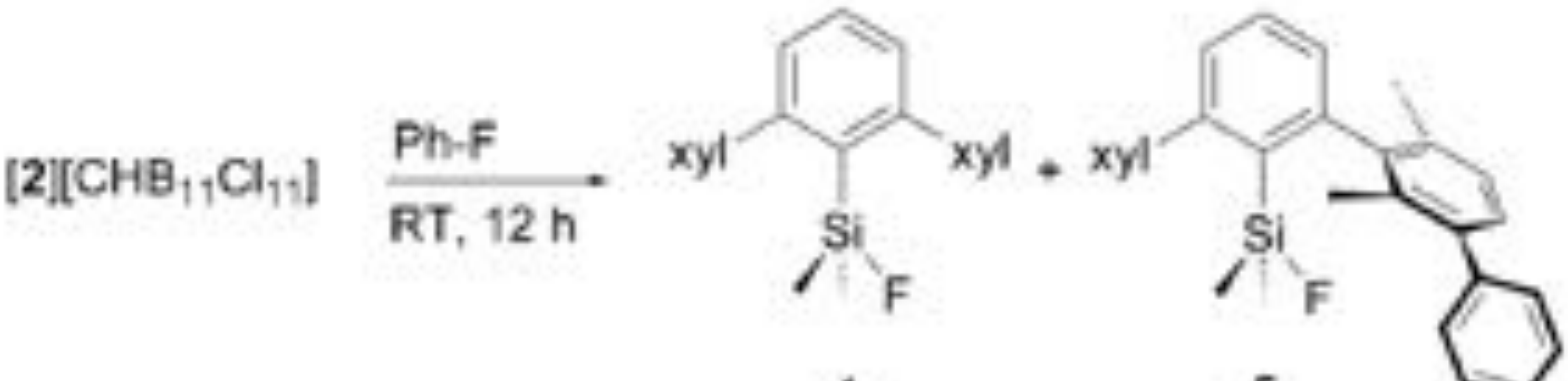
$Ph_3C[HCB_{11}H_5Cl_6]$ as WCA catalyst



carborane anion



Douvris, Ozerov, Science 2008, 321, 1188



4 **5**

Scheme 2. C–F activation of fluorobenzene by $\mathbf{2}^+$ to give fluorosilanes **4** and **5**.

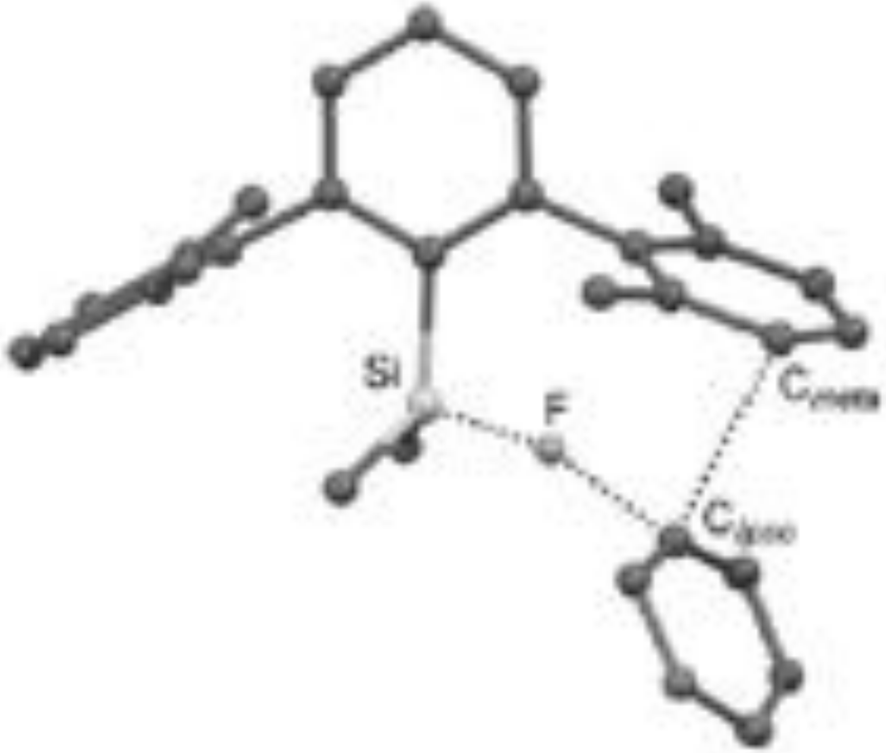
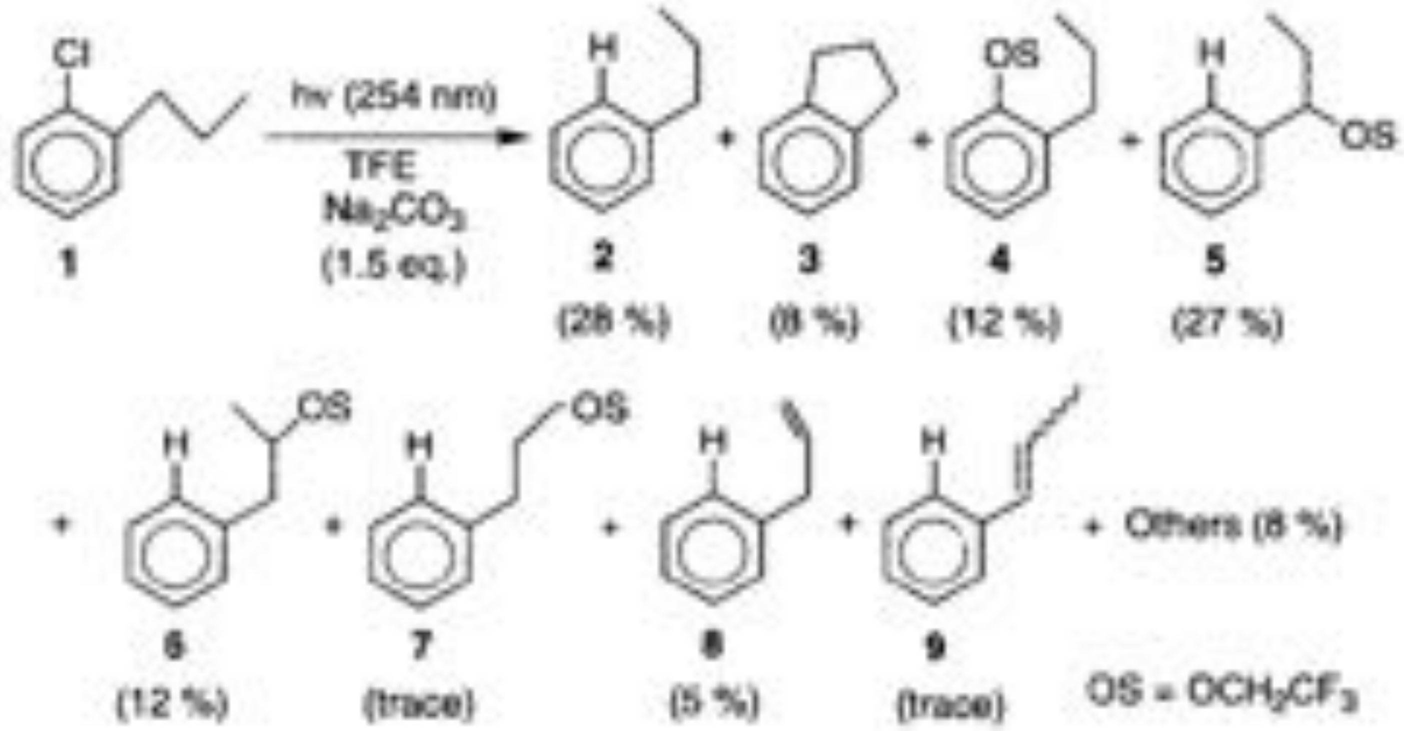
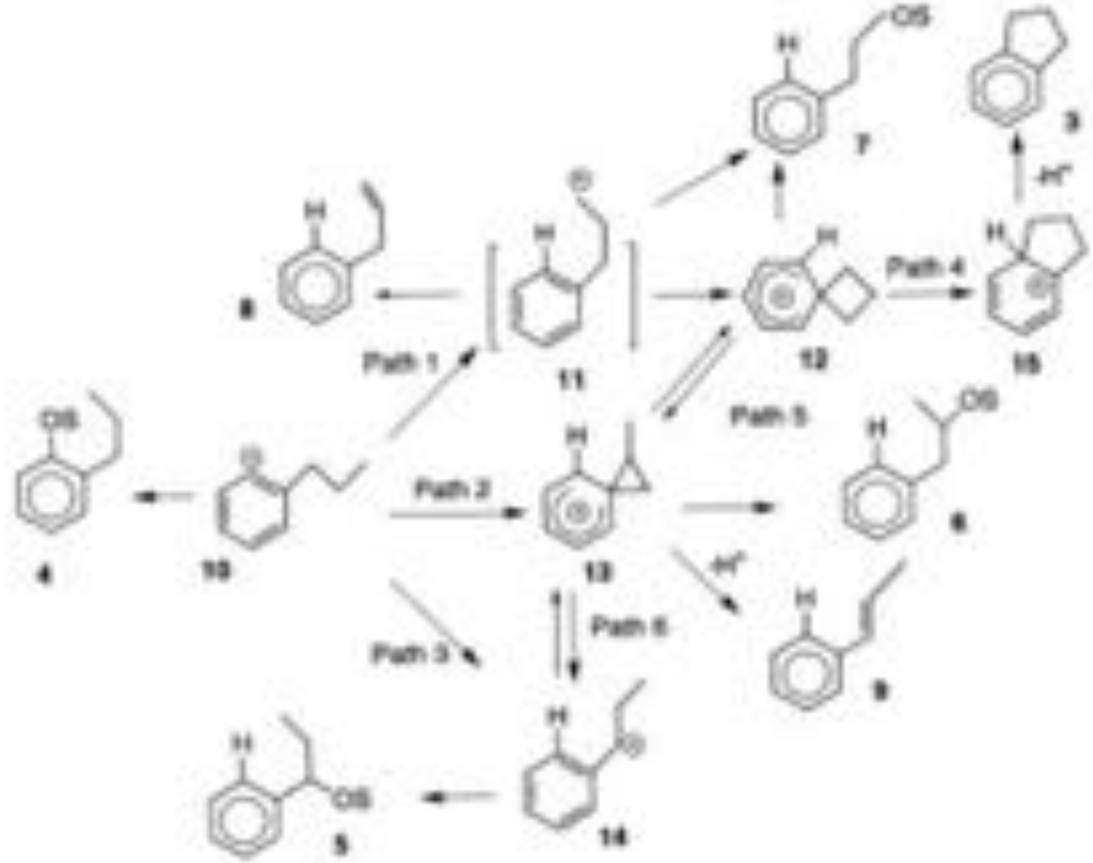


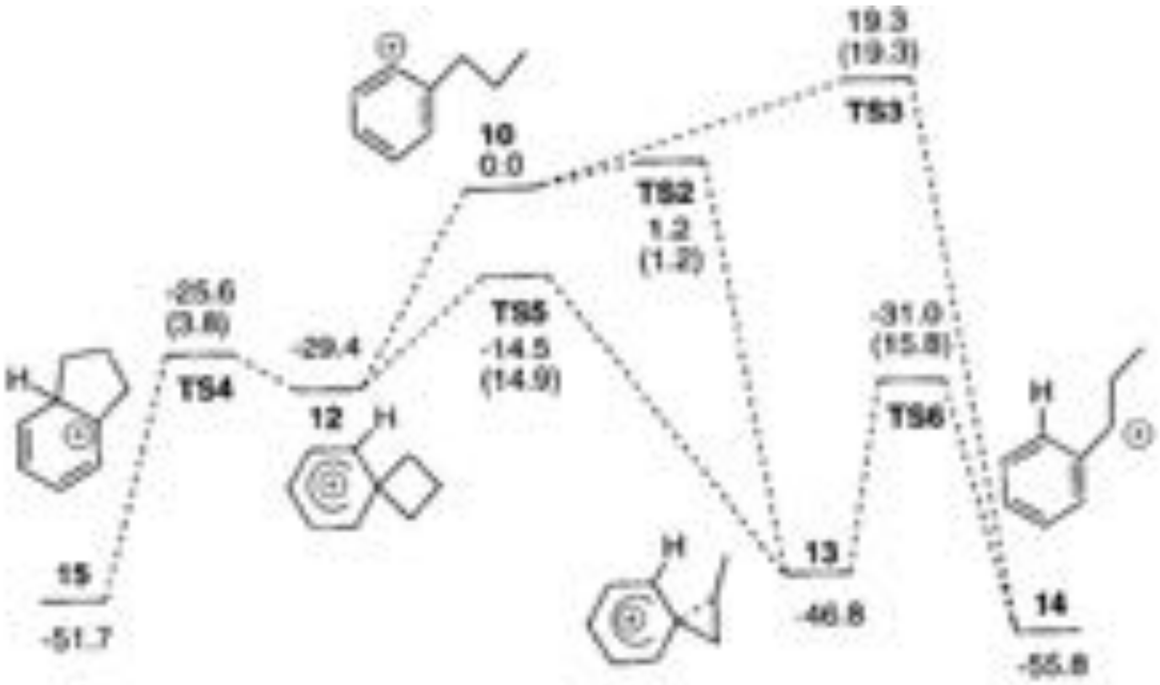
Figure 2. Calculated transition state for $\mathbf{2}^+$ + PhF → **5** (B98/DZ-(2df,pd)). Si–F 1.680 Å, F–C_{ipso} 2.189 Å, C_{ipso}–C_{meta} 2.849 Å. H atoms omitted for clarity.

Theoretical Study on Reactivity of Phenyl Cation with Propyl Group at *Ortho*-Position

Kenzi Hori, Takaaki Sonoda, Masayuki Harada, Suzuko Yamazaki-Nishida, Tetrahedron, 2000, 56, 1429-1436

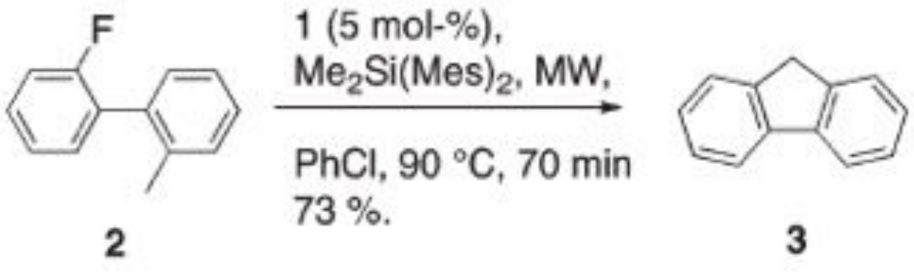


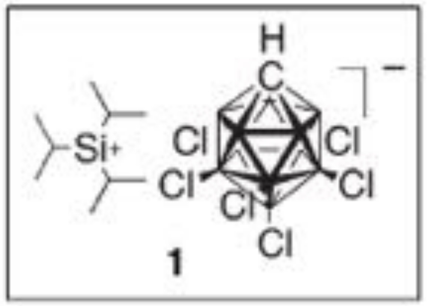


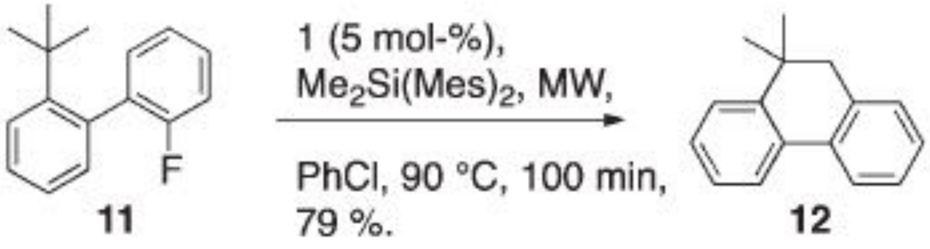


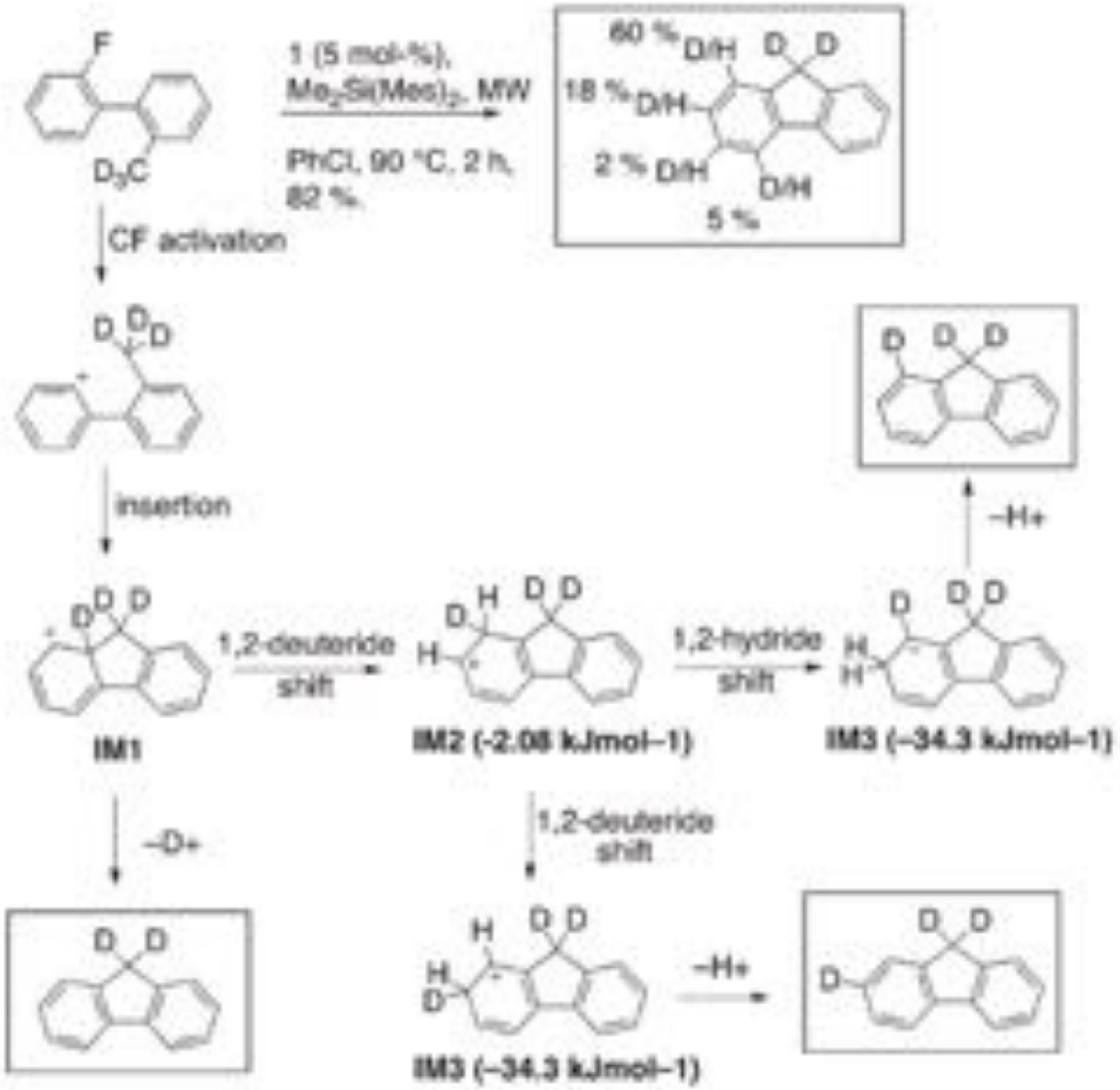
Intramolecular C-H Insertion vs. Friedel-Crafts Ccoupling Induced by Silyl Cation-promoted C-F Activation

Oliver Allemann, Kim K. Baldridge, Jay S. Siegel, Org. Chem. Front., 2015, 2,1018





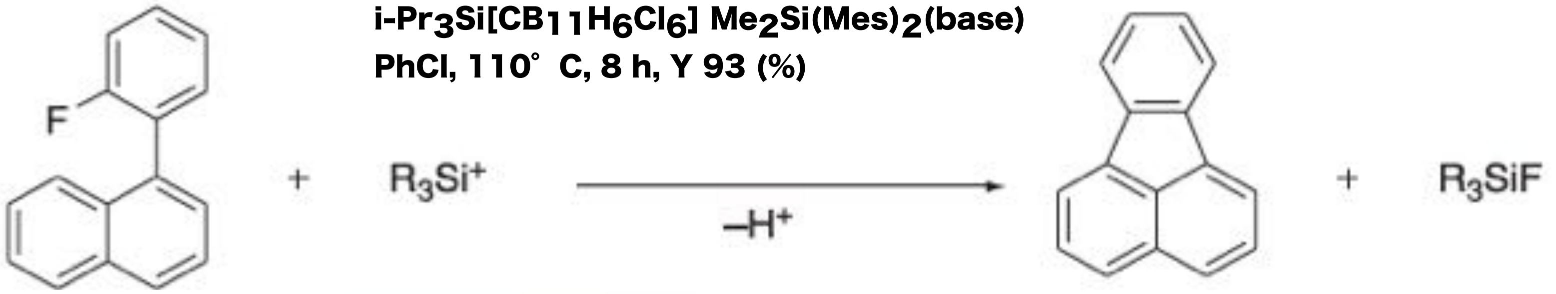


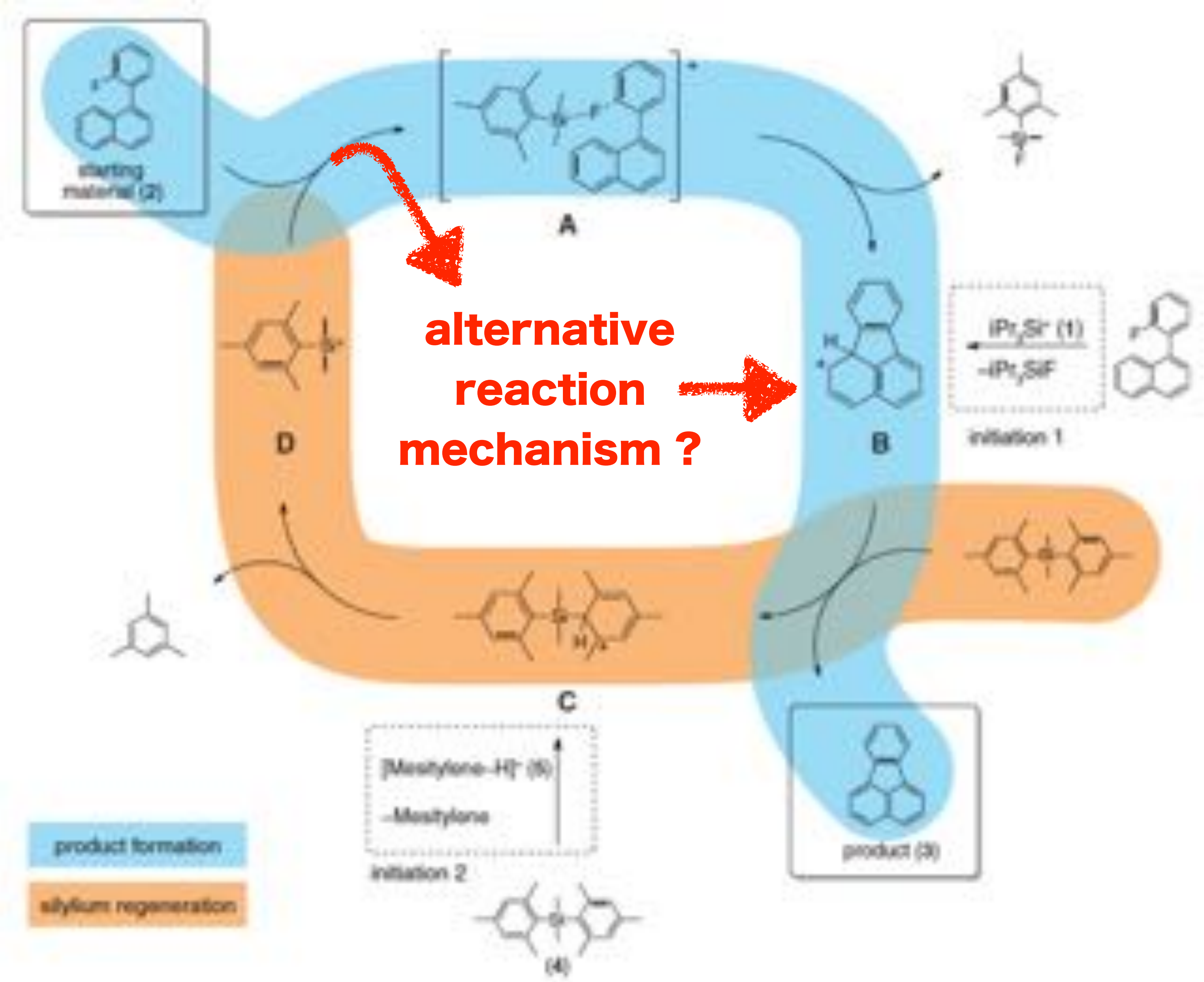


Proton-Catalyzed, Silane-Fueled Friedel-Crafts Coupling of Fluoroarenes

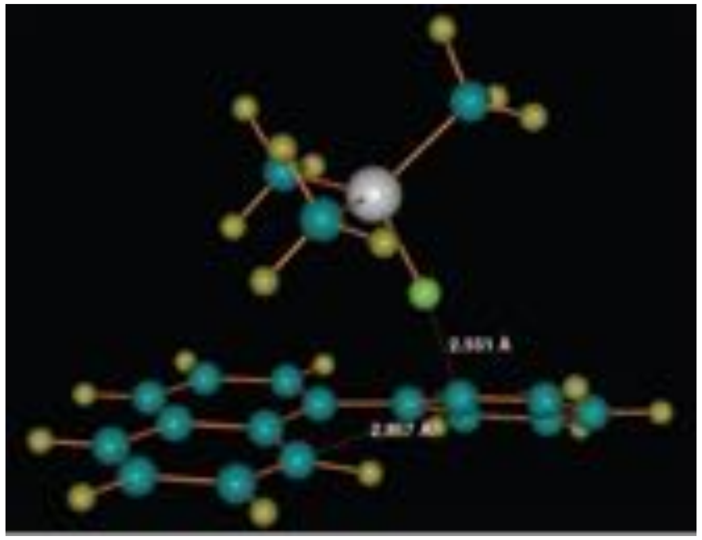
Oliver Allemann, Simon Duttwyler, Paola Romanato, Kim K. Baldridge, Jay S. Siegel

Science, 2011, 332, 574


i-$Pr_3Si[CB_{11}H_6Cl_6]$ $Me_2Si(Mes)_2$(base)
PhCl, 110° C, 8 h, Y 93 (%)



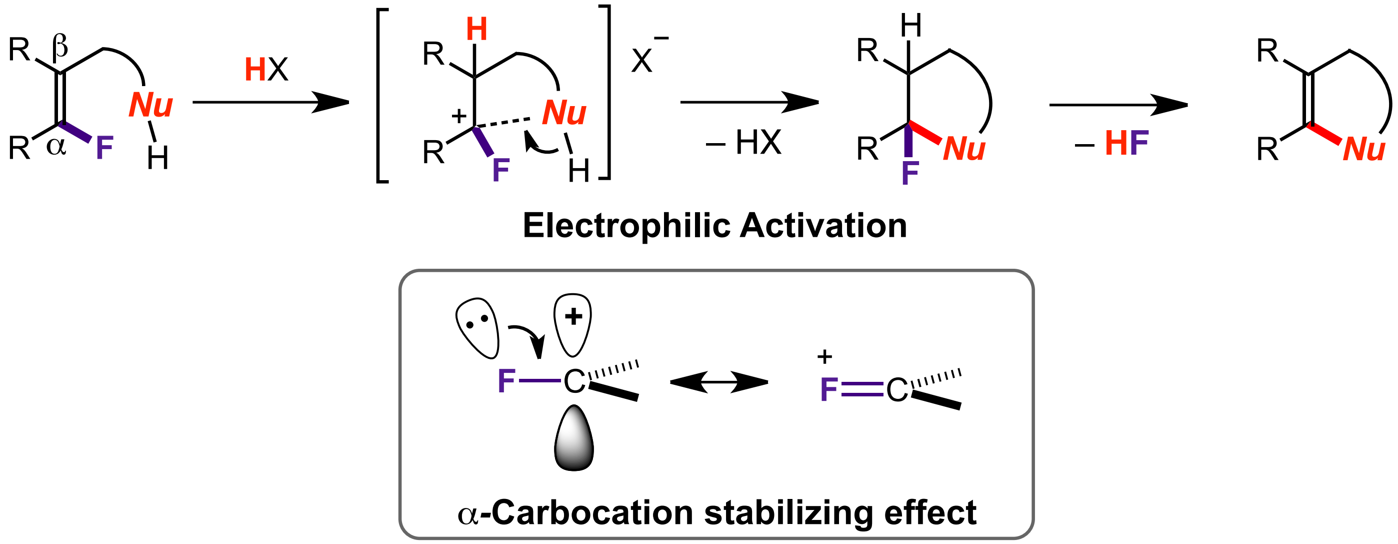
alternative reaction mechanism ?

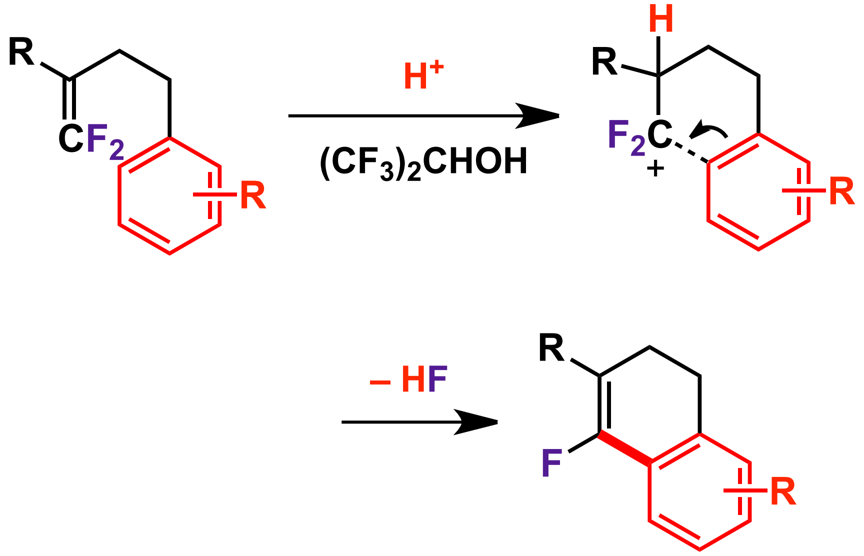


MP2/DZ(2df,pd)//B98/DZ(2df,pd) calculated transition state(TS), for fluoride abstraction from 1-(2-fluorophenyl)-naphthalene

Vinylic C–F bond cleavage under acidic conditions

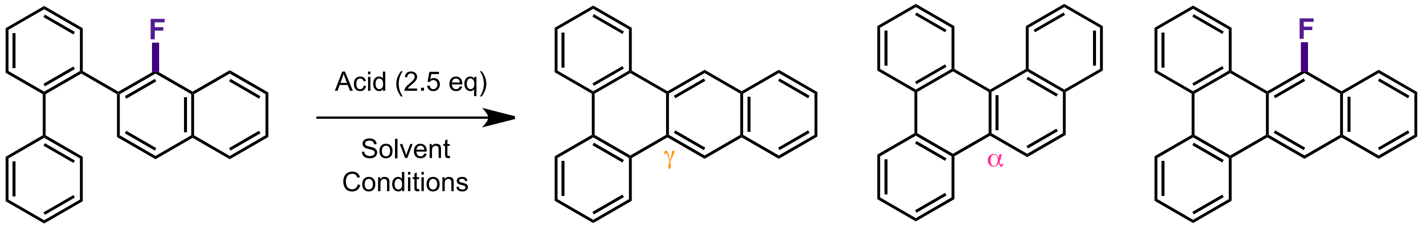
· *HF Elimination*





Ichikawa, J. et al. *Synthesis* 2005, *1*, 39.
Ichikawa, J. et al. *Org. Lett.* 2007, *9*, 4639.

Ichikawa, J. et al. *Angew. Chem., Int. Ed.* 2008, *47*, 4870.
Ichikawa, J. et al. *Chem. Eur. J.* 2011, *17*, 1275.

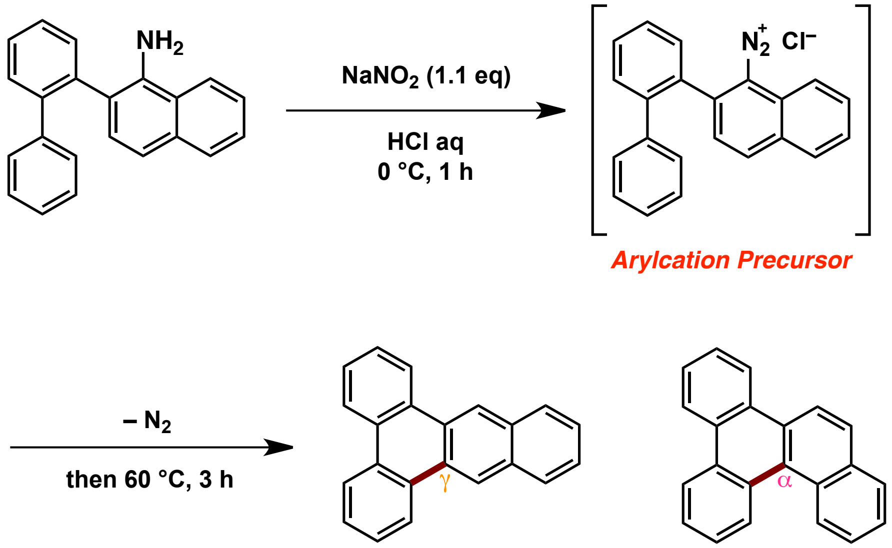


1 **2** **3**

Entry	Acid	Solvent	Conditions	**1** (%)	**2** (%)	**3** (%)	
1	$FSO_3H{\bullet}SbF_5$	$(CF_3)_2CHOH–CH_2Cl_2$	0 °C, 15 min	12	0	38	**Method A**
2	TiF_4	$(CF_3)_2CHOH$	60 °C, 12 h	84	0	0	**Method B**

^{1}H NMR yield.

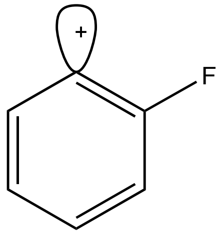
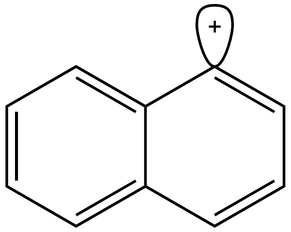
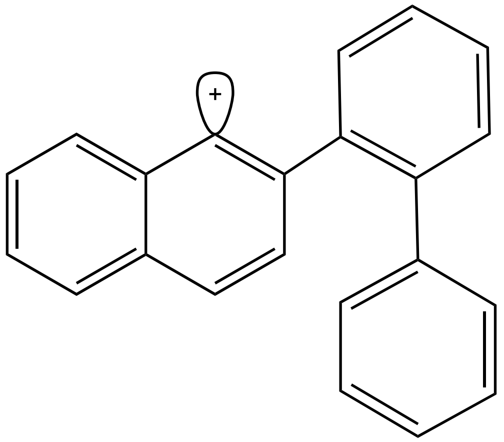
Cf.



0% **92%**

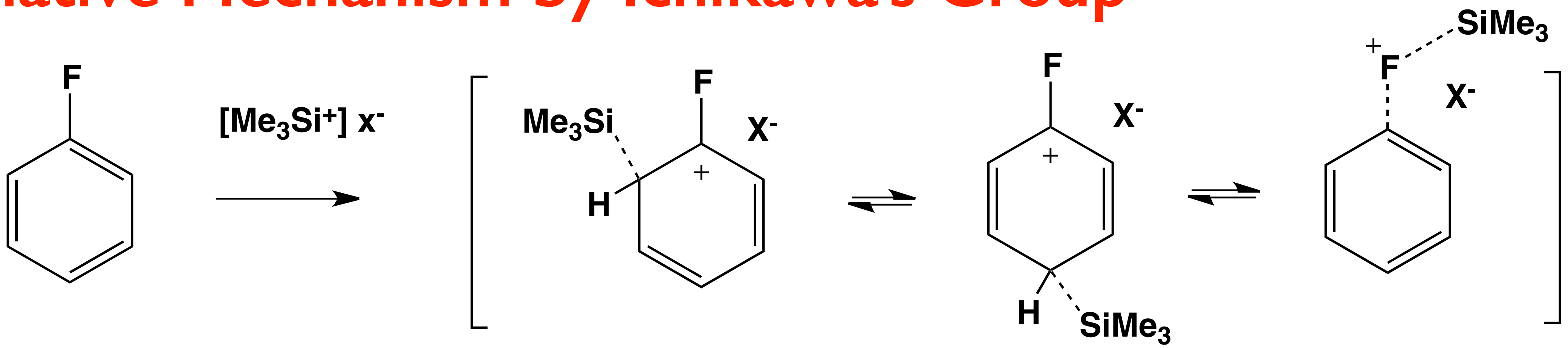
Relative stabilizing energies of some carbocations and trimethylsilyl cations

$$Ph^+ + Ar\text{-}F(\text{or } R\text{-}F) \xrightarrow{\Delta E} Ph\text{-}F + Ar^+(\text{or } R^+)$$

Ar^+(or R^+)	(B3LYP 6-311+G*// 6-311+G**)	ΔE(kcal/mol)
CH_3^+		-22.52
$2\text{-}FC_6H_4^+$		-16.24
Ph^+		0
CH_2Cl^+		3.62
$1\text{-}NaPh^+(1\text{-}C_{10}H_7^+)$		8.13
2-(2-Ph-Ph)-Naph$^+$	 (B3LYP 6-311+G*// 6-31+G**)	19.36
Me_3Si^+		19.62

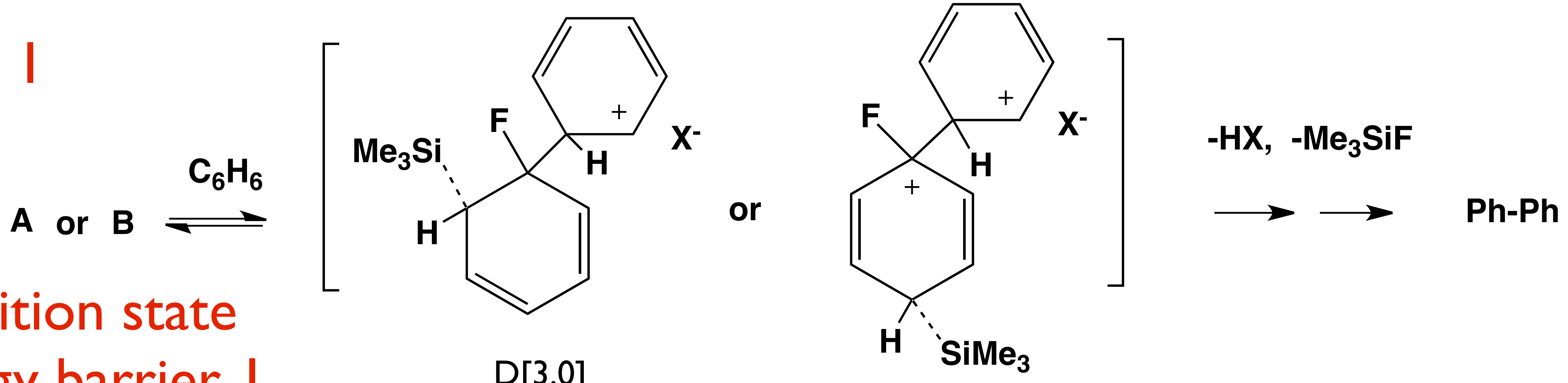
trimethylsilyl cation is more stable than phenyl cation

Alternative Mechanism by Ichikawa's Group



A [8.2] B [8.0] C [0] kcal/mol

Route 1

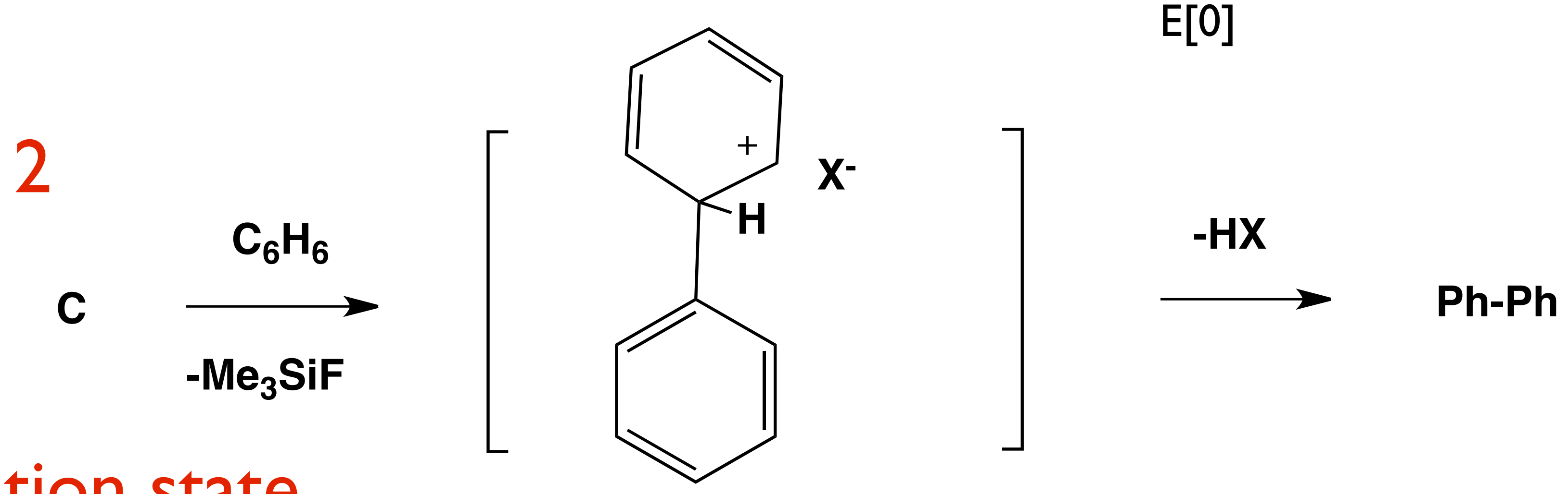


D[3.0]

E[0]

transition state energy barrier 1

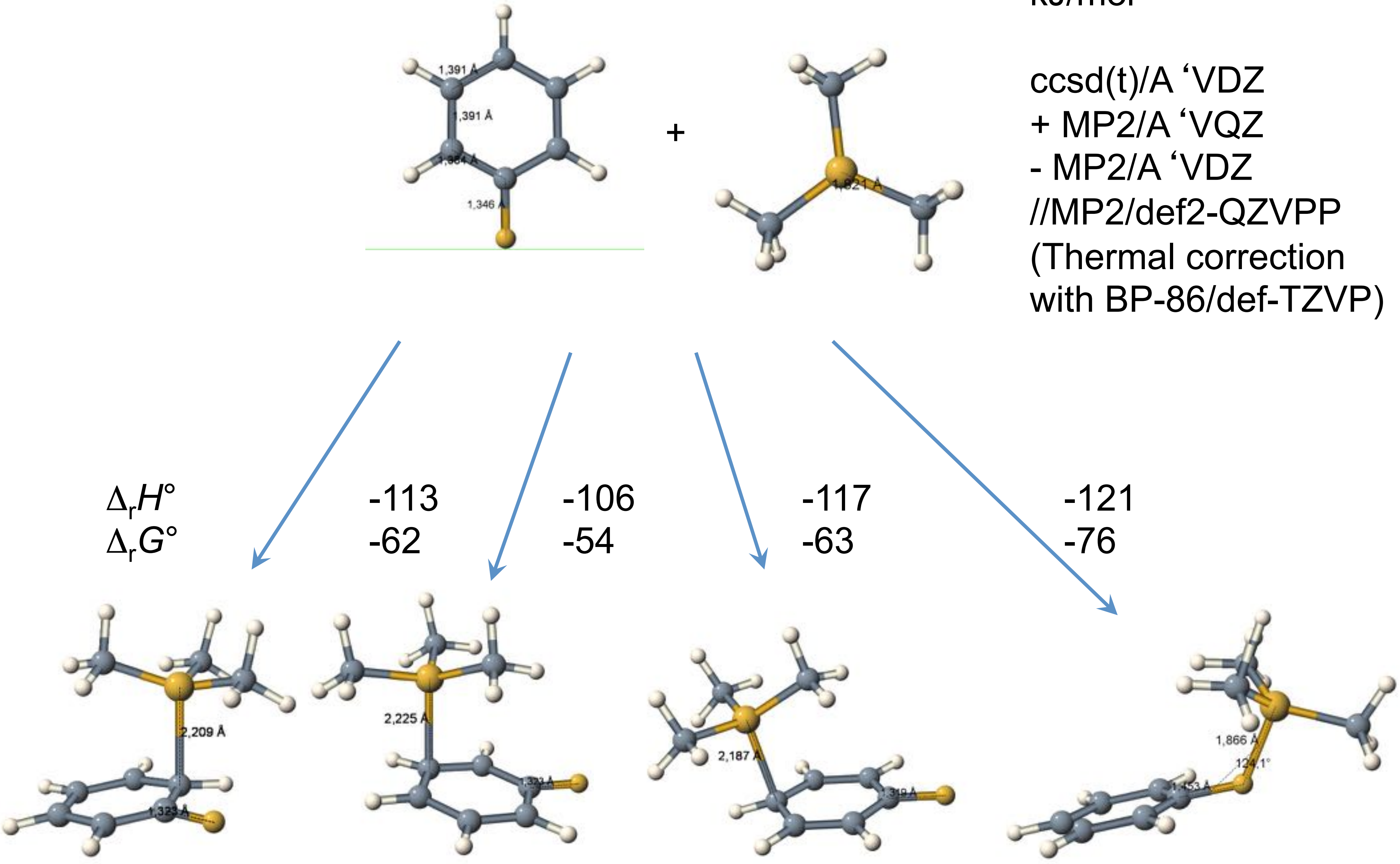
Route 2



transition state energy barrier 2

PhF/tmsBr/AlBr3 system

Stability of PhF*tms+



Gas phase, 298K,
kJ/mol

ccsd(t)/A ‘VDZ
+ MP2/A ‘VQZ
- MP2/A ‘VDZ
//MP2/def2-QZVPP
(Thermal correction
with BP-86/def-TZVP)

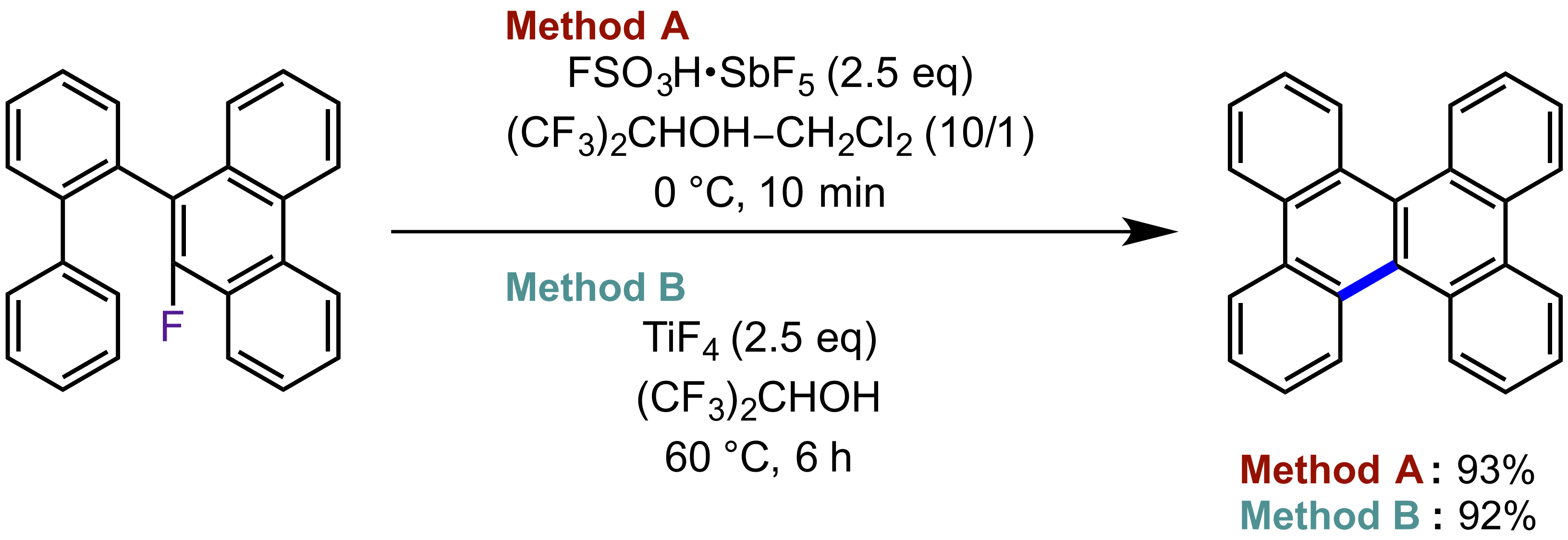
$\Delta_r H°$	-113	-106	-117	-121
$\Delta_r G°$	-62	-54	-63	-76

MP2/def2-QZVPP structures

by Daniel Himmel in Freiburg University

Relative Stability	(B3LYP 6-311+G*// 6-311+G**)	ΔE(kcal/mol)
C_6H_5-F-H^+		0
C_6H_5F-H^+(o)		34.66
C_6H_5F-H^+(m)		28.49
C_6H_5F-H^+(p)		36.77
C_6H_5-F-$SiMe_3^+$		0
C_6H_5F-$SiMe_3^+$(o)		-2.08
C_6H_5F-$SiMe_3^+$(m)		-4.39
C_6H_5F-$SiMe_3^+$(p)		-1.24
C_6H_5-Cl-$SiMe_3^+$		0
C_6H_5Cl-$SiMe_3^+$(o)		-1.24
2-(2-Ph-Ph)-Naph-F-$SiMe_3^+$	(6-311+G*// 6-31+G**)	0
2-(2-Ph-Ph)-NaphF-$SiMe_3^+$(p)	(6-311+G*// 6-31+G**)	-33.28

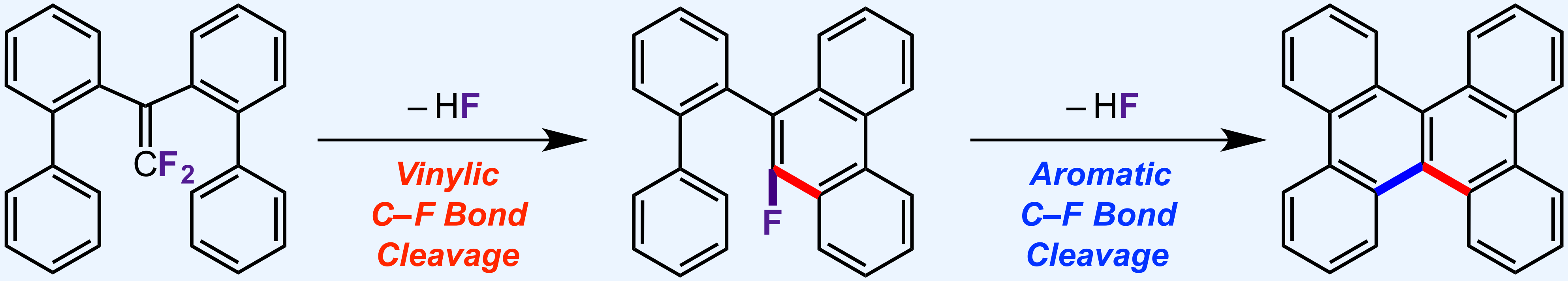
Aromatic C–F Bond Cleavage



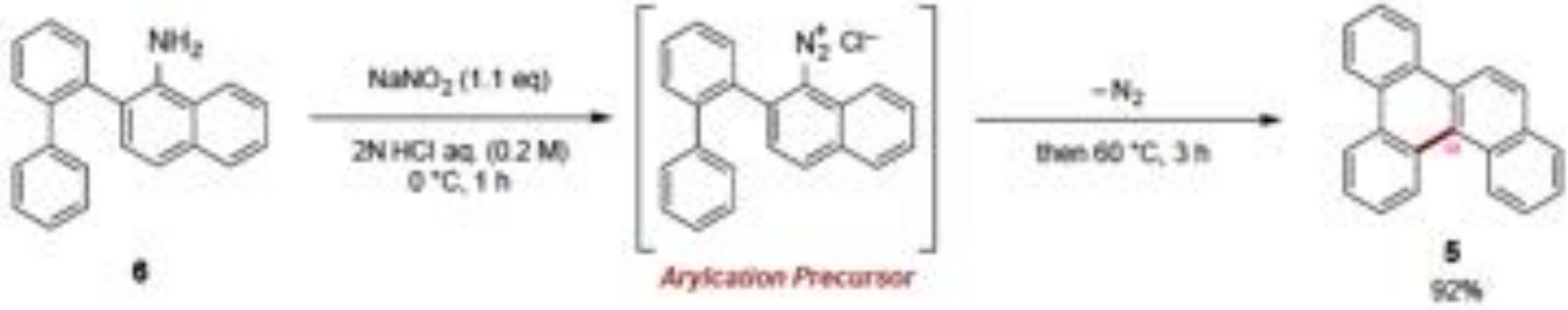
Method A
$FSO_3H \cdot SbF_5$ (2.5 eq)
$(CF_3)_2CHOH$–CH_2Cl_2 (10/1)
0 °C, 10 min

Method B
TiF_4 (2.5 eq)
$(CF_3)_2CHOH$
60 °C, 6 h

Method A: 93%
Method B : 92%



4. Mechanistic Study

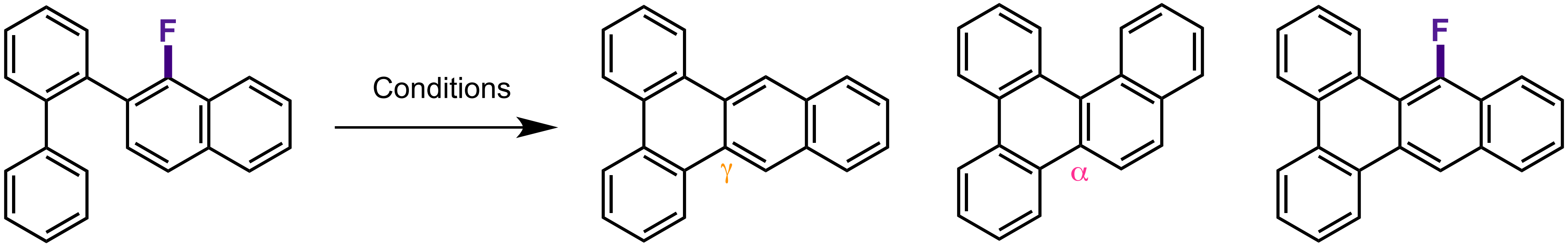


Scheme 2. Arylcation Path

→ The cyclization via the arylcation generated from the aryldiazonium salt was examined. Not benzo[*c*]triphenylene **4** but benzo[*g*]chrysene **5** was obtained as a sole product (**Scheme 2**).

→This result supports that the reaction of Ar–F bond cleavage proceeds through the fluoroarenium intermediate not the arylcation.

Screening of Acids



	1	**2**	**3**
$FSO_3H{\bullet}SbF_5$ (2.5 eq) $(CF_3)_2CHOH–CH_2Cl_2$/ 0 °C, 15 min	12%	0%	38%
TiF_4 (2.5 eq) **$(CF_3)_2CHOH$/ 60 °C, 12 h**	**84%**	0%	0%

2. Proposed Reaction Mechanism

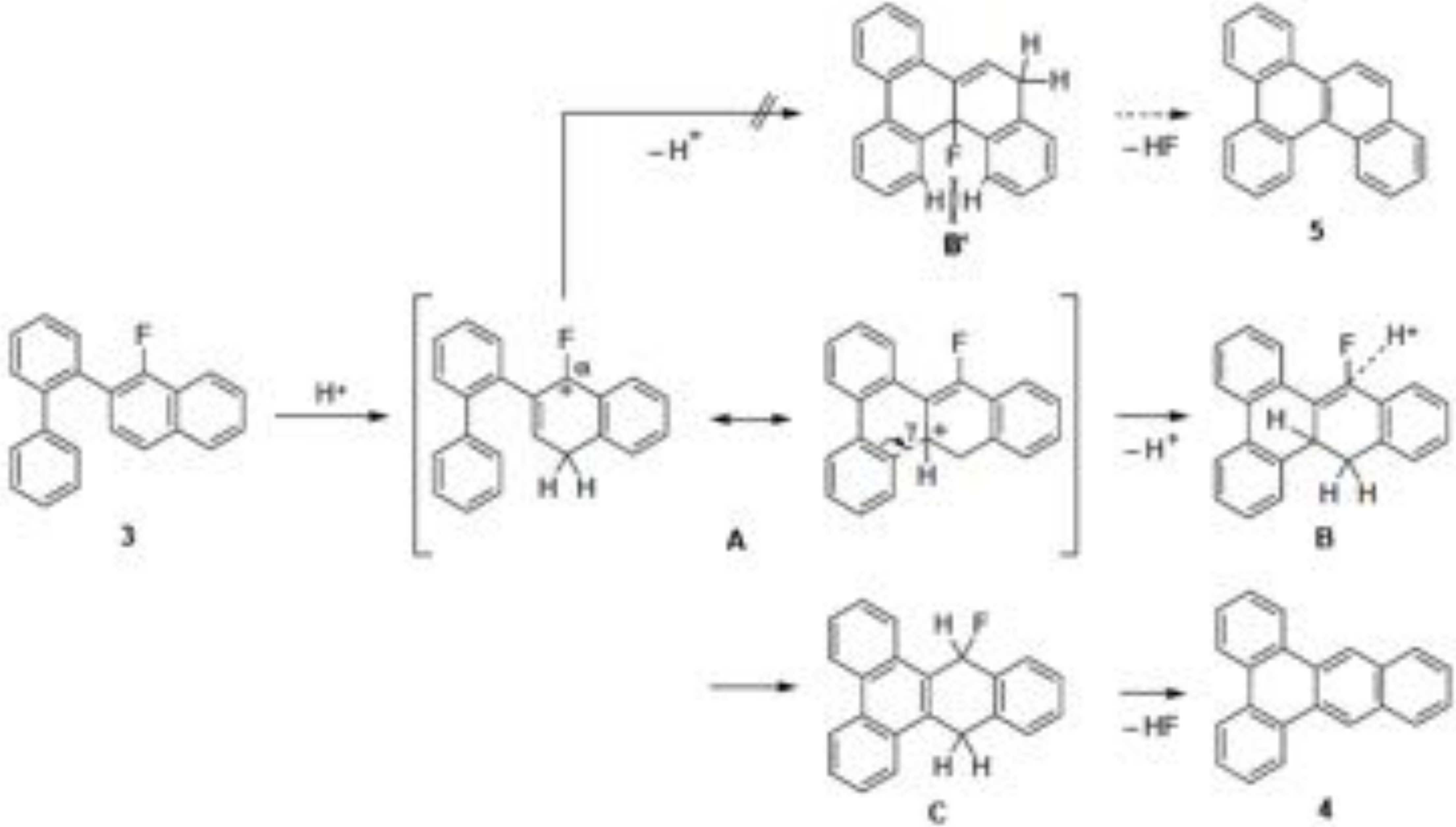
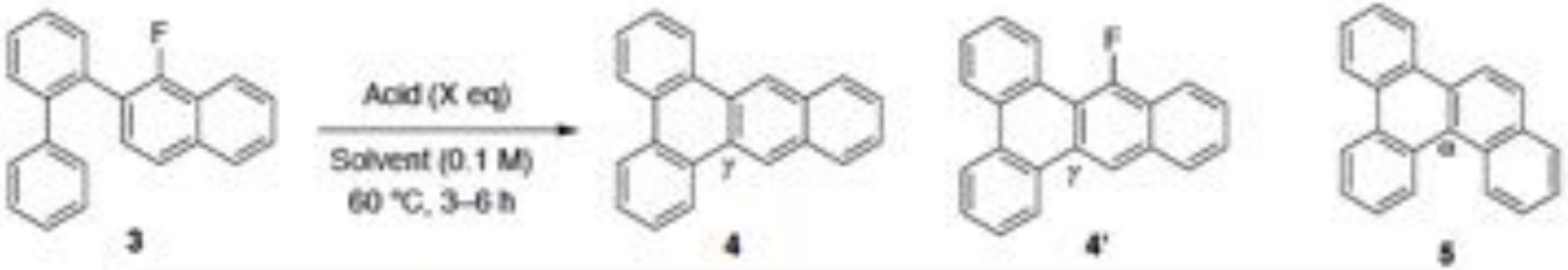


Figure 1. Proposed Mechanism and Selective C–C Bond Formation at Position γ to Fluorine

→ A plausible reaction mechanism is shown in **Figure 1**. The cyclization is induced by protonation or metallation of the naphthalene moiety, in which a Friedel–Crafts-type cylization proceeds through cationic intermediate **A**, resulting in aromatic C–F bond cleavage and C–C bond formation.

3. Screening of Acids and Solvents

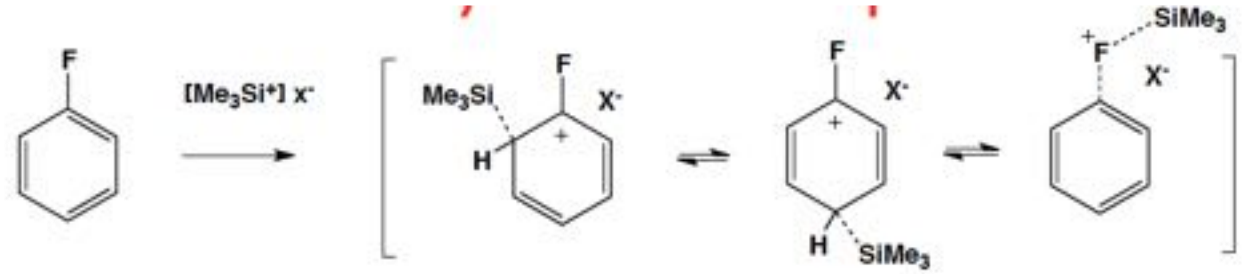


entry	Acid (X eq)	Solvent	**4** (%)	**4'** (%)	**5** (%)	recov (%)
1	TsOH (2.5 eq)	$(CF_3)_2CHOH$	-	-	-	quant.
2	TfOH (2.5 eq)	$(CF_3)_2CHOH$	97	-	-	trace
3	TiF_4 (2.5 eq)	$(CF_3)_2CHOH$	47	10	-	39
4	$TiCl_4$ (2.5 eq)	$(CF_3)_2CHOH$	-	-	-	quant.
5	ZrF_4 (2.5 eq)	$(CF_3)_2CHOH$	-	-	-	quant.
6	$ZrCl_4$ (2.5 eq)	$(CF_3)_2CHOH$	99	-	-	trace
7	$Al(OTf)_3$ (2.5 eq)	$(CF_3)_2CHOH$	-	-	-	quant.
8	$AlCl_3$ (2.5 eq)	$(CF_3)_2CHOH$	99(98)	-	-	-
9	$BF_3{\cdot}OEt_2$ (2.5 eq)	$(CF_3)_2CHOH$	-	-	-	quant.
10	TMSOTf (2.5 eq)	$(CF_3)_2CHOH$	52	-	-	51
11	TMSF–$Al[OC(CF_3)_3]$ (2.5 eq)	$(CF_3)_2CHOH$	-	-	-	quant.
12*	TMSF–$Al[OC(CF_3)_3]$ (2.5 eq)	PhCl	95(97)	-	-	-
13	$AlCl_3$ (2.5 eq)	PhCl	99	-	-	-
14	**$AlCl_3$ (1.5 eq)**	**PhCl**	**99(99)**	-	-	-
15	$AlCl_3$ (1.0 eq)	PhCl	72	-	-	23

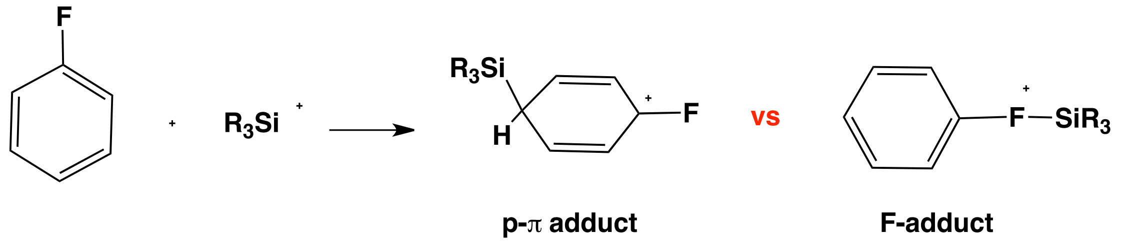
^{1}H, ^{19}F NMR yield. Isolated yield is shown in parentheses. *110 °C, 24 h.

→$AlCl_3$, TfOH, $ZrCl_4$ is better than TiF_4 for this cyclization (TiF_4 gave oxidized byproduct **4'**). PhCl was possible to be used as solvent instead of HFIP (**Table 1**).

Proposed mechanism-1



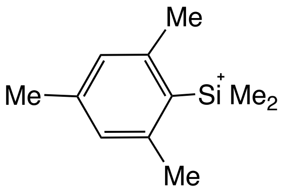
o-π-Si **p-π-Si** **F-Si**



p-π adduct F-adduct

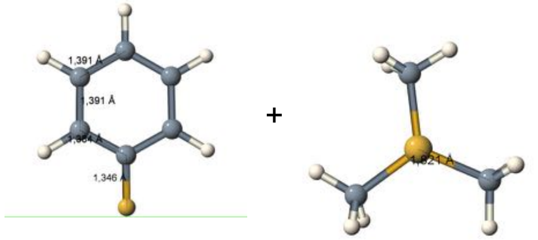
R_3Si^+: Me_3Si^+ ⟹ $MesMe_2Si^+$ ⟹ $i\text{-}Pr_3Si^+$

$MesMe_2Si^+$



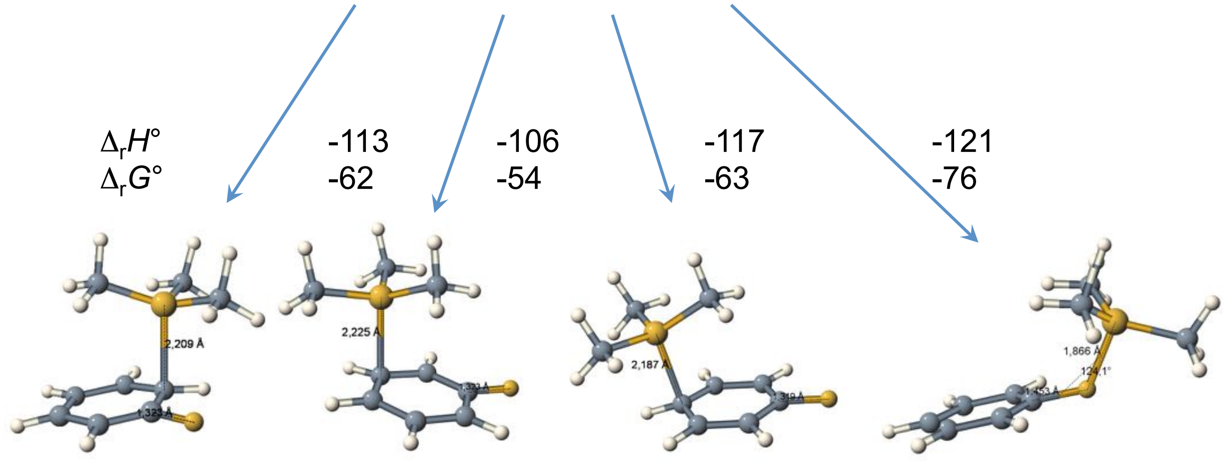
PhF/tmsBr/AlBr3 system

Stability of PhF*tms+



Gas phase, 298K, kJ/mol

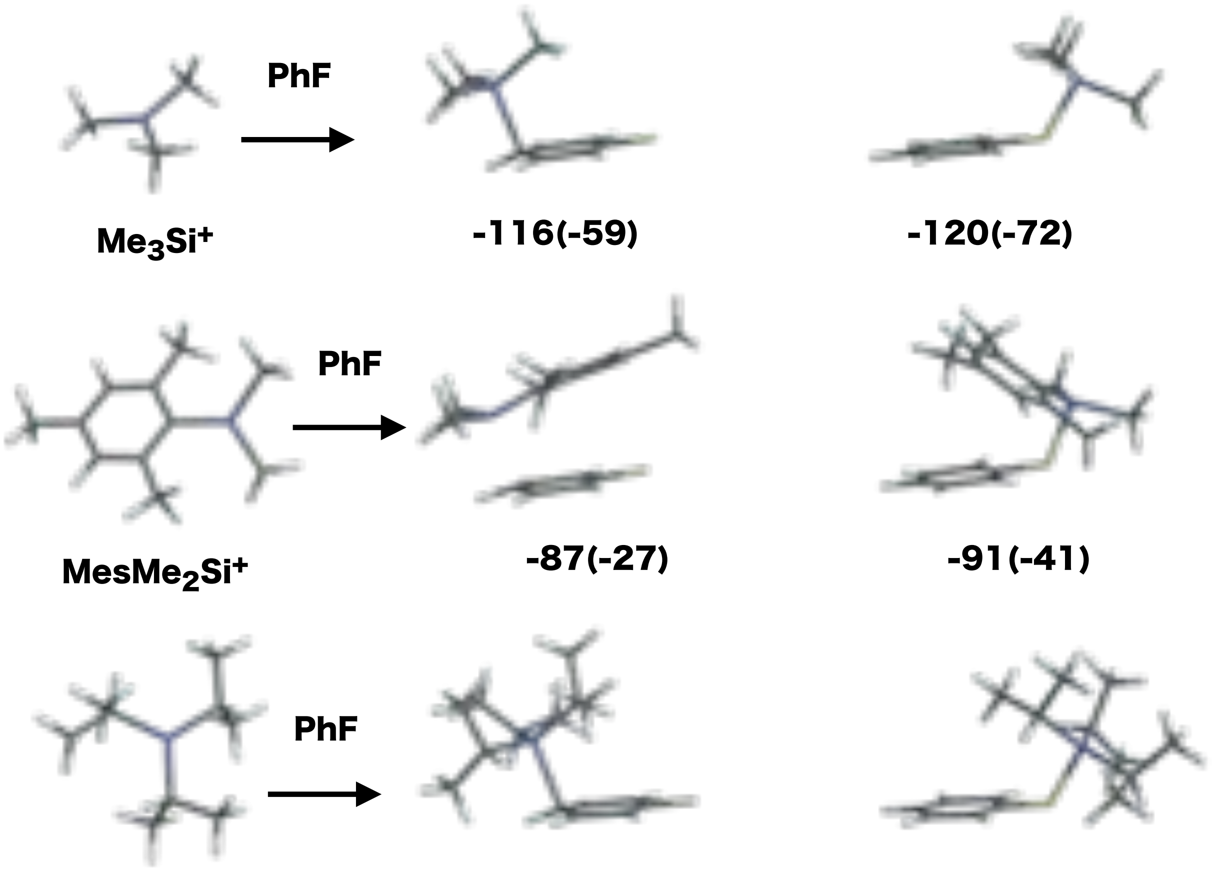
ccsd(t)/A ‘VDZ
+ MP2/A ‘VQZ
- MP2/A ‘VDZ
//MP2/def2-QZVPP
(Thermal correction with BP-86/def-TZVP)



MP2/def2-QZVPP structures

o-π-Si **m-π-Si** **p-π-Si** **F-Si**

ΔH0(ΔG0) change in adduct formation in gas phase

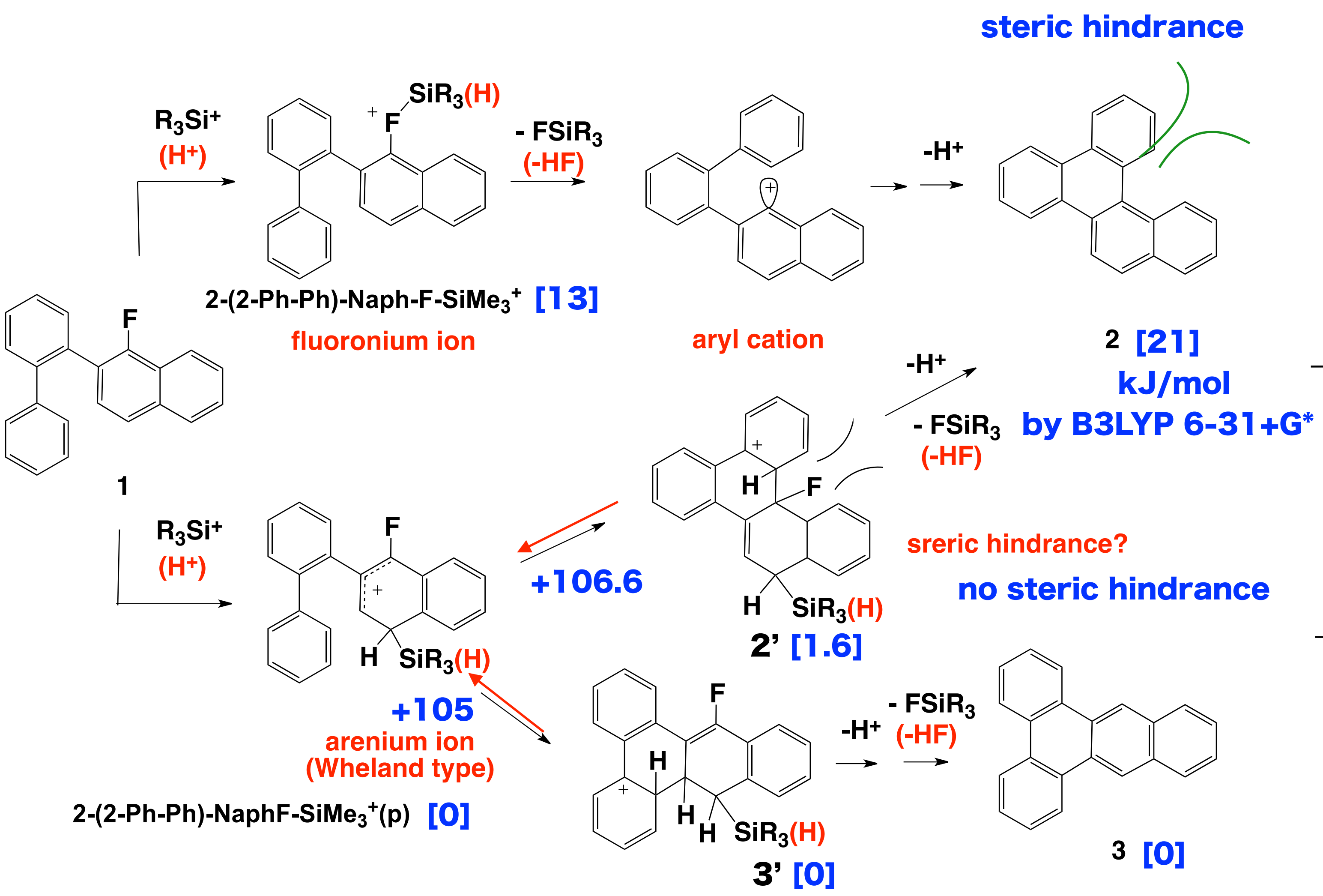


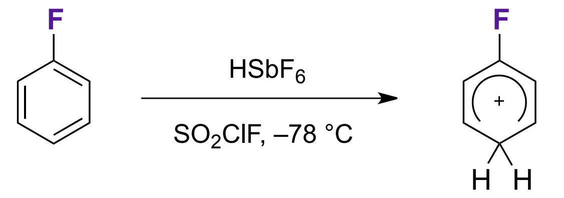
	p-π-adduct	F-adduct
Me_3Si^+	-116(-59)	-120(-72)
$MesMe_2Si^+$	-87(-27)	-91(-41)
$i\text{-}Pr_3Si^+$	-95(-39)	-109(-61)

kJ/mol by CCSD(T)/A’VDZ plus MP2/A'VQZ

Proposed mechanism-2

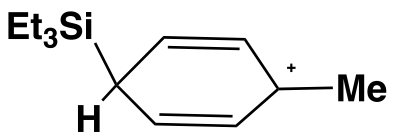
Mechanism for intramolecular cyclization of fluoronaphtaharene derivatives promoted by sily cation and protic acid.





Fluoroarenium Ion

Olah, G. A. et al. *J. Org. Chem.* **1973**, *38*, 3212.



$(C_6F_5)_4B^-$

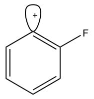
VS

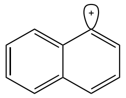
$[Mes_3Si]^+\ [CB_{11}Cl_6Me_6]^-$

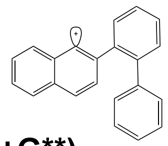
C. A. Reed, J. B. Lambert et al., Science 2002, 297, 825.

Relative stabilizing energies of some carbocations and trimethylsilyl cations

$$Ph^+ + Ar\text{-}F(\text{or } R\text{-}F) \xrightarrow{\Delta E} Ph\text{-}F + Ar^+(\text{or } R^+)$$



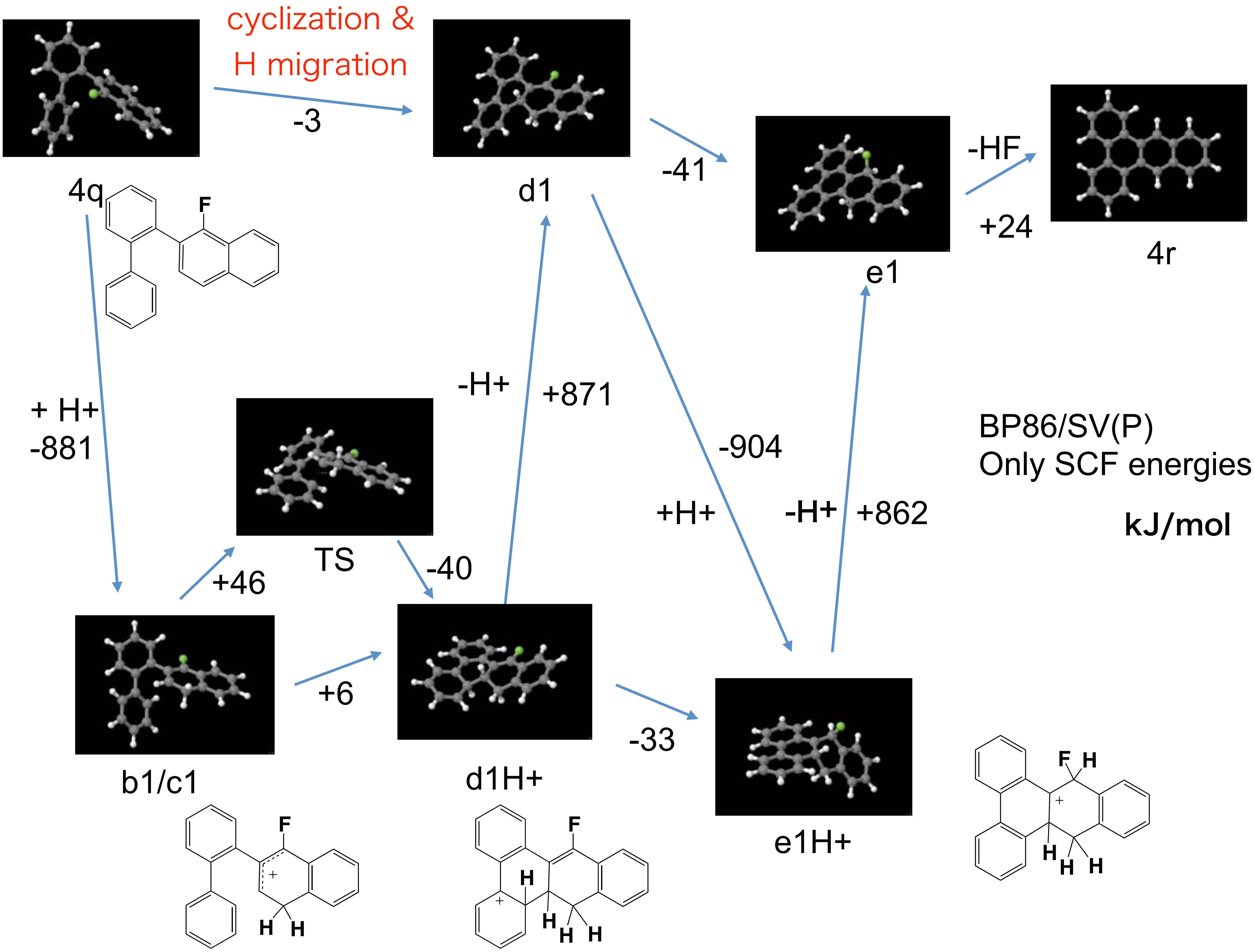




Ar^+(or R^+)	(B3LYP 6-311+G*// 6-311+G**)	ΔE(kJ/mol)
CH_3^+		-94
$2\text{-}FC_6H_4^+$		-68
Ph^+		0
CH_2Cl^+		15
$1\text{-}NaPh^+(1\text{-}C_{10}H_7^+)$		34
2-(2-Ph-Ph)-Naph$^+$	(B3LYP 6-311+G*// 6-31+G**)	81
Me_3Si^+		82

Relative stabilizing energies of adducts with proton and trimethylsilyl cations

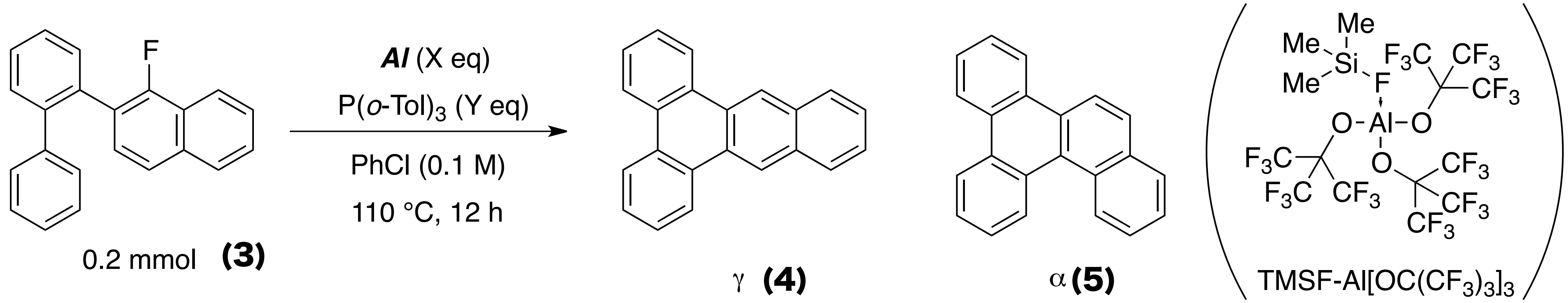
adducts	(B3LYP 6-311+G*// 6-311+G**)	ΔE(kJ/mol)
$C_6H_5\text{-}F\text{-}H^+$		0
$C_6H_5F\text{-}H^+$(o)		145
$C_6H_5F\text{-}H^+$(m)		119
$C_6H_5F\text{-}H^+$(p)		154
$C_6H_5\text{-}F\text{-}SiMe_3^+$		0
$C_6H_5F\text{-}SiMe_3^+$(o)		-9
$C_6H_5F\text{-}SiMe_3^+$(m)		-18
$C_6H_5F\text{-}SiMe_3^+$(p)		-5
$C_6H_5\text{-}Cl\text{-}SiMe_3^+$		0
$C_6H_5Cl\text{-}SiMe_3^+$(o)		-5
2-(2-Ph-Ph)-Naph-F-SiMe$_3^+$	(B3LYP 6-31+G*// 6-31+G*)	0
2-(2-Ph-Ph)-NaphF-SiMe$_3^+$(p)		13



BP86/SV(P)
Only SCF energies

kJ/mol

Experimental results-2



entry	***Al*** (X eq)	P(*o*-Tol)$_3$ (Y eq)	γ (%)	α (%)	recov. (%)
1	TMSF-Al[OC(CF$_3$)$_3$]$_3$ (1.2 eq)	1.6	trace	0	86
2	TMSF-Al[OC(CF$_3$)$_3$]$_3$ (0.1 eq)	1.6	0	0	80
3	TMSF-Al[OC(CF$_3$)$_3$]$_3$ (1.2 eq)	none	92	trace	0
4	AlCl$_3$ (1.2 eq)	1.6	trace	0	84
5[a]	AlCl$_3$ (1.5 eq)	none	99	trace	0

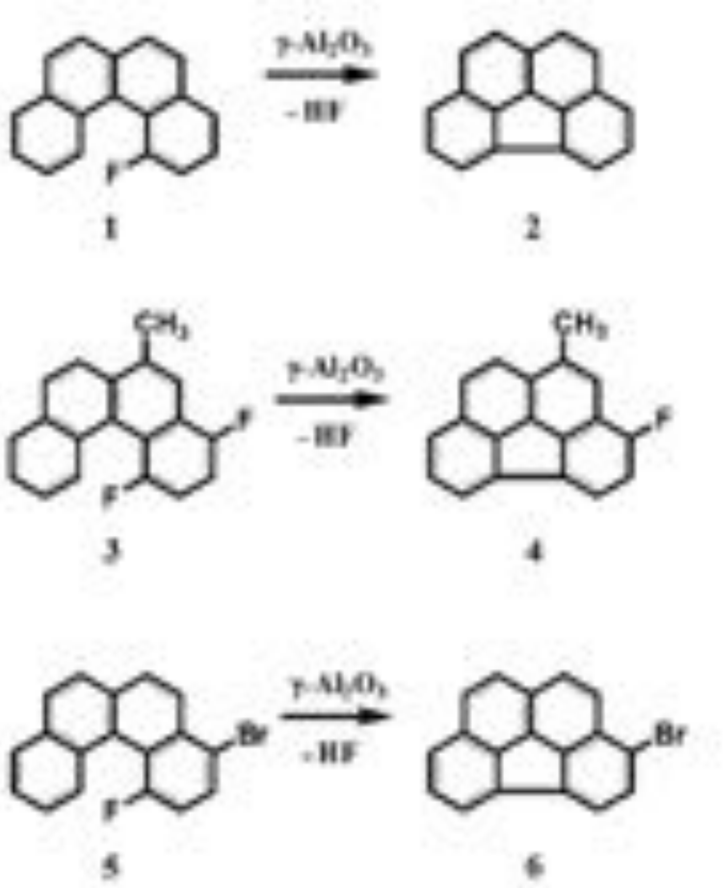
^{1}H NMR yield.
a: 60 °C, 3 h.

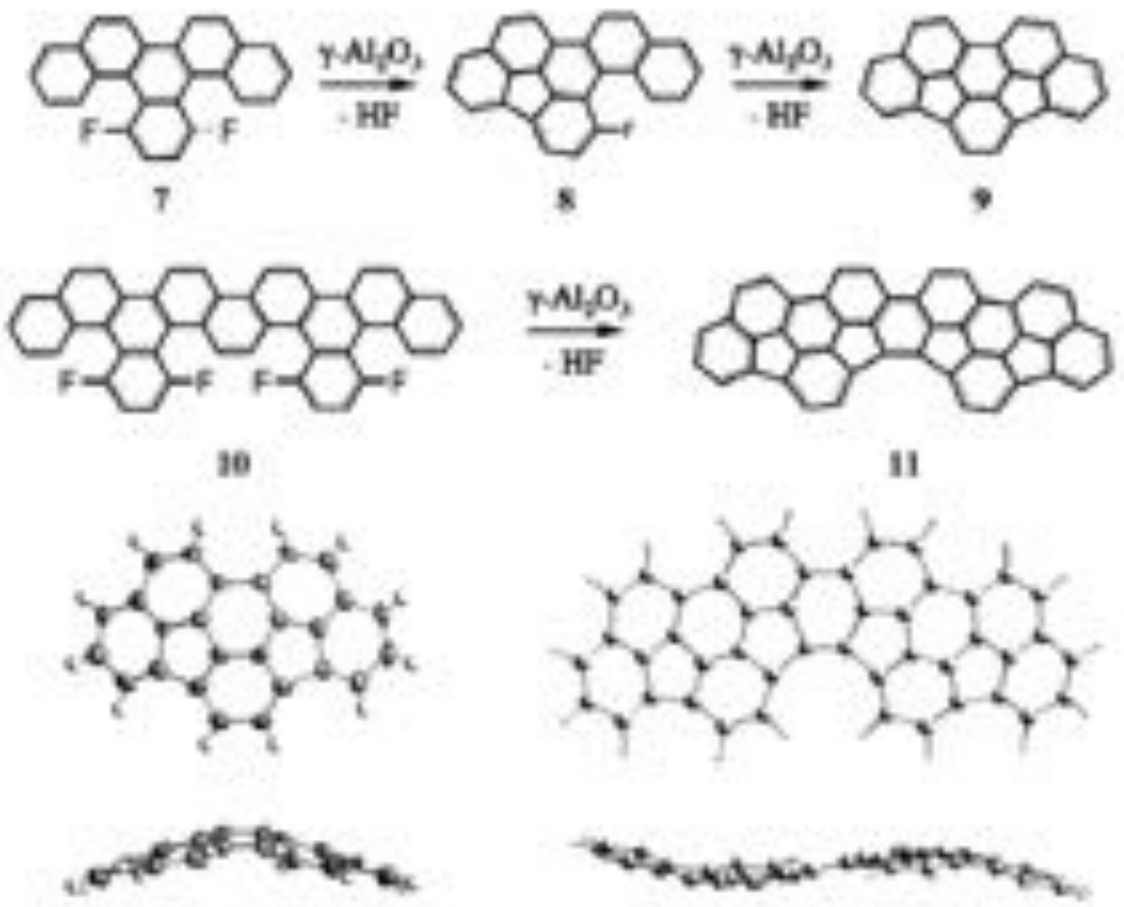
Cf. Experimental result by N. Suzuki, J. Ichikawa, and K. Yu. Amsharov

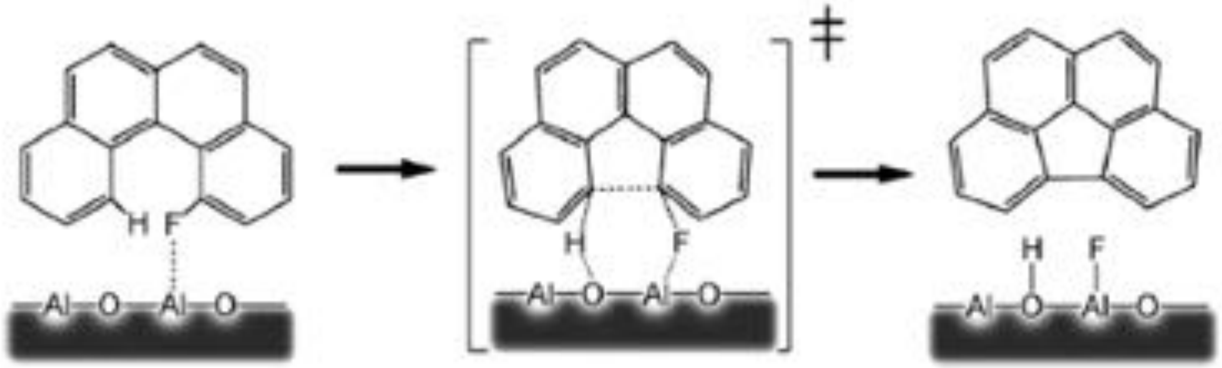
N. Suzuki et al., Chem Comm, 2016,

Facile Bucky-Bowl Synthesis by Regiospecific Cove-Region Closure by HF Elimination

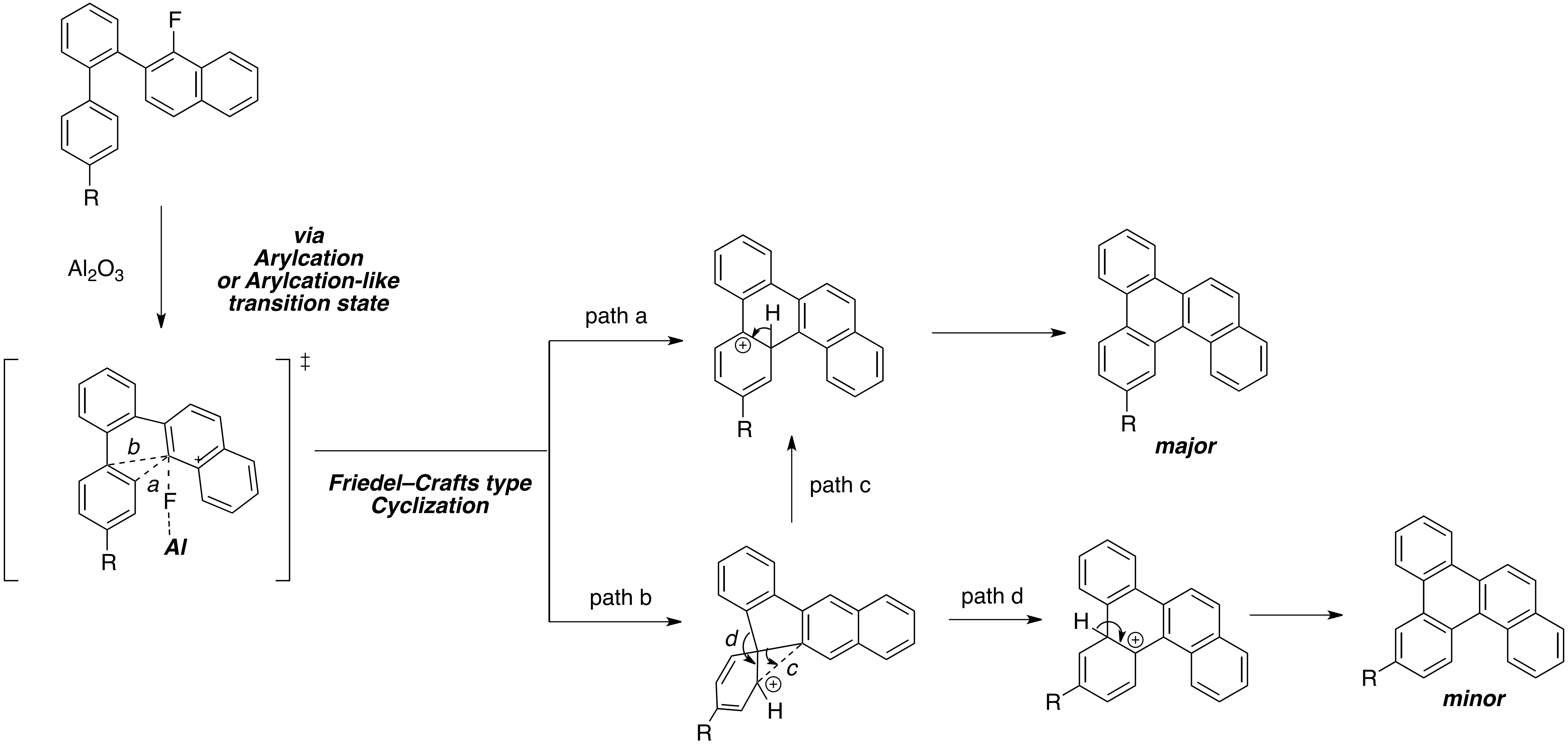
K. Yu. Amsharov, M. A. Kabdulov, Martin Jansen, Angew. Chem. Int. Ed. 2012, 51, 4594 –4597







Proposed mechanism-3



Al_2O_3

via Arylcation or Arylcation-like transition state

Friedel–Crafts type Cyclization

path a

path b

path c

path d

major

minor

‡

２０１７年度　有機合成化学特論レポートについて

今回４日間の市川・園田の講義で紹介した内容（有機合成反応におけるフッ素効果、フロンティア軌道論、弱配位性アニオン種、有機反応機構論、工業化学的応用）に関連して、各自の研究テーマとの可能なつながりについて考えたことをA4１枚程度にまとめること。

講義欠席１回につきフッ素化学に関する論文を１報づつ読んで、その概要をA4１枚程度にまとめ、自分のコメントをつけること。

提出締切：７月３１日
提出先：化学事務室前のレポートボックス

担当：市川淳士