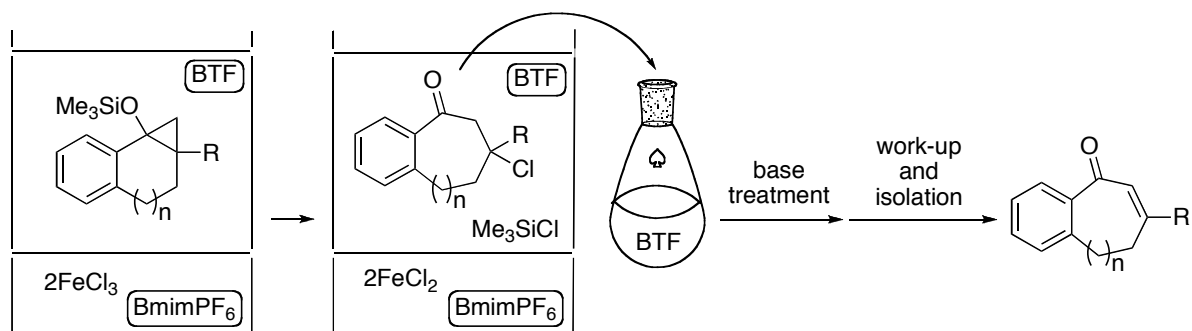


## Graphical Abstract

**Novel biphasic reaction system of ferric chloride dissolved imidazolium hexafluorophosphate and benzotrifluoride: application to electron transfer reaction of cyclopropyl silyl ethers**

Hiroyuki Tsuchida, Eietsu Hasegawa\*



**Novel biphasic reaction system of ferric chloride dissolved  
imidazolium hexafluorophosphate and benzotrifluoride:  
application to electron transfer reaction of cyclopropyl silyl ethers**

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**Abstract**

Ferric chloride ( $\text{FeCl}_3$ ) promoted electron transfer oxidation of bicyclic cyclopropyl silyl ethers was performed in biphasic solution system of 1-butyl-3-methylimidazolium hexafluorophosphate ( $\text{BmimPF}_6$ ) and benzotrifluoride (BTF). The resulting chloro-substituted ring-expanded cycloalkanones were treated with an appropriate base to produce substituted cyclic enones. These two-step reactions were successfully devised to proceed in a simpler manner in which the ordinary work-up operations for the former oxidation step, such as water-quench, extraction, and evaporation, were omitted; imidazole was found to be the most suitable base for the latter elimination step.

**1. Introduction**

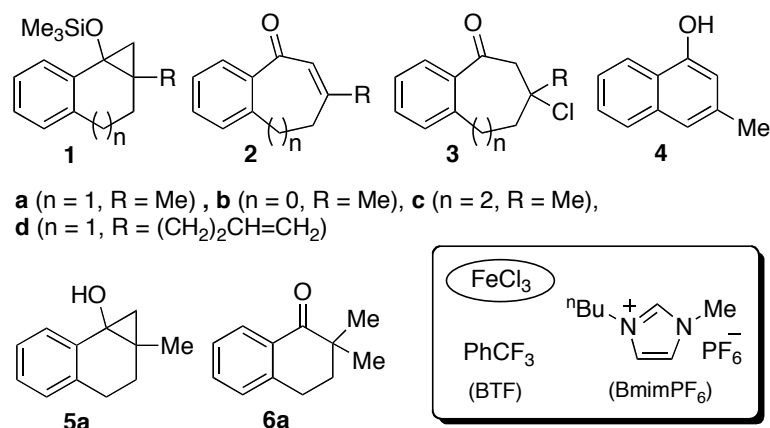
Development of practically convenient as well as environmentally benign procedures to promote the transformation of organic molecules should be appreciated not only for organic synthesis but also for green sustainable chemistry.<sup>1</sup> Among the efforts to achieve this

objective is the use of environmentally benign reagents and solvents. Iron salts are recognized as one of the least expensive and toxic reagents, and thus the use of iron salt reagents is beneficial.<sup>2</sup> Some imidazolium salts, known as room temperature ionic liquids and environmentally benign solvents, have been frequently used for organic synthesis.<sup>3</sup> As suggested by Ogawa and Curran, benzotrifluoride (PhCF<sub>3</sub>, BTF) is also known to be an environmentally benign solvent, and thus BTF could replace benzene and methylene chloride in several cases.<sup>4</sup> On the other hand, a procedure to promote the sequential chemical processes with less experimental operations is also compatible with green sustainable chemistry. For example, one-pot reaction that promotes sequential processes in a single flask is one of the representative examples.<sup>5</sup>

Electron transfer (ET) is a fundamental chemical process that is operating in chemical as well as biological reduction and oxidation reactions, and various ET based synthetic procedures have been developed.<sup>6,7</sup> Several years ago, we planned to develop synthetically useful procedures that could promote the desired ET reactions in a green sustainable manner, and have reported several successful examples.<sup>8</sup> In the course of these efforts, we encountered an intriguing observation in which addition of 1-butyl-3-methylimidazolium hexafluorophosphate (BmimPF<sub>6</sub>) to ferric chloride (FeCl<sub>3</sub>) in BTF significantly accelerated the ring-expansion reaction of a bicyclic cyclopropyl silyl ether.<sup>8c</sup> Upon addition of BmimPF<sub>6</sub>, solid FeCl<sub>3</sub> dissolved in this ionic liquid and the reaction proceeded under the liquid-liquid biphasic condition.

In this paper, we would like to report the characteristic feature of this novel biphasic reaction system of FeCl<sub>3</sub> dissolved in BmimPF<sub>6</sub>, which could be recognized as FeCl<sub>3</sub>-BmimPF<sub>6</sub> hybrid reagent, and BTF to promote electron transfer reaction of the title

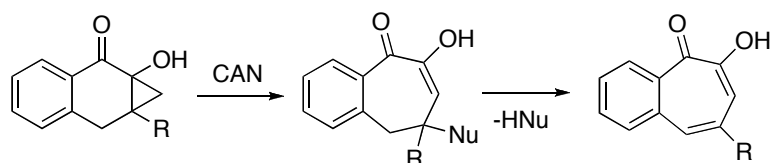
substrates. Substrates and products together with representative reagents and solvents investigated are shown in Chart 1.



**Chart 1.**

## 2. Results and Discussion

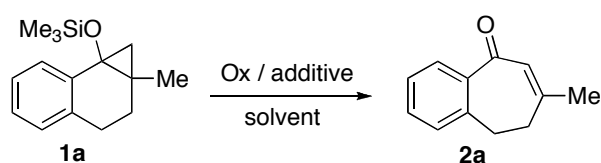
In our earlier effort, we have found that ceric ammonium nitrate,  $\text{Ce}(\text{NH}_4)_2(\text{NO}_3)_6$  (CAN), was effective for oxidative ring-opening reaction of certain bicyclic cyclopropanol derivatives as shown below.<sup>9</sup>



Thus, silyl ether **1a** was subjected to the reaction with CAN in  $\text{CH}_3\text{CN}$ , and desired ring-expanded enone **2a** was obtained in moderate yield as shown in Table 1 (entry 1).<sup>8e</sup> Then, we replaced  $\text{CH}_3\text{CN}$  by BTF, and found the reaction did not go to completion, and only a trace amount of **2a** was formed; deprotected cyclopropanol **5a** was the major isolable product (entry 2).  $\text{FeCl}_3$  with pyridine in DMF was also effective to obtain **2a** in good yield after the treatment of  $\beta$ -chlorobenzosuberone **3a** with a methanolic NaOAc solution at reflux (entry

3).<sup>8e</sup> We were rather surprised to find that toluene could be used for the reaction giving **2a** in moderate yield although FeCl<sub>3</sub> appears to be insoluble in toluene (entry 4). On the other hand, BTF was not as effective as above two solvents (entry 5).<sup>8c</sup> However, addition of BmimPF<sub>6</sub> to this reaction mixture completely consumed **1a** and gave **2a** in the comparable yield to the reaction conducted in DMF (entries 3 and 6).<sup>8c,e</sup>

**Table 1.** Reaction of **1a** with oxidizing reagents (Ox)<sup>a</sup>



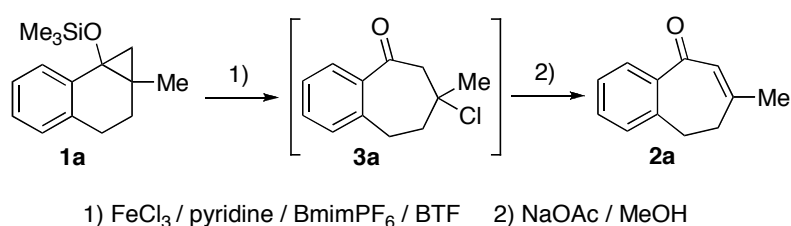
entry	Ox	additive (equiv vs <b>1a</b> )	solvent	recovery of <b>1a</b> (%)	yield of <b>2a</b> (%)
1	CAN <sup>c</sup>	none	CH <sub>3</sub> CN	0	53
2	CAN <sup>c</sup>	none	BTF	50	Trace <sup>d</sup>
3 <sup>b</sup>	FeCl <sub>3</sub>	pyridine (1.0)	DMF	0	72
4 <sup>b</sup>	FeCl <sub>3</sub>	pyridine (1.0)	PhCH <sub>3</sub>	0	59
5 <sup>b</sup>	FeCl <sub>3</sub>	pyridine (1.0)	BTF	67	15
6 <sup>b</sup>	FeCl <sub>3</sub>	pyridine (1.0) BmimPF <sub>6</sub> (2.2)	BTF	0	68 <sup>e</sup>

<sup>a</sup>Substrate **1a** (0.50 mmol), Ox (2.2 equiv), solvent (5.0-10.0 mL), at room temperature for 1 h. <sup>b</sup>Crude product mixture was heated with NaOAc (5.0 equiv) in MeOH (2.0-5.0 mL) at 85 °C for 2 h. <sup>c</sup>Ce(NH<sub>4</sub>)<sub>2</sub>(NO<sub>3</sub>)<sub>6</sub>. <sup>d</sup>**5a** was obtained (22%). <sup>e</sup>**6a** was obtained (12%).

These preliminary observations prompted us to further explore the characteristics of this new reagent system of FeCl<sub>3</sub> with BmimPF<sub>6</sub> in BTF. Our working hypothesis for the observation was that the liquid-liquid biphasic system of FeCl<sub>3</sub> dissolved in BmimPF<sub>6</sub> and BTF might provide better condition for an effective contact between **1a** and Fe(III) ion

compared to the solid-liquid biphasic system of FeCl<sub>3</sub> and BTF. If so, the quantity of BmimPF<sub>6</sub> might influence the reaction, which was examined at first. In these experiments, instead of water-quench and Et<sub>2</sub>O extraction used for the experiments in Table 1, separation of BTF layer followed by the rinse of BmimPF<sub>6</sub> layer with Et<sub>2</sub>O was performed (see Experimental section).<sup>10</sup> The results are summarized in Table 2. In all entries, NaOAc treatment of crude **3a** afforded **2a** in various yields depending on the quantity of BmimPF<sub>6</sub> while trace amount of **6a** was also detected in certain case. Addition of some quantities of BmimPF<sub>6</sub> increased both the conversion of **1a** and the yields of **2a** (entries 1, 2, and 3), however further addition significantly decreased them (entries 4 and 5).

**Table 2.** BmimPF<sub>6</sub> quantity effect on the oxidation of **1a** with FeCl<sub>3</sub> and pyridine in BTF<sup>a</sup>



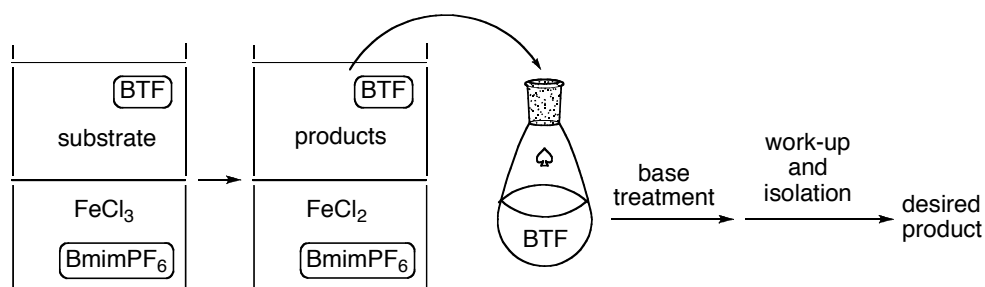
entry	BmimPF <sub>6</sub> (mL) (equiv vs <b>1a</b> )	recovery of <b>1a</b> (%)	yield of <b>2a</b> (%)
1 <sup>b</sup>	0.00 (0.0)	67	15
2	0.10 (1.0)	0	50
3	0.23 (2.2)	0	62
4	0.50 (4.8)	31	29
5	1.00 (9.6)	44	23

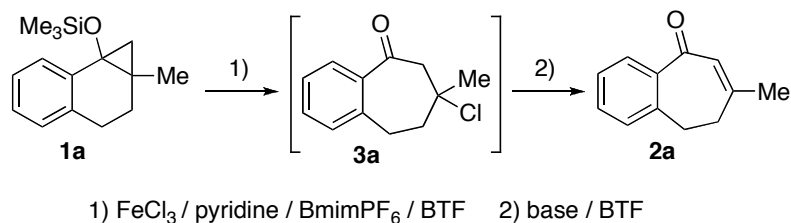
<sup>a</sup>Substrate **1a** (0.50 mmol), FeCl<sub>3</sub> (2.2 equiv), pyridine (1.0 eq), BTF (5.0 mL), at room temperature for 1 h. Crude product mixture was heated with NaOAc (5.0 equiv) in MeOH (5.0 mL) at 85 °C for 2 h. <sup>b</sup>Same as the entry 5 of Table 1.

The solubility of solid FeCl<sub>3</sub> in BTF appears to be minimal since BTF became only pale yellow upon addition of FeCl<sub>3</sub>. The oxidation reaction of **1** in BTF was indeed inefficient

without BmimPF<sub>6</sub> (entry 5 in Table 1). On the other hand, addition of BmimPF<sub>6</sub> to FeCl<sub>3</sub> resulted in the formation of liquid phase containing FeCl<sub>3</sub>. Notably, this brown colored liquid appears to be in part dissolved in BTF because BTF phase clearly colored yellow by mixing these two phases. Increasing the quantity of BmimPF<sub>6</sub> decreased the concentration of FeCl<sub>3</sub>, and therefore the reaction was gradually decelerated by adding more quantity of BmimPF<sub>6</sub> (entries 4 and 5 in Table 2).

We next attempted to devise the simpler experimental operations, which is illustrated in Figure 1. If upper BTF layer of the reaction mixture is transferred to another flask and subsequently treated with appropriate base, requisite two-step transformations could be achieved in simpler manner. For this purpose, we needed to search for the base compatible with BTF. As shown in Table 3, NaOAc which is insoluble in BTF was not efficient (entry 1). Thus, we examined BTF soluble amine bases. While pyridine was not effective at all (entry 2), more basic Et<sub>3</sub>N promoted the reaction (entry 5). Raising the reaction temperature and extending the reaction time increased the yield of **2a** (entry 6). Notably, imidazole was effective to give **2a** in the best yields (entries 3 and 4). On the other hand, an attempt to optimize the reaction conditions using strong base 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) was less successful (entries 7 and 8). Consequently, imidazole was chosen for the further experiments.



**Figure 1.**

entry	base	pK <sub>a</sub> (conjugate acid)	temp (°C)	time (h)	yield of <b>2a</b> (%)
1	NaOAc	4.75 <sup>c</sup>	85	2	35
2	pyridine	5.2 <sup>c</sup>	85	2	0 <sup>b</sup>
3	imidazole	6.95 <sup>d</sup>	85	21	61
4	imidazole	6.95 <sup>d</sup>	120	21	57
5	Et <sub>3</sub> N	10.65 <sup>e</sup>	85	2	41 <sup>b</sup>
6	Et <sub>3</sub> N	10.65 <sup>e</sup>	120	21	56
7	DBU	14.3 <sup>f</sup>	85	2	22
8	DBU	14.3 <sup>f</sup>	r. temp	2	0 <sup>b</sup>

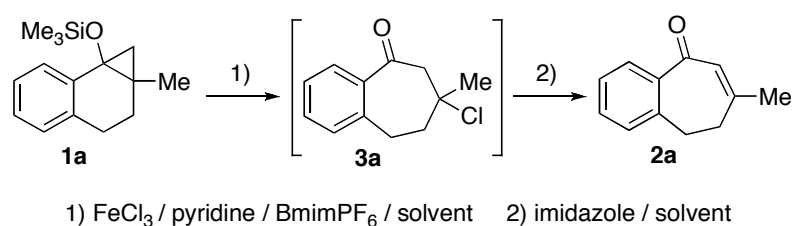
<sup>a</sup>Substrate **1a** (0.50 mmol), FeCl<sub>3</sub> (2.2 equiv), pyridine (1.0 equiv), BmimPF<sub>6</sub> (2.2 equiv), BTF (5.0 mL), at room temperature for 1 h. BTF layer containing crude product mixture was treated with base (5.0 equiv) after additional BTF (2.0 mL) was combined. <sup>b</sup>Unreacted **3a** was detected by <sup>1</sup>H NMR. <sup>c</sup>Bordwell, F. G. *Acc. Chem. Res.* **1988**, *21*, 456-463. <sup>d</sup>Hall, H. K, Jr. *J. Am. Chem. Soc.* **1957**, *79*, 5441-5444. <sup>e</sup>Bruice, T. C.; Schmir, G. L. *J. Am. Chem. Soc.* **1958**, *80*, 148-156. <sup>f</sup>Leffek, K. T.; Pruszynski, P.; Thanapaalasingham, K. *Can. J. Chem.* **1989**, *67*, 590-595.

In order to determine the utility of BTF, screening of other solvents was also performed. We chose toluene and cyclohexane, which dissolve compounds such as **1a**, **2a** and **3a**, and are insoluble in BmimPF<sub>6</sub>. As shown in Table 4, less quantity of BTF (1.0 mL) did not significantly change the yield of **2a** (compare entry 2 to 1). However, the reaction in neat



ionic liquid without BTF, resulted in no formation of **2a** (entry 3). Then, BTF was replaced with toluene and cyclohexane. Mixing each solvent with BmimPF<sub>6</sub> resulted in the formation of biphasic solutions. When the reaction of **1a** was conducted under the formed biphasic conditions, the yields of **2a** were quite low in both cases (entries 4 and 5).<sup>11</sup> These observations clearly suggest that the use of proper quantity of BTF is essential and BTF is certainly superior to toluene and cyclohexane for the FeCl<sub>3</sub> promoted biphasic reaction with BmimPF<sub>6</sub>.

**Table 4.** Solvent effect on the oxidation of **1a** and the subsequent elimination of **3a**<sup>a</sup>



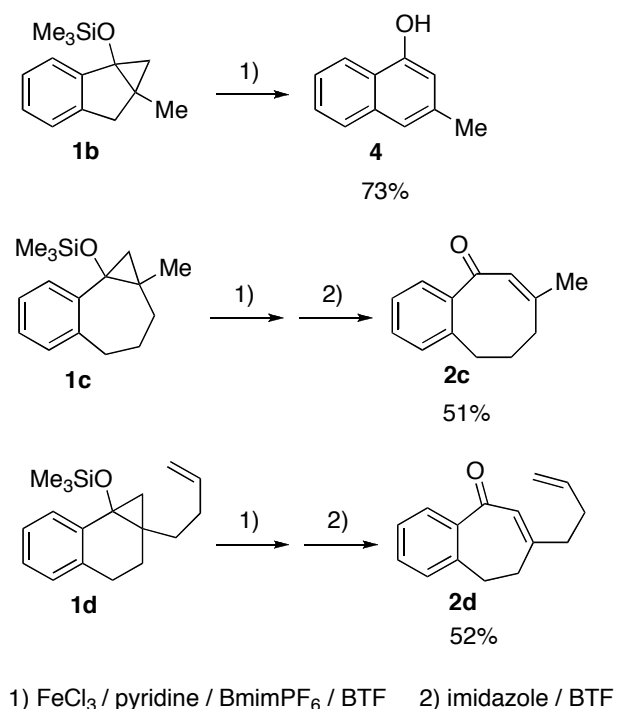
entry	solvent (mL)	yield of <b>2a</b> (%)
1 <sup>b</sup>	BTF (5.0)	61
2	BTF (1.0)	60
3	no <sup>c</sup>	0 <sup>d</sup>
4	PhCH <sub>3</sub> (5.0)	14
5	<i>c</i> -C <sub>6</sub> H <sub>12</sub> (5.0)	trace

<sup>a</sup>Substrate **1a** (0.50 mmol), FeCl<sub>3</sub> (2.2 equiv), pyridine (1.0 equiv), BmimPF<sub>6</sub> (2.2 equiv), at room temperature for 1 h. Organic layer containing crude product mixture was heated at 85 °C with imidazole (5.0 equiv) for 18-21 h after addition of same solvent (2.0 mL). <sup>b</sup>Same as the entry 3 of Table 3. <sup>c</sup>BTF (2.0 mL) was used for the reaction with imidazole. <sup>d</sup>**5a** was obtained (7%).

We also examined the following experiments to further devise the reaction procedure.<sup>12</sup> First, the elimination reaction of **3a** with imidazole was conducted in biphasic solutions

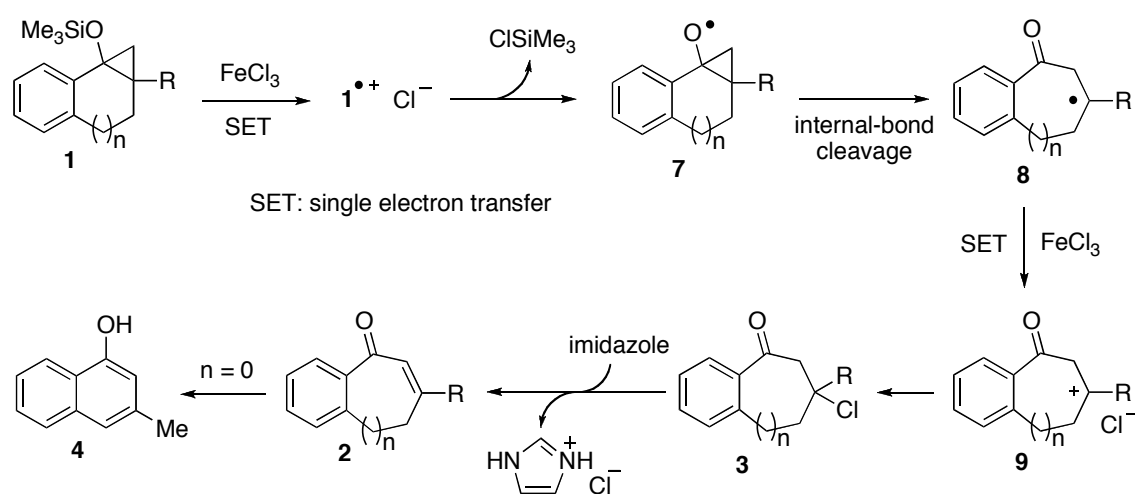
without a prior separation of a BTF layer from a BmimPF<sub>6</sub> layer. However, this one-pot procedure resulted in the less formation of **2a** (34%) than that for the above described two-step procedure (see entry 3 in Table 3). Secondly, we attempted to reuse the recovered BmimPF<sub>6</sub> layer from the biphasic solutions after the reaction of **1a**, and found that **3a** was indeed obtained, however, its yield was low (33%).

As described above, the new procedure in which FeCl<sub>3</sub> promoted oxidation in the biphasic solvent system of BmimPF<sub>6</sub> and BTF followed by imidazole treatment in BTF was found to be effective for the transformation of **1a** to **2a**. Then, this procedure was applied to other substrates such as **1b**, **1c**, and **1d** (Scheme 1). In the reactions of **1c** and **1d**, the corresponding ring-expanded enones **2c** and **2d** were obtained in moderate yields. On the other hand, the imidazole treatment was not necessary for the reaction of **1b** to obtain naphthol **4** in good yield.



**Scheme 1.**

On the basis of the related investigations,<sup>8a,c,e,f,13</sup> plausible reaction pathways are shown in Scheme 2. Single electron transfer (SET) from the substrate **1** to FeCl<sub>3</sub> to give the pair of radical cation of **1** and chloride ion. Desilylation within the formed ion pair follows. Cyclopropoxy radical **7**, that is a hypothetical intermediate,<sup>14</sup> undergoes regioselective ring-opening to produce tertiary alkyl radical **8** that is subsequently oxidized by another equivalent of FeCl<sub>3</sub> to give thermodynamically stable tertiary carbocation **9**. Addition of the simultaneously generated chloride ion to **9** gives the chlorine adduct **3**. Heating **3** with imidazole leads the elimination of HCl giving enones **2**. In the case of **1b**, aromatization of the expected enone **2b** spontaneously occurred without imidazole to give naphthol **4**.



**Scheme 2.**

### 3. Conclusion

We have developed a novel liquid-liquid biphasic reaction system utilizing a combination of FeCl<sub>3</sub> and BmimPF<sub>6</sub> in BTF, which could promote electron transfer reaction

of bicyclic cyclopropyl silyl ethers to give chloro-substituted ring-expanded cycloalkanones. Following treatment of these compounds with an appropriate base finally produced substituted cyclic enones. Also noteworthy is that these two-step reactions were successfully performed in BTF which allowed us to skip the ordinary work-up operations for the former oxidation step, such as water- quench, extraction, and evaporation, and find imidazole as the best suitable base for the latter elimination step. FeCl<sub>3</sub> is among the most convenient and least expensive iron reagents, and can be used not only as oxidizing reagent<sup>15</sup> but also as Lewis acid.<sup>2,16</sup> Therefore, our newly developed procedure must be also applicable to other reactions in which both FeCl<sub>3</sub> and imidazolium salts are used.<sup>17</sup> Currently, related investigation is undergoing in our group.

## 4. Experimental section

### 4.1 General

NMR spectra were recorded in CDCl<sub>3</sub> with Me<sub>4</sub>Si as an internal standard at 200 MHz and 270 MHz for <sup>1</sup>H-NMR, and 50 MHz and 68 MHz for <sup>13</sup>C-NMR. Column chromatography was performed with silica gel (Wakogel C-200). Preparative TLC was performed on 20 cm x 20 cm plates coated with silica gel (Wakogel B-5F). FeCl<sub>3</sub> and Ce(NH<sub>4</sub>)<sub>2</sub>(NO<sub>3</sub>)<sub>6</sub> were purchased and used for the reactions. BTF, anhydrous DMF and BmimPF<sub>6</sub> were purchased and used without distillation. MeCN was distilled over P<sub>2</sub>O<sub>5</sub> and subsequently distilled with K<sub>2</sub>CO<sub>3</sub>. Substrates **1a-d**<sup>8c,13</sup> were synthesized according to literature procedures. Substrates and products (**2a**,<sup>13</sup> **2c**,<sup>13</sup> **2d**,<sup>13</sup> **3a**,<sup>13</sup> **4**,<sup>8c</sup> **5a**,<sup>8f</sup> and **6a**<sup>13</sup>) are known compounds.

## 4.2 Reaction with oxidizing reagents.

### 4.2.1. $FeCl_3$ or $Ce(NH_4)_2(NO_3)_6$ promoted reaction of **1a** in DMF or MeCN.

$FeCl_3$  promoted reaction of **1a** in DMF was previously reported.<sup>8e</sup> An MeCN solution (6 mL) of **1a** (123.2 mg, 0.50 mmol) was added to  $Ce(NH_4)_2(NO_3)_6$  (603.0 mg, 1.10 mmol) in MeCN (4 mL) under  $N_2$ . The resulting mixture was stirred under  $N_2$  at room temp for 1 h. Then, it was extracted with  $Et_2O$  (30 mL x 3) after addition of water. The extract was treated with water, sat. aqueous  $Na_2S_2O_3$ , sat. aqueous  $NaHCO_3$ , sat. aqueous  $NaCl$ , and dried over anhydrous  $MgSO_4$ . The residue obtained after concentration was subjected to TLC ( $CH_2Cl_2/n-C_6H_{14} = 1/1$ , three times) to give **2a** (45.6 mg, 0.265 mmol, 53%).

### 4.2.2. $FeCl_3$ promoted reaction of **1a** in the presence or absence of $BmimPF_6$ in BTF

A BTF solution (3 mL) of **1a** (123.2 mg, 0.50 mmol) was added to  $FeCl_3$  (178.4 mg, 1.10 mmol) and pyridine (0.040 mL, 0.50 mmol) in the presence or absence of  $BmimPF_6$  (0.23 mL, 1.10 mmol) in BTF (2 mL) under  $N_2$ . The resulting mixture was stirred under  $N_2$  at room temp for 1 h. Then, it was extracted with  $Et_2O$  (30 mL x 3) after addition of water. The extract was treated with water, sat. aqueous  $Na_2S_2O_3$ , sat. aqueous  $NaHCO_3$ , sat. aqueous  $NaCl$ , and dried over anhydrous  $MgSO_4$ . The residue obtained after concentration was subjected to TLC ( $CH_2Cl_2/n-C_6H_{14} = 1/1$ ) to give **3a**. In the absence of  $BmimPF_6$ , 82.7 mg of **1a** (0.34 mmol, 67 %) was also recovered. Then,  $NaOAc$  (5.0 equiv. vs. converted **1a**) and  $MeOH$  (2-5 ml) was added to **3a**. The mixture was refluxed at 85 °C for 2 h. After cooling, the mixture was concentrated, then water (30 ml) was added. The mixture was extracted with  $Et_2O$  (30 ml x 3). The extract was treated with water, sat. aqueous  $Na_2S_2O_3$ , sat. aqueous  $NaHCO_3$ , sat. aqueous  $NaCl$ , and dried over anhydrous  $MgSO_4$ . The residue obtained after

concentration was subjected to TLC ( $\text{CH}_2\text{Cl}_2/n\text{-C}_6\text{H}_{14} = 1/1$ ) to give **2a**, 12.7 mg (0.074 mmol, 15 %) or 58.5 mg (0.34 mmol, 68 %) in the absence or presence of BmimPF<sub>6</sub>, respectively.

#### 4.2.3. BmimPF<sub>6</sub> quantity effect on FeCl<sub>3</sub> promoted reaction of **1a** in BTF

A BTF solution (3 mL) of **1a** (123.2 mg, 0.50 mmol) was added to FeCl<sub>3</sub> (178.4 mg, 1.10 mmol), pyridine (0.040 mL, 0.50 mmol), and BmimPF<sub>6</sub> (0.10-1.00 mL, 0.96-9.6 mmol) in BTF (2 mL) under N<sub>2</sub>. The resulting mixture was stirred under N<sub>2</sub> at room temp for 1 h. Then, a BmimPF<sub>6</sub> layer was rinsed with Et<sub>2</sub>O (2 mL) after separation from a BTF layer. The residue obtained after concentration of BTF and Et<sub>2</sub>O was subjected to TLC ( $\text{CH}_2\text{Cl}_2/n\text{-C}_6\text{H}_{14} = 1/1$ ) to give **1a** and **3a**. Then, **3a** was subjected to NaOAc treatment described above to give **2a**.

#### 4.2.4. Base effect on the elimination of **3a** derived from **1a** in BTF

A BTF solution (3 mL) of **1a** (123.2 mg, 0.50 mmol) was added to FeCl<sub>3</sub> (178.4 mg, 1.10 mmol), pyridine (0.040 mL, 0.50 mmol), and BmimPF<sub>6</sub> (0.23 mL, 1.1 mmol) in BTF (2 mL) under N<sub>2</sub>. The resulting mixture was stirred under N<sub>2</sub> at room temp for 1 h. Then, a BmimPF<sub>6</sub> layer was rinsed with BTF (2 mL) after separation from BTF layer. A base (2.5 mmol) was added to BTF solution, and the mixture was stirred at room temp ~120 °C for 2-21 h. After cooling, the mixture was filtrated and concentrated. The residue was subjected to TLC ( $\text{CH}_2\text{Cl}_2/n\text{-C}_6\text{H}_{14} = 1/1$ ) to give **2a**.

#### 4.2.5. Solvent effect on the oxidation of **1a** and the subsequent elimination of **3a**

**1a** (123.2 mg, 0.50 mmol) in solvent (0.0-3.0 mL) was added to FeCl<sub>3</sub> (178.4 mg, 1.10

mmol), pyridine (0.040 mL, 0.50 mmol), and BmimPF<sub>6</sub> (0.23 mL, 1.1 mmol) in an appropriate solvent (0.0-2.0 mL) under N<sub>2</sub>. The resulting mixture was stirred under N<sub>2</sub> at room temp for 1 h. Then, a BmimPF<sub>6</sub> layer was rinsed with same solvent (2 mL) after separation from the solvent layer. Imidazole (170.2 mg, 2.5 mmol) was added to this solution, and the mixture was heated at 85 °C for 18-21 h. After cooling, the mixture was filtrated and concentrated. The residue was subjected to TLC to give **2a**.

#### *4.2.6. General procedure of FeCl<sub>3</sub> promoted reaction of 1 and sequential elimination of 3 in BTF*

A BTF solution (3 mL) of **1a** (123.2 mg, 0.50 mmol) was added to FeCl<sub>3</sub> (178.4 mg, 1.10 mmol), pyridine (0.040 mL, 0.50 mmol), and BmimPF<sub>6</sub> (0.23 mL, 1.1 mmol) in BTF (2 mL) under N<sub>2</sub>. The resulting mixture was stirred under N<sub>2</sub> at room temp for 1 h. Then, a BmimPF<sub>6</sub> layer was rinsed with BTF (2 mL) after separation from BTF layer. Imidazole (170.2 mg, 2.5 mmol) was added to BTF solution, and the mixture was heated at 85 °C for 21 h. After cooling, the mixture was filtrated and concentrated. The residue was subjected to TLC to give **2a**. Same treatment of **1c** and **1d** gave **2c** (0.253 mmol, 51%) or **2d** (0.258 mmol, 52%), respectively. In the case of **1b**, **4** (57.6 mg, 0.364 mmol, 73%) was obtained without NaOAc treatment.

#### *4.2.7. FeCl<sub>3</sub> promoted reaction of 1a and sequential elimination of 3a in biphasic solutions without separation of a BTF layer from a BmimPF<sub>6</sub> layer*

A BTF solution (3 mL) of **1a** (123.2 mg, 0.50 mmol) was added to FeCl<sub>3</sub> (178.4 mg, 1.10 mmol), pyridine (0.040 mL, 0.50 mmol), and BmimPF<sub>6</sub> (0.23 mL, 1.1 mmol) in BTF (2

mL) under N<sub>2</sub>. The resulting mixture was stirred under N<sub>2</sub> at room temp for 1 h. Imidazole (170.2 mg, 2.5 mmol) was added, and the biphasic solution mixture was heated at 85 °C for 21 h. After cooling, the mixture was filtrated by Celite and concentrated. The residue was subjected to TLC (CH<sub>2</sub>Cl<sub>2</sub>/*n*-C<sub>6</sub>H<sub>14</sub> = 1/1, three times) to give **2a** (29.5 mg, 0.171 mmol, 34%).

#### 4.2.8. The reaction of **1a** with the recovered BmimPF<sub>6</sub> after the reaction of **1a**.

A BTF solution (5 mL) of **1a** (123.2 mg, 0.50 mmol) was added to the BmimPF<sub>6</sub> layer that was separated from the BTF layer after the reaction of **1a** with FeCl<sub>3</sub> (2.2 equiv). The resulting mixture was stirred under N<sub>2</sub> at room temp for 1 h. Then, BmimPF<sub>6</sub> layer was rinsed with BTF (2 mL) after separation from BTF layer. Imidazole (170.2 mg, 2.5 mmol) was added to BTF solution, and the mixture was heated at 85 °C for 21 h. After cooling, the mixture was filtrated and concentrated. The residue was subjected to TLC (CH<sub>2</sub>Cl<sub>2</sub>/*n*-C<sub>6</sub>H<sub>14</sub> = 1/1, twice) to give **2a** (28.2 mg, 0.164 mmol, 33%).

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10. Same experiments using toluene were conducted (comparable to entries 3, 4, and 5 in Table 2). However, the reactions were not completed (contrastive to entry 4 in Table 1). Results are as follows. The quantity of BmimPF<sub>6</sub> (equiv) : 2.2, 4.8, 9.6; the recovery of **1a** (%) : 68, 39, 52; the yield of **2a** (%): 16, 26, 23, respectively.
11. The difference of the yield of **2a** between the result reported in the footnote 10 and that of entry 4 in Table 4 could be due to the difference of the solvent to rinse BmimPF<sub>6</sub> phase.

While Et<sub>2</sub>O was used in the former experiment, toluene was used in the latter. These observations also suggest that toluene would not be an effective extraction solvent toward BmimPF<sub>6</sub>.

12. Although these devised procedures, that are more compatible with green chemistry, do not reach the satisfactory level at this moment, the improvement of them would be certainly the future subject to investigate. We thank two reviewers who independently suggested us to conduct these experiments.
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