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Electrophilic iodine(I) compounds induced semipinacol rearrangement via C–X bond cleavage

Nobuya Tsuji\textsuperscript{a}, Yusuke Kobayashi\textsuperscript{a}, Yoshiji Takemoto\textsuperscript{a,\dagger}

Neutral electrophilic iodine(I) species proved to be efficient reagents for C–X bond cleavage of various cyclic and acyclic α-silyloxyhalides, and the induced desilylative semipinacol rearrangement provided the corresponding ketones in good yields. The reaction is operationally simple, and proceeds under mild conditions with good functional group compatibility.

Mechanistic investigations, including computational studies, were also performed.

Alkyl halides are one of the most fundamental synthetic intermediates in organic synthesis, and have been used for a variety of bond-forming reactions via halide abstraction by halophilic Lewis acids, such as Ag, Mg, Zn, and In.\textsuperscript{1–4} Recently, Huber et al. reported that a non-metallic multidentate iodoimidazolium salt could be used for C–Br bond cleavage of benzylic bromides, promoting a Ritter-type reaction (Scheme 1a).\textsuperscript{5} They reported that the reaction was driven by “halogen bond”, i.e., the interaction between an electron-deficient iodine atom and a Lewis base.\textsuperscript{6} They also achieved the same reaction using iodontriazolium\textsuperscript{7} and iodopyridinium salts\textsuperscript{8} as halogen bond donors. The same group also reported the first halogen bond donor-catalyzed nucleophilic substitution of 1-chloroisochroman using catalytic amounts of electron-deficient multidentate iodoarenes as halogen bond donors.\textsuperscript{9} Although the existence of halogen bond has been known for more than a century,\textsuperscript{10} almost all research has been conducted in the fields of supramolecular chemistry and crystal engineering.\textsuperscript{11} Only a few reactions involving halogen bond as the driving force have been reported in the field of synthetic chemistry\textsuperscript{12–15} and the two reactions described above are the only examples involving cleavage of C–X bonds.\textsuperscript{5}

These pioneering studies showed the potential use of halogen bond in synthetic chemistry, but the field is still in its infancy because of its limited scope and reactions. Although Huber’s halogen bond donor reagent unambiguously induces C–X bond cleavage with reactive benzylic bromides, the yields depend on the choice of substrate so strongly that a primary benzyl bromide did not provide any of the desired amide. We became curious as to whether this intriguing interaction could be strong enough to activate such unreactive C–X bonds as non-benzylic halides or primary halides. We envisaged that complete charge transfer from the alkyl halide to iodine(I) compounds could promote this transformation; highly electrophilic iodine(I) species could activate such C–X bonds to afford a reactive carbocation intermediate, simultaneously forming a covalent I–X bond (Scheme 1b).

Scheme 1. Reactions induced by halide abstraction

In this paper we report an electrophilic iodine(I)-promoted semipinacol rearrangement using N-iodosuccinimide (NIS) and N-iodosaccharin (NISac) as halogen bond donors.\textsuperscript{16} To the best of our knowledge, there has been no previous report showing that readily available NIS or NISac are efficient reagents for activation of the C–X bond of an alkyl halide.

We started the investigation with alkyl bromide 1a (Table 1). We first tried commercially available electron-deficient iodoarenes and perfluoroiodoalkanes, but none of these afforded the desired compound (entries 1–4).
iodoimidazolium salt 4, which has an electron-deficient iodine atom, was also examined, but no reaction was observed under these conditions (entry 5). These results indicated that there is only insufficient interaction between these electron-deficient iodine atoms and alkyl halides. We then examined various electrophilic iodine(I) compounds, including NIS,\textsuperscript{17} NISac (5),\textsuperscript{18} and Barluenga’s reagent (6), and they proved to be efficient reagents for this transformation (entries 6–8). NIS promoted the desired rearrangement to afford 2a in 72% yield. When NISac was used, 1a was consumed in only 15 min but the yield of 2a decreased slightly. With Barluenga’s reagent (6), the reaction proceeded sluggishly and the yield was lower. N-bromosuccinimide (NBS) did not provide any rearranged product (entry 9). Molecular iodine, succinimide, and tetrabutylammonium iodide (TBAI) were also examined, but none of them induced the rearrangement (entries 10–12). These control experiments suggest that neither molecular iodine nor iodide is capable of promoting this reaction, and that the electrophilic iodine(I) compounds themselves are the active species.

Table 1. Optimization of reaction conditions

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reagent</th>
<th>Solvent</th>
<th>Time (h)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>n-C8F17I</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>2</td>
<td>n-C10F21I</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>3</td>
<td>C6F5I</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>6</td>
<td>NIS</td>
<td>CH2Cl2</td>
<td>8.5\textsuperscript{c}</td>
<td>72</td>
</tr>
<tr>
<td>7</td>
<td>NISac (5)</td>
<td>CH2Cl2</td>
<td>15 min\textsuperscript{c}</td>
<td>62</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>CH2Cl2</td>
<td>48</td>
<td>58</td>
</tr>
<tr>
<td>9</td>
<td>NBS</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>10</td>
<td>I2</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>11</td>
<td>succinimide</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>12</td>
<td>TBAI</td>
<td>CH2Cl2</td>
<td>24</td>
<td>n.d.\textsuperscript{b}</td>
</tr>
<tr>
<td>13</td>
<td>NIS</td>
<td>MeCN</td>
<td>18\textsuperscript{d}</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>NIS</td>
<td>MeNO\textsubscript{2}</td>
<td>40 min\textsuperscript{c}</td>
<td>75 (69\textsuperscript{e})</td>
</tr>
<tr>
<td>15</td>
<td>NIS</td>
<td>EtNO\textsubscript{2}</td>
<td>5.5\textsuperscript{d}</td>
<td>45</td>
</tr>
</tbody>
</table>

\textsuperscript{a} NMR yields based on dimethylsulfoxide as an internal standard.

\textsuperscript{b} Not detected.

\textsuperscript{c} Reaction mixture was stirred until consumption of 1a.

\textsuperscript{d} Isolated yield.

The choice of solvent also turned out to be crucial (entries 13–15). The reaction in nitromethane gave 2a more rapidly and in a better yield than that in dichloromethane. Acetonitrile and nitroethane provided 2a but the yields were low. None of the other polar and non-polar solvents investigated afforded 2a, presumably because of their reactivity toward NIS, or the insolubility of NIS in them.

Table 2. Scope and limitations

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a</td>
<td>(86%, from 1b: R = TMS)</td>
<td>72</td>
</tr>
<tr>
<td>2f</td>
<td>(64%, from 1e: R = HO)</td>
<td>58</td>
</tr>
<tr>
<td>2g</td>
<td>(89%, from 1d: R = TMS, X = COF)</td>
<td>75</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Unless otherwise noted, R = TBS, X = Br.

\textsuperscript{b} NMR yields based on dimethylsulfoxide as an internal standard.

\textsuperscript{c} The reaction was conducted at 35 °C.

\textsuperscript{d} The reaction was performed in MeNO\textsubscript{2}/CH2Cl2 (2:1).

With the optimized conditions in hand, the reaction scope and limitations were examined (Table 2). Substrate 1b, bearing a trimethylsilyl group, afforded the desired product 2a in excellent yield, but the unprotected haloether 1c gave 2a in a lower yield. It is worth noting that C–Cl bond activation of 1d successfully provided the rearranged product 1a in 93% yield. The cyclohexanone 2e, cyclooctanone 2f, and even acyclic ketone 2g were also obtained in moderate to good yields. When substrate 1h bearing a tert-butyl group on the cyclohexane ring was employed, the reaction took place to afford 2h in a highly diastereoselective manner.\textsuperscript{19} The tetrahydropyran derivative, bearing a Lewis basic oxygen atom, also yielded the rearranged product 2i in moderate yield. Notably, various substituents on aromatic rings, including fluoride, chloride, bromide, cyanide, and methoxy carbonyl groups, were compatible with the reaction conditions, affording the corresponding ketones 2j–n in 63–85% yields.

We then thought that less reactive alkyl halides could be activated by NISac (5), which has stronger Lewis acidity than NIS, according to Table 1. As expected, 5 promoted the rearrangement of secondary bromide 1o and primary bromide 1p, albeit in moderate yields (Scheme 2). Interestingly, the rearrangement of 1o afforded 2e as a major product despite the fact that 2o would be obtained if the reaction proceeds in a
concerted manner. At this point, we assumed that our reaction proceeded via a carbocation intermediate. To verify this hypothesis, we examined the reaction using chiral substrate 1b (Scheme 3). NIS- and NISac-mediated semipinacol rearrangements of chiral 1a provided 2a in excellent yields, but the enantiomeric excess dropped to 11%. These results suggest that the iodine (I) compounds induced reaction proceeds mainly in a stepwise manner, via a benzylic carbocation intermediate.

Additionally, we detected MS signals of IBr₂ unable to send this reaction to completion, even after 24 h. This result is discounted because a catalytic amount of NIS or NISac was found in the reaction mixture (Scheme 3). NBS > I₂. Iodoimidazolium triflate did not promote the reaction significantly even after 24 h, and IBr₂ was the most reactive halogen among the tested ones in the reaction mixture.

When the reaction was performed under visible light the reproducibility was poor; this result is supported by the idea that the main reaction process does not proceed via a carbocation intermediate, via a benzylic carbocation intermediate.

A plausible reaction mechanism is shown in Scheme 4. First, the interaction between the alkyl halide and halophilic Lewis acid activates of the C–X bond (I). Subsequent release of iodine halide and silylated counter anion affords carbocation II, which can undergo 1,2-alkyl migration to provide oxonium cation III. Further, desilylation of III yields the rearranged product 2.

Several experiments were conducted to gain further insights into the reaction mechanism. When the reaction was performed under visible light the reproducibility was poor; this result supports the idea that the main reaction process does not involve an iodine radical. The radical mechanism can also be discounted because a catalytic amount of NIS or NISac was unable to send this reaction to completion, even after 24 h. Additionally, we detected MS signals of IBr₂ (286.7) and I₂Br⁻ (334.7) from the crude reaction mixture of 1a; these were not detected in iodine bromide solutions in dichloromethane.

Finally, to evaluate Lewis acidity of NIS and NISac, the maximum electrostatic potential (ESP) energy surface was calculated and compared with those of several organoiodine compounds, since the values ($V_{S_{\text{max}}}$) are reported to have relationship with the Lewis acidity of the electron-deficient organoiodine compounds (termed as $\sigma$-hole). As expected, the results correlated closely with the experimental data, as shown in Table 1; the order of the maximum values was NISac > iodomiazidazolium triflate > NIS > IBr > n-C₆F₁₇I > C₆F₅I, NBS > I₂. Iodomiazidazolium triflate did not promote the rearrangement of 1, despite its relatively high value, suggesting that complete charge transfer from the bromine atom of 1 to the iodine atom on reagents such as NIS and NISac is vital for the rearrangement of 1; this step would be the driving force of the reaction.

In conclusion, we developed a novel NIS- and NISac-induced desilyative semipinacol rearrangement of various halohydrin silyl ethers. Not only reactive benzyl bromides, but also less reactive benzyl chlorides, non-benzylic secondary bromides, and even primary bromides afforded the rearranged product. The experimental results suggest that the reaction proceeds predominantly via a carbocation intermediate through XB-mediated C–X bond activation. Computational studies indicated that N–I bond cleavage of NIS and NISac should facilitate the X–I covalent bond formation, promoting the subsequent rearrangement. Our results open a new door to electrophilic iodine(I) species promoted and catalyzed reactions through C–X bond activation.

Acknowledgement

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Notes and references

The elongation of reaction time did not induce any racemization.


Very recently, activation of glycosyl halides by XBD was reported by Huber’s group, see R. Castelli, S. Schindler, S. M. Walter, F. Kniep, H. S. Overkleeft, G. A. van der Marel, S. M. Huber and J. D. C. Codée, Chem. – Asian. J., 2014, 9, 2095.


The appearance of the reaction mixture also changes from colorless to brown as the reaction proceeds. See the Supplementary Information for details.


The diastereomic ratio was determined using $^1$H NMR. Relative configuration of $2g$ was determined by analogy with V. L. Rendina, D. C. Moebius and J. S. Kingsbury, Org. Lett., 2011, 13, 2004.

Et$_2$Zn mediated unprotected bromohydrin afforded only $2o$. See ref. 3.

The elongation of reaction time did not induce any racemization.

Because obtained $2a$ were not complete racemic compounds, still concerted pathway should be also involved in the transformation, in some degree.