Evidence for the Intracomplex Reaction in Gattermann−Koch Formylation in Superacids: Kinetic and Regioselectivity Studies

Mutsuo Tanaka,*,†,⊥ Masahiro Fujiwara,† Qiang Xu,† Yoshie Souma,† Hisanori Ando,§ and Kenneth K. Laali*,‡

Contribution from Osaka National Research Institute, AIST, 1-8-31, Midorigaoka, Ikeda, Osaka 563, Japan, Research Institute of Innovative Technology for the Earth, 9-2, Kizugawadai, Kizu-cho, Sorakugun, Kyoto 619-02, Japan, and Department of Chemistry, Kent State University, Kent, Ohio 44242

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Abstract: Kinetic and regioselectivity data are reported for the Gattermann−Koch formylation of *m*-xylene, 1-methylnaphthalene, and toluene in HF−SbF_5 and CF_3SO_3H−SbF_5 as a function of SbF_5/substrate molar ratio. The kinetic study for *m*-xylene formylation in HF−SbF_5 provided crucial evidence in favor of intracomplex reaction via a third-order rate equation, $[ArH][ArH_2^+SbF_6^-][CO]$, where the formylation electrophile HCO^+ is generated by CO protonation by the arenium ion. Dependence of regioselectivity on substrate, superacid, and SbF_5/substrate molar ratio showed that high *para* regioselectivity stems from intracomplex reaction and the observed regioselectivity reflects the ratio between the intracomplex and the conventional reactions. Comparison in regioselectivity between Gattermann−Koch formylation and Friedel−Crafts formylation with use of HCOF suggested that regioselectivity trends do not reflect the nature of the electrophile but the reaction pathway; the Friedel−Crafts formylation also appears to have intracomplex reaction character.

Introduction

The electrophilic aromatic substitution reaction is a widely used classical method to prepare various aromatic compounds. The conventional reaction, whose mechanism and selectivity have been extensively investigated by Olah et al.[1] and other groups,[1−8] is illustrated in eq 1.

$$P + A \longrightarrow E^+ \overset{ArH}{\rightleftharpoons} \underset{\pi\text{-complex}}{[ArH\bullet E^+]} \longrightarrow \underset{\sigma\text{-complex}}{[ArHE^+]} \longrightarrow ArE + H^+ \qquad (1)$$

In the conventional aromatic substitution reaction, the formation and the attack of the electrophile are separated steps. The electrophile is formed and dispersed in the reaction medium before the attack on an aromatic compound. However, Cacace et al. recently proposed an alternative route, the intracomplex reaction (eq 2) whereby the electrophilic substitution occurs within the complex formed upon addition of a σ-complex to the proelectrophile.[9]

$$ArH_2^+ + P \longrightarrow [ArH_2^+\bullet P] \rightleftharpoons \underset{\pi\text{-complex}}{[ArH\bullet E^+]} \longrightarrow \underset{\sigma\text{-complex}}{[ArHE^+]} \longrightarrow ArE + H^+ \qquad (2)$$

In eq 2, a protonated aromatic compound ArH_2^+ acts as an acid to activate the proelectrophile P to the electrophile E^+. It has been suggested that if aromatic substitution actually occurs within the complex without separation of the reagents, then the intracomplex reaction should manifest as a distinct reaction pathway with special kinetic and mechanistic features. When the electrophile escapes into the medium and reacts with the aromatic substrate at some later stage, then eq 2 is reduced to the conventional eq 1, whose only peculiarity is that the acid used to activate the proelectrophile is a protonated aromatic compound. Cacace et al. succeeded in demonstrating this concept in the gas phase by a combination of mass spectrometric and radiolytic techniques.[9]

In a scenario that combines Olah's concept with Cacace's concept, if the electrophile and the aromatic substrate formed through proton transfer between a proelectrophile and a protonated aromatic compound react extremely fast within the complex, the intracomplex reaction may influence not only the kinetic features but also the regioselectivity because the aromatic compound is protonated *para* to the substituent under acidic conditions,[10] resulting in the formation of an electrophile at the *para* position. The transition intermediate should strongly resemble a π-complex, namely, the *para*-oriented π-complex

† Osaka National Research Institute.
‡ Kent State University.
§ Research Institute of Innovative Technology for the Earth.
⊥ Postdoctoral research fellow in the Laali group (1996-1997).
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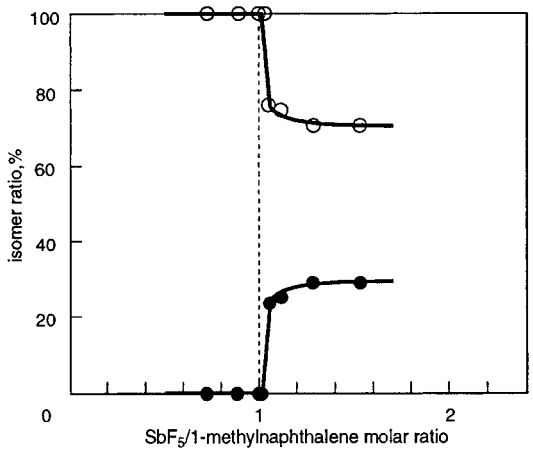
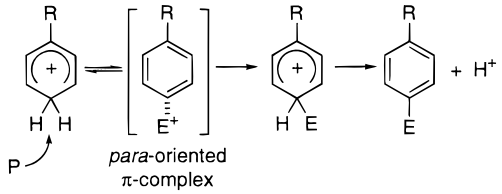


Figure 1. Isomer ratio of monoaldehyde in 1-methylnaphthalene formylation with HF−SbF_5. The formylation was carried out with HF (500 mmol) and 1-methylnaphthalene (10 mmol) at 0 °C for 2 h under 20 atm of CO pressure. The symbols ○ and ● represent 1-methyl-4- and 1-methyl-2-naphthaldehyde, respectively.

(eq 3), and high *para* regioselectivity is expected in *ortho-para* regioselective reactions.



(3)

While the high reactivity of the electrophile is necessary for the intracomplex reaction, the basicity of aromatic compounds is another significant factor for the intracomplex reaction resulting in the high *para* regioselectivity. When the intracomplex reaction is predominant, basic aromatic compounds will show higher *para* regioselectivity because the electrophile is produced closer to the aromatic compounds which is not necessarily the case in the conventional reaction.

The Gattermann−Koch formylation[11] is a typical electrophilic substitution reaction with high *para* regioselectivity.[12] In previous work,[13] it was found, however, that the regioselectivity of 1-methylnaphthalene formylation in HF−SbF_5 drastically changes at the point where the SbF_5/1-methylnaphthalene molar ratio is 1; the isomer ratio of 1-methyl-2-:1-methyl-4-naphthaldehyde is 0:1 or 3:7 depending on the SbF_5/1-methylnaphthalene molar ratio (Figure 1). Similarly, the formylation yield changed drastically at the same point, consistent with the change of the mechanism as depicted in Figure 2. Such anomalous rate and regioselectivity changes cannot be explained through a conventional substitution mechanism.

The paper reports the first example of the intracomplex reaction in the Gattermann−Koch formylation in superacids showing not only kinetic features but also a regioselectivity typical of the intracomplex reaction.

Results and Discussion

Kinetic Study of *m*-Xylene Formylation. The protonation equilibrium of aromatic compounds by superacids influences

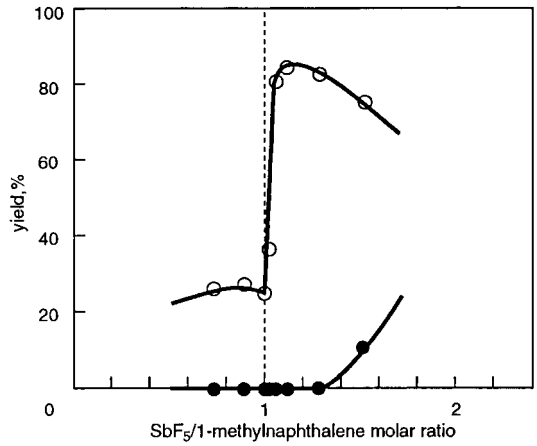


Figure 2. Yields of mono- and dialdehyde in 1-methylnaphthalene formylation with HF−SbF_5. The formylation was carried out with HF (500 mmol) and 1-methylnaphthalene (10 mmol) at 0 °C for 2 h under 20 atm of CO pressure. The symbols ○ and ● represent mono- and dialdehyde, respectively.

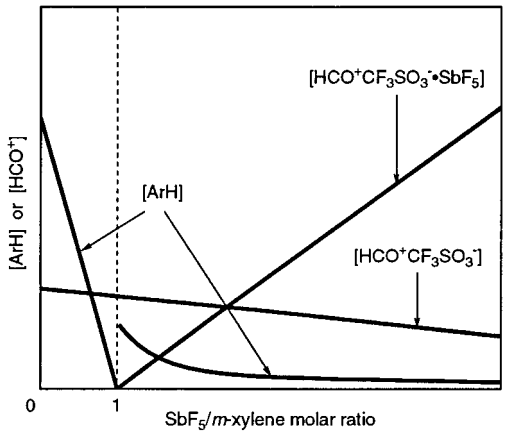


Figure 3. Relationships of [ArH] and [HCO^+] with the SbF_5/*m*-xylene molar ratio.

the apparent rate of the Gattermann−Koch formylation.[14] In order to derive the rate equations for *m*-xylene formylation in CF_3SO_3H−SbF_5, we applied the following assumptions: (1) when the SbF_5/*m*-xylene molar ratio is less than 1, the formyl cation produced by CF_3SO_3H brings about the formylation and the role of CF_3SO_3H·SbF_5 is to protonate *m*-xylene; and (2) when the SbF_5/*m*-xylene molar ratio exceeds 1, the formyl cation produced by CF_3SO_3H·SbF_5 effects the formylation. The dependence of the SbF_5/*m*-xylene molar ratio on the *m*-xylene and the formyl cation concentrations is shown in Figure 3.[14] On the basis of kinetic studies, two second-order reactions and one pseudo-first-order reaction are obtained, depending on the SbF_5/*m*-xylene ratio (eq 4).

$$\begin{aligned} &SbF_5/m\text{-xylene} \le 1 \\ &-\frac{d[ArCHO]}{dt} = k[ArH][HCO^+CF_3SO_3^-] \\ &SbF_5/m\text{-xylene} \ge 1 \\ &-\frac{d[ArCHO]}{dt} = k'[HCO^+CF_3SO_3^-\cdot SbF_5] \\ &-\frac{d[ArCHO]}{dt} = k'[ArH][HCO^+CF_3SO_3^-\cdot SbF_5] \end{aligned} \qquad (4)$$

Interestingly, when the SbF_5/*m*-xylene molar ratio is greater than 1, the pseudo-first-order reaction appears. This observation is clearly a peculiar feature of the Gattermann−Koch formylation because this means that $HCO^+CF_3SO_3^-$, which should have

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been produced in sufficient concentration to appear in a second-order rate expression, does not react with *m*-xylene under these conditions. If the Gattermann−Koch formylation proceeds through the intracomplex reaction, its rate equation should be different from that of the conventional reaction as described in eq 5.

$$\begin{aligned}&\text{Conventional Reaction}\\&\mathrm{ArH + HCO^+ \xrightarrow{k} ArCHO + H^+}\\&-\frac{\mathrm{d[ArCHO]}}{\mathrm{dt}} = \mathrm{k[ArH][HCO^+]}\\&\text{Intracomplex Reaction}\\&\mathrm{ArH_2^+ + CO \xrightarrow{k'} ArCHO + H^+}\\&-\frac{\mathrm{d[ArCHO]}}{\mathrm{dt}} = \mathrm{k'[ArH_2^+][CO]}\end{aligned} \tag{5}$$

However, the two equations differ only by kinetic constant values, which could not been determined (eq 6).

$$\begin{aligned}&\text{Conventional Reaction}\\&-\frac{\mathrm{d[ArCHO]}}{\mathrm{dt}} = \mathrm{k[ArH][HCO^+]}\\&\text{Intracomplex Reaction}\\&\mathrm{ArH + H^+ \rightleftharpoons ArH_2^+}\\&\mathrm{CO + H^+ \rightleftharpoons HCO^+}\\&K_{ArH} = \frac{[ArH_2^+]}{[ArH][H^+]} \quad K_{CO} = \frac{[HCO^+]}{[CO][H^+]}\\&-\frac{\mathrm{d[ArCHO]}}{\mathrm{dt}} = \mathrm{k'[ArH_2^+][CO]} = \mathrm{k'}\frac{K_{ArH}}{K_{CO}}\mathrm{[ArH][HCO^+]}\end{aligned} \tag{6}$$

In eq 6, K_{ArH} and K_{CO} are protonation equilibrium constants in superacids for ArH and CO, respectively. We previously found that whereas in the Gattermann−Koch formylation the formyl cation acts not only as an electrophile but also as a Brønsted acid,[15] formylation predominates over sulfonation under conditions where most arenes are protonated. These observations suggest that the Gattermann−Koch formylation has a peculiar mechanism, compatible with that of the intracomplex reaction eq 2.

In $CF_3SO_3H-SbF_5$, the formylation is brought about by CF_3SO_3H and controlled by protonation of *m*-xylene with $CF_3SO_3H{\cdot}SbF_5$ when the SbF_5/*m*-xylene molar ratio is less than 1.[14] On the other hand, in HF, no formylation occurs in the absence of SbF_5,[12d,e] namely, it is effected by $HF{\cdot}SbF_5$ under all conditions. Therefore, the formylation rate equation in $HF-SbF_5$ is mechanistically informative especially when the SbF_5/*m*-xylene molar ratio is less than 1. As for formylation of *m*-xylene in $CF_3SO_3H-SbF_5$,[14] we applied the following assumptions: (1) when the SbF_5/*m*-xylene ratio is less than 1, the concentration of *m*-xylene protonated by $HF{\cdot}SbF_5$, $[ArH_2^+SbF_6^-]$, corresponds to the original concentration of added SbF_5, $[HF{\cdot}SbF_5]_o$; and (2) when the SbF_5/*m*-xylene molar ratio exceeds 1, the concentration of $[ArH_2^+SbF_6^-]$ is the original concentration of added *m*-xylene, $[ArH]_o$. The concentration of CO, [CO], was assumed to be the original concentration of CO, $[CO]_o$, because of the extremely low conversion into HCO^+.[14] The results are shown in Figures 4 and 5. Surprisingly, the third-order rate equation, $[ArH]^2[HCO^+SbF_6^-]$, appeared when the SbF_5/*m*-xylene molar ratio was less than 1 as shown in Figure 4. Since it would be difficult to explain why two neutral aromatic molecules are necessary for the formylation, and a trimolecular collision is improbable in solution, the equation should be presented as $[ArH][ArH_2^+SbF_6^-][CO]$ (eq 7) according to eq 6, where ArH and $ArH_2^+SbF_6^-$ form a complex similar, for example, to the complex of the tropylium cation with aromatic compounds.[16]

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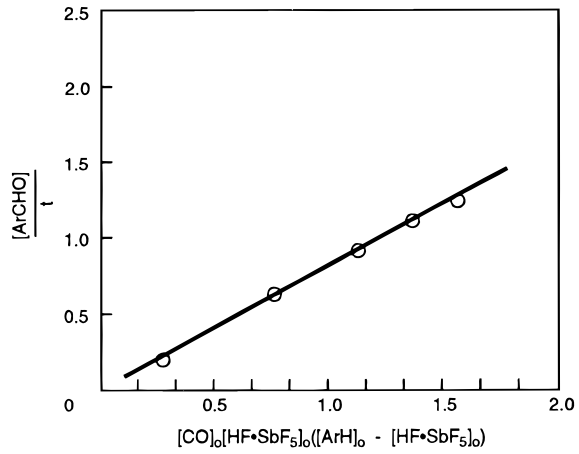

Figure 4. Correlation of $[CO]_o[HF{\cdot}SbF_5]_o([ArH]_o - [HF{\cdot}SbF_5]_o)$ with [ArCHO]/*t*. The formylation was carried out with HF (500 mmol), SbF_5 (5.5−9.5 mmol), and *m*-xylene (10 mmol) at 0 °C for 30 s under 20 atm of CO pressure.

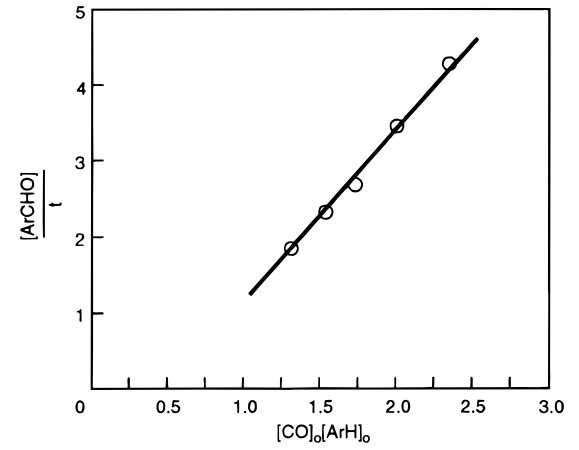

Figure 5. Correlation of $[CO]_o[ArH]_o$ with [ArCHO]/*t*. The formylation was carried out with HF (500 mmol), SbF_5 (120−200 mmol), and *m*-xylene (10 mmol) at 0 °C for 15 s under 20 atm of CO pressure.

$$-\frac{\mathrm{d[ArCHO]}}{\mathrm{dt}} = \mathrm{k'[ArH]^2[HCO^+]} = \mathrm{k'}\frac{K_{CO}}{K_{ArH}}\mathrm{[ArH][ArH_2^+][CO]} \tag{7}$$

This equation shows that the $[ArH]/[ArH_2^+SbF_6^-]$ complex produces the formyl cation $[HCO^+SbF_6^-]$, which reacts within the complex, according to the intracomplex mechanism, when the SbF_5/*m*-xylene molar ratio is less than 1. On the other hand, when the SbF_5/*m*-xylene molar ratio exceeds 1, the second-order formylation rate equation, $[ArH][HCO^+SbF_6^-]$, is observed as expected. However, it remained to be ascertain whether the intracomplex mechanism holds at SbF_5/*m*-xylene molar ratios greater than 1.

Regioselectivity and Relative Rate of the Intracomplex and the Conventional Formylation. The high *para* regioselectivity of the Gattermann−Koch formylation in $HF-SbF_5$ (Figure 1) is clearly caused by the intracomplex reaction when the SbF_5/1-methylnaphthalene molar ratio is less than 1. Probing the reaction under conditions where the SbF_5/1-methylnaphthalene molar ratio was 1 provided an important clue. Monoaldehyde

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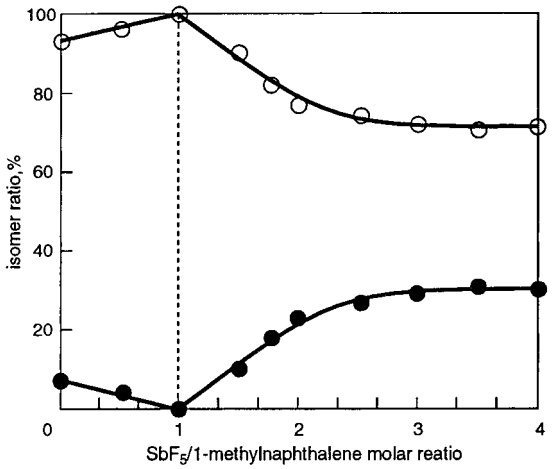
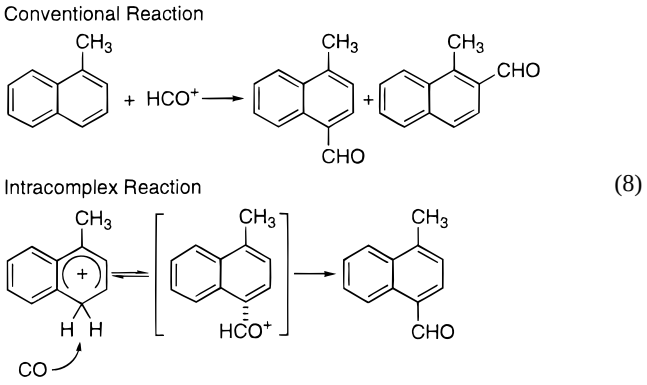


Figure 6. Isomer ratio of monoaldehyde in 1-methylnaphthalene formylation with $CF_3SO_3H-SbF_5$. The formylation was carried out with CF_3SO_3H (200 mmol) and 1-methylnaphthalene (10 mmol) at 0 °C for 2 h under 20 atm of CO pressure. Dialdehyde was not formed under these conditions. The symbols ○ and ● represent 1-methyl-4- and 1-methyl-2-naphthaldehyde, respectively.

was obtained in 90% yield and 94% *para* regioselectivity when the SbF_5/1-methylnaphthalene molar ratio was just above 1 within experimental error (±5%) as shown in Figures 1 and 2, strongly suggesting that formylation proceeded via the intracomplex reaction with the high *para* regioselectivity even when the SbF_5/1-methylnaphthalene molar ratio was greater than 1. On the other hand, it is clear that the conventional formylation shows both *para* and *ortho* regioselectivities (eq 8).



(8)

In order to investigate the ratio between the intracomplex and the conventional reactions, the formylation of 1-methylnaphthalene in $CF_3SO_3H-SbF_5$ was investigated because it seems to proceed via the intracomplex reaction showing high *para* regioselectivity when the SbF_5/1-methylnaphthalene molar ratio is around 1, especially when the formylation is described by the pseudo-first-order reaction. The regioselectivity change also appeared in the formylation of 1-methylnaphthalene in $CF_3SO_3H-SbF_5$ as depicted in Figure 6. As expected, the *para* regioselectivity showed a maximum at a SbF_5/1-methylnaphthalene molar ratio of 1. This trend devotes simultaneous operation of the intracomplex and the conventional pathways. When the SbF_5/1-methylnaphthalene molar ratio was less than 1, formylation by CF_3SO_3H proceeded through both mechanisms whereby formylation by $CF_3SO_3H{\cdot}SbF_5$ proceeded through the intracomplex mechanism. Therefore, the *para* regioselectivity increased with the SbF_5/1-methylnaphthalene molar ratio, reflecting the increased extent of the intracomplex reaction by $CF_3SO_3H{\cdot}SbF_5$. When the SbF_5/1-methylnaphthalene molar ratio was 1, formylation proceeded exclusively through the intracomplex reaction by $CF_3SO_3H{\cdot}SbF_5$ to produce only 1-methyl-4-naphthaldehyde. When the SbF_5/1-methylnaphthalene molar ratio was greater than 1, the formylation by $CF_3SO_3H{\cdot}SbF_5$ proceeded through both the intracomplex and the conventional mechanisms. Hence, *para* regioselectivity decreased with an increase in the SbF_5/1-methylnaphthalene molar ratio, reflecting the increased rate of the conventional reaction. These results suggest that the regioselectivity in the formylation reflects the ratio between the intracomplex and the conventional reactions.

Table 1. Formylation of Toluene in $HF-SbF_5$[a]

SbF_5/substrate molar ratio	yield (%)	*ortho* (%)	*meta* (%)	*para* (%)
0.5	34	2.9	0.3	96.8
1	78	3.2	0.6	96.2
2	90	6.1	0.6	93.3
4	94	10.7	0.6	88.7
8	94	13.1	0.6	86.3
20	96	22.2	0.5	77.3

[a] The formylation was carried out with HF (500 mmol) and toluene (10 mmol) under 20 atm of CO pressure at 0 °C for 1 h.

In the formylation of 1-methylnaphthalene, the regioselectivity changes more drastically in $HF-SbF_5$ than in $CF_3SO_3H-SbF_5$. The different regioselectivity trends in $HF-SbF_5$ and $CF_3SO_3H-SbF_5$ seem to derive from the difference in the nature of the superacid. Whereas regular HF is weaker than CF_3SO_3H, $HF-SbF_5$ is one of strongest superacids known.[17] Therefore, 1-methylnaphthalene forms a more stable σ-complex in $HF-SbF_5$ than in CF_3SO_3H-SbF_5, which can be a critical factor in controlling the ratio between the intracomplex and the conventional reactions. The switch of the formylation mechanism from the intracomplex to the conventional reaction as a function of the superacid/substrate molar ratio may reflect the stability of the σ-complex, because the rate of the intracomplex reaction is adversely affected by an increase in the stability of the σ-complex.[9] This corresponds to the result of the 1-methylnaphthalene formylation in $HF-SbF_5$, which leads to the most stable σ-complex, causing a more drastic change in the formylation mechanism than in $CF_3SO_3H-SbF_5$.

In order to clarify this inference, we examined whether a lower basicity aromatic compound, toluene, exhibits a similar regioselectivity change in $HF-SbF_5$. Formylation of toluene at low temperature in $HF-SbF_5/SO_2ClF$ shows low regioselectivity.[12a] The formylation of toluene in $HF-SbF_5$ in the −78 to 0 °C range displayed no regioselectivity change, but changed depending on the SbF_5/toluene molar ratio as shown in Table 1. As expected, the regioselectivity change, reflecting the transition from the intracomplex to the conventional mechanism, was gradual, being observed when the SbF_5/toluene ratio largely exceeded 1. On the other hand, at SbF_5/substrate ratios less than 1, toluene showed less *para* regioselectivity than 1-methylnaphthalene. This trend, which is in contrast with that of the conventional electrophilic aromatic substitutions, is consistent with the specific features of the intracomplex reaction as mentioned in the introduction. These results clearly reflect that the basicity of toluene is significantly less than that of 1-methylnaphthalene.

Friedel−Crafts (HCOF) and Gattermann−Koch (CO) Formylations. The existence of a dication as the true electrophile in electrophilic aromatic substitutions has been proposed in cases where higher acidity H_o increases the reaction rate.[18] Taking into account the protonation equilibrium of aromatic

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Table 2. Friedel−Crafts and Gattermann−Koch Formylation of 1-Methylnaphthalene[a]

SbF_5/substrate molar ratio	reagent	temp (°C)	time	yield of aldehyde (%)	isomer ratio of 2-:4-aldehyde
1	HCOF	0	1 h	15	7:93
1.25	HCOF	0	1 h	45	6:94
1.25	HCOF	−40	1 h	33	6:94
2	HCOF	−40	1 h	50	6:94
1	CO	0	2 h	24	0:100
1.25	CO	0	10 min	12	32:68
1.25	CO	−40	2 h	13	36:64

[a] The formylation was carried out with HF (500 mmol) and 1-methylnaphthalene (10 mmol) under 20 atm of CO pressure or with HCOF (80 mmol).

compounds in superacids, in the HF−SbF_5 system the formyl cation could in principle be a mono- or a dication, depending on the SbF_5/1-methylnaphthalene molar ratio (eq 9).

$$\underset{SbF_5/1\text{-methylnaphthalene}\le 1}{HCO^+} \underset{-H^+}{\overset{H^+}{\rightleftharpoons}} \underset{SbF_5/1\text{-methylnaphthalene}\ge 1}{HCOH^{2+}} \quad (9)$$

If the regioselectivity change illustrated in Figure 1 is derived from the difference in the nature of the formyl cation (mono- or dication), our data (Figure 1) imply that the regioselectivity at the *para* position of 1-methylnaphthalene should be high for the monocation but low for the dication.

In order to clarify whether the difference in the nature of formyl cation electrophile causes the regioselectivity change of the Gattermann−Koch formylation, the reaction of 1-methylnaphthalene with HCOF, the Friedel−Crafts formylation, was carried out in HF−SbF_5 and its regioselectivity was compared with that of the Gattermann−Koch formylation. The Friedel−Crafts formylation clearly does not involve CO, but the formyl cation produced by ionization of HCOF.[19] These results revealed a significant difference in the regioselectivity as shown in Table 2. In the case of the Friedel−Crafts formylation, the regioselectivity was constant regardless of the SbF_5/1-methylnaphthalene molar ratio, even at values as high as 2, where the formyl cation can be further protonated (protosolvated) to be dicationic. Therefore, we concluded that the regioselectivity change is not caused by the change in the nature of the electrophile.[20] This conclusion is also supported by the result of the 1-methylnaphthalene formylation in CF_3SO_3H−SbF_5 in Figure 6. The regioselectivity change under conditions where the SbF_5/1-methylnaphthalene molar ratio is less than 1 cannot be explained in terms of the nature of the formyl cation.

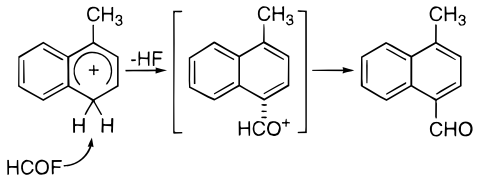
In the formylation of 1-methylnaphthalene in HF−SbF_5, the Friedel−Crafts reaction seems to proceed via the conventional route, as does the Gattermann−Koch formylation, when the SbF_5/1-methylnaphthalene molar ratio is greater than 1. Similar regioselectivity is expected in both formylations, because both involve the same reactive species, $HCO^+SbF_6^-$. However, different regioselectivities were observed as shown in Table 2. Under these conditions, Friedel−Crafts formylation showed higher *para* regioselectivity than the Gattermann−Koch formylation. Furthermore, when the SbF_5/1-methylnaphthalene molar ratio was greater than 2, the Friedel−Crafts formylation did not occur at all at 0 °C in HF−SbF_5. These results imply that the Friedel−Crafts formylation proceeds via the formyl cation from the reaction of HCOF with the σ-complex, namely, via the intracomplex route because neutral HCOF is far more accessible to a cationic charged σ-complex than the positively charged HCO^+ (eq 10).

Table 3. Friedel−Crafts Formylation of Toluene[a]

SbF_5/substrate molar ratio	yield (%)	*ortho* (%)	*meta* (%)	*para* (%)
0.5	22	33.3	2.1	64.6
1	28	35.5	2.1	62.4
1.5	26	36.5	2.3	61.2
1.6	20	25.7	2.2	72.1
1.8	25	17.7	1.8	80.5
2	53	6.8	0.7	92.5
4	71	9.3	0.7	90.0
8	90	11.4	0.6	88.0
20	94	20.1	0.5	79.4

[a] The formylation was carried out with HF (500 mmol), toluene (10 mmol), and HCOF (80 mmol) at 0 °C for 1 h.

Friedel-Crafts Intracomplex Reaction



(10)

Should the Friedel−Crafts formylation have the same intracomplex nature as the Gattermann−Koch formylation, the regioselectivity should show the specific features of the intracomplex reaction and would be controlled by the stability of the protonated aromatic compounds.

In order to clarify the above inference, the Friedel−Crafts formylation of a lower-basicity compound, toluene, was investigated. When the formylation was carried out in HF−SbF_5, *para* regioselectivity was low compared with the 1-methylnaphthalene formylation as shown in Table 3, consistent with the specific regioselectivity trends of the intracomplex reaction. On the other hand, the Friedel−Crafts formylation of toluene showed quite a different trend compared with that of 1-methylnaphthalene when the SbF_5/toluene molar ratio was greater than 2.[21] Under these conditions, the regioselectivity of the toluene formylation shows a similar trend as that of the Gattermann−Koch formylation. The transition of the formylation mechanism from the Friedel−Crafts to the Gattermann−Koch formylation is suggested because of higher reactivity of toluene compared to 1-methylnaphthalene, which is a specific feature of the intracomplex reaction.[9]

Conclusions

Kinetics and regioselectivity evidence in the superacid-catalyzed Gattermann−Koch formylation point to the intracomplex electrophilic aromatic substitution character. The significant feature of the intracomplex reaction in regioselectivity is that the regioselectivity reflects both the structure and the stability of the arenium ion as a reaction precursor. The observation of the intracomplex reaction resulting in the high *para* regioselectivity in the Gattermann−Koch formylation is

(18) (a) Olah, G. A.; Rasul, G.; Aniszfeld, R.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1992**, *114*, 5608. (b) Olah, G. A. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 767. (c) Saito, S.; Sato, Y.; Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1994**, *116*, 2312. (d) Saito, S.; Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1995**, *117*, 11081. (e) Olah, G. A.; Rasul, G.; York, C.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1995**, *117*, 11211. (f) Ohwada, T.; Yamazaki, T.; Suzuki, T.; Saito, S.; Shudo, K. *J. Am. Chem. Soc.* **1996**, *118*, 6220.

(19) In control experiments, HCOF was decomposed to HF and CO immediately in HF, and the Gattermann−Koch formylation did not occur under atmospheric CO pressure under these conditions.

(20) The kinetic study for the formylation shows that HCO^+ is the electrophile under these conditions, however, possible involvment of dication $HCOH^{2+}$ cannot be excluded.

(21) In control experiments, the elimination of formyl group was not observed under the same conditions.

in all probability a consequence of the very short lifetime of the formyl cation in superacids under the reaction conditions in solution.

Experimental Section

All materials were of the highest available purity and used without further purification. HF and CF_3SO_3H contained 0.1 mol and 5 mol % H_2O, respectively. H_2O was considered to form $H_2O{\cdot}SbF_5$ quantitatively as an inert additive. The identification of products was performed by NMR (^{1}H-, ^{13}C-NMR, H−H COSY, C−H COSY, and COLOC) and mass spectra after separation by distillation, recrystallization, and HPLC. The yields were determined by GC, and the isomer distributions were determined by GC and NMR.

Gattermann−Koch Formylation Procedures.[22] Substrate (10 mmol) was added to a solution of Lewis acids with HF or CF_3SO_3H in a Hastelloy autoclave (100 mL) equipped with a Hastelloy magnetic stirrer bar under temperature control. The autoclave was sealed, and CO (20 atm) was introduced with vigorous stirring. After the raction was over, the autoclave was depressurized and opened. The reaction mixture was quenched with ice water and extracted with benzene.

Friedel−Crafts Formylation Procedures. HCOF (80 mmol, 3.84 g), which was prepared from KHF_2, HCOOH, and C_6H_5COCl according to the literature,[23] was added to a solution of substrate (10 mmol) with HF and SbF_5 in a Teflon round-bottom flask (300 mL) under temperature control with vigorous stirring. After 1 h, the reaction mixture was quenched with ice water and extracted with benzene.

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(22) The Koch−Haaf carboxylation was negligible because only traces of carboxylic acids were detected.

(23) Olah, G. A.; Kuhn, S. J. *Chem. Ber.* **1956**, *89*, 866.