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Chlorination of aliphatic hydrocarbons, aromatic compounds, and olefins in subcritical carbon tetrachloride

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ABSTRACT

The reactions of various substrates including aliphatic hydrocarbons, aromatic compounds, and olefins were investigated in subcritical carbon tetrachloride. Ketones and sulfones were stable under the employed conditions. The coupling adducts between olefins and carbon tetrachloride were obtained from the reactions of olefins.

Much attention has been paid to supercritical and subcritical water as a medium for chemical reactions, since it has quite unique properties such as low polarity and the change of the pK_w value ($pK_w = 11.2$ at 250 °C).[1] Supercritical alcohols are also attractive solvents because of unique reactivities such as direct addition of alcohols to alkenes.[2]

Direct introduction of halogen substituents into various classes of organic molecules can be achieved by free-radical reactions. Especially, halogenation of aliphatic hydrocarbons and side chains of aromatic hydrocarbons has been reported by many researchers.[3–5]

In our continuing studies concerning the halogenation of organic compounds,[6] we were interested in the chlorination of organic compounds under high temperature conditions. We planned to chlorinate organic substrates by the reactions of chloro radical generated from the C–Cl bond cleavage of carbon tetrachloride under high temperature conditions. We report the free-radical chlorination of a variety of compounds in high temperature carbon tetrachloride.

First, adamantane (**1**) was chosen as the model compound of aliphatic hydrocarbons. The critical temperature of carbon tetrachloride is 283 °C.[7] The reaction was conducted at 250 °C on 7 MPa for 4 h to give 1-chloroadamantane (**2**), 1,3-dichloroadamantane (**3**), and 2-chloroadamantane (**4**) in 52, 9, and 3% yields, respectively (*Caution*: see Ref. 8) (Table 1, entry 1).[8] Prolonged heating for 9 h gave the dichloro compound **3** in 73% yield together with small amounts of **2** (4%) and **4** (2%) (entry 2). When the reaction was performed at 300 °C, the Teflon crucible equipped in the stainless autoclave melted in spite of the good yield (60%) of **2** (entry 3). We carried out all the reactions at 250 °C because of the above reason. Similarly, chlorocyclododecane (**6**) and dichlorocyclododecane (**7**) were produced in 35 and 12% yields from the reaction of **5** at 250 °C for 7 h, respectively (entry 4). Dichloride **7** was obtained as an inseparable mixture. The positions of the second chlorine atom in **7** are not clear. The reaction of 2,2,3,3-tetramethylbutane (**8**) gave 1-chloro-2,2,3,3-tetramethylbutane (**9**) in a low yield (3%) (entry 5). The relative ease of substitution of hydrogen was tertiary > secondary > primary.

The reactions of the side chains of aromatic hydrocarbons were examined. Toluene (**10**) was chlorinated at the benzylic position in subcritical carbon tetrachloride (entry 6). Reactions of diphenylmethane (**12**) and triphenylmethane (**14**) gave chlorides **13** and **15** in 53 and 99% yields, respectively (entries 7 and 8). The yields of the products were increased with the introduction of the phenyl group, since the resulting radical became more stable. Chlorination of 1-methylnaphthalene (**16**) led to the formation of chloride **17** and dichloride **18** in 36 and 37% yields, respectively (entry 9).

Next, we conducted the reactions of a variety of aromatic compounds at 250 °C for 7 h. The results are summarized in Table 2. Nitrobenzene was easily converted into chlorobenzene with the evolution of nitrogen dioxide (entry 1). Several reports including photo-initiated chlorination[3] and gas-phase reactions[9] for the

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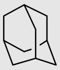
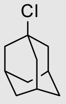
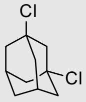
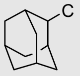
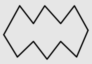
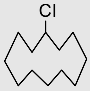
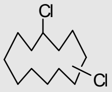
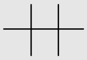
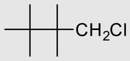
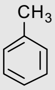
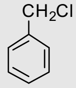
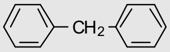
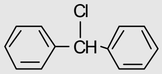
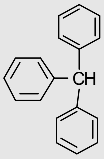
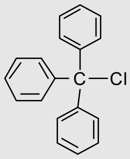
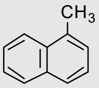
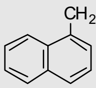
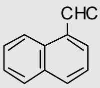
Table 1
The reactions of various hydrocarbons in high temperature CCl_4[a]

Entry	Substrate	Time (h)	Products (Yield[b] (%))			Recovery[b] (%)
1	 **1**	4	 **2** (52)	 **3** (9)	 **4** (3)	(15)
2	**1**	9	**2** (4)	**3** (73)	**4** (2)	(0)
3[c]	**1**	2	**2** (60)	**3** (21)	**4** (4)	(0)
4	 **5**	7	 **6** (35)	 **7** (12)		(34)
5	 **8**	7	 **9** (3)[d]			(95)[d]
6	 **10**	7	 **11** (24)[d]			(74)[d]
7	 **12**	7	 **13** (53)			(42)
8	 **14**	7	 **15** (99)			(0)
9	 **16**	7	 **17** (36)	 **18** (37)		(5)

[a] Reagents and conditions: Substrates 4.0 mmol, CCl_4 15 mL, temp. 250 °C, N_2.
[b] Isolated yields.
[c] Temp. 300 °C.
[d] The yields were calculated on the basis of the peak of 1,4-dioxane using ^{1}H NMR spectroscopy.

transformation of nitrobenzene to chlorobenzene have been reported. Halogen exchange reactions were investigated. Fluorobenzene was recovered without any changes after 7 h (entry 2). Chlorobenzene was stable under the employed conditions and further nuclear substitution did not proceed (entry 3). Transformation of bromobenzene to chlorobenzene proceeded smoothly (entry 4). Many reports have been known for chlorodebromination of bromobenzene by photo-induced chlorination,[10–12] the use of sulfuryl chloride-BPO,[12] and gas-phase chlorination.[9] Although the yield of chlorobenzene was low (50%) at 250 °C because of the production of large amounts of decomposed materials, chlorobenzene was obtained at 240 °C in the quantitative yield (90%) from the reaction of iodobenzene (entries 5 and 6). It was reported that chlorodeiodination occurred by use of sulfuryl chloride-BPO, while iodobenzene dichloride was produced by photo-induced chlorination of iodobenzene.[10,13,14] Iodobenzene dichloride is the somewhat unstable compound which decomposes on heating above the melting point (ca. 101–103 °C), affording chiefly *p*-chloroiodobenzene.[13b] These materials were not detected by ^{1}H NMR spectroscopy and *t.l.c.* in our experiments achieved at 200–250 °C, indicating that iodobenzene was transformed to chlorobenzene, exclusively (entries 5–8).

The displacement of other substituents on the benzene ring was investigated. The reaction of benzaldehyde gave not only benzoyl chloride (64%), but also a small amount of chlorobenzene (15%) (entry 9). It was reported that photochemical chlorination[15] and the use of sulfuryl chloride-BPO[16] extensively afforded benzoyl

Table 2
The reactions of various aromatic substrates in high temperature CCl_4[a]

Entry	Substrate	Products (Yield[b] (%))	Recovery[b] (%)
1	$PhNO_2$	PhCl (90)	(0)
2	PhF	N.R.[f]	(97)
3	PhCl	N.R.[f]	(99)
4	PhBr	PhCl (94)	(0)
5	PhI	PhCl (50)	(0)
6[c]	PhI	PhCl (90)	(0)
7[d]	PhI	PhCl (31)	(65)
8[e]	PhI	PhCl (13)	(84)
9	PhCHO	PhCOCl (64) PhCl (15)	(19)
10	PhOMe	$PhOCH_2Cl$ (71)	(27)
11	PhSMe	$PhSCH_2Cl$ (54) $PhSCHCl_2$ (18)	(26)
12	CH_3COCH_3	N.R.[f]	(76)
13	$PhCOCH_3$	N.R.[f]	(89)
14	$CH_3COCH_2CH_3$	$CH_3COCHClCH_3$ (21)	(56)
15	$CH_3COCH_2COCH_3$	N.R.[f]	(78)
16	CH_3COCH_2COOEt	N.R.[f]	(77)
17	$EtSO_2Et$	$EtSO_2CHClCH_3$ (3)	(87)
18	$(CH_2)_4SO_2$	N.R.[f]	(92)
19	$PhSO_2Me$	PhCl (8)	(87)

[a] Reagents and conditions: substrates 4.0 mmol, CCl_4 15 mL, temp. 250 °C, time 7 h, N_2.

[b] The yields were calculated on the basis of the peak of 1,4-dioxane using ^1H NMR spectroscopy.

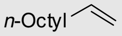
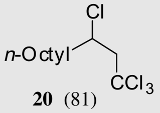
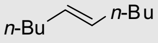
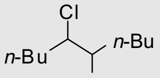
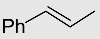
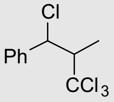
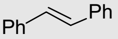
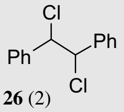
[c] Temp. 240 °C.

[d] Temp. 220 °C.

[e] Temp. 200 °C.

[f] No reaction.

Table 3
The reactions of various olefins in high temperature CCl_4[a]

Entry	Substrate	Time (h)	Products (Yield[b] (%))	Recovery[b] (%)
1	 **19**	8	 **20** (81)	(0)
2	 **21**	7	 **22** (12)	(21)
3	 **23**	7	 **24** (74)	(5)
4	 **25**	8	 **26** (2)	(98)

[a] Reagents and conditions: Substrates 4.0 mmol, CCl_4 15 mL, temp. 250 °C, N_2.

[b] Isolated yields.

chloride, while gas-phase chlorination of benzaldehyde at 375 °C gave chlorobenzene in a low yield (<10%) together with a large amount of carbon, probably through intermediate benzoyl and phenyl radicals.[9] Reactions under subcritical conditions are milder than gas-phase reactions,[1] so that decomposition to carbon was suppressed. Chlorination occurred at the methyl groups for the reactions of anisole and thioanisole (entries 10 and 11).

In the cases of ketones, chlorination was not observed at the methyl groups or proceeded quite slowly at the methylene group (entries 12–14). Surprisingly, even in the cases of the 1,3-dicarbonyl compounds, which are more active than simple ketones, reactions did not occur at the activated methylene groups (entries 15 and 16). It has been reported that these ketones involving 1,3-dicarbonyl compounds were easily chlorinated by the traditional methods such as photo-induced chlorination[17] and the use of sulfuryl chloride[4] via the ionic mechanism. Sulfones were stable under the employed conditions, and most of starting materials were recovered (entries 17–19). Chlorobenzene was produced in a low yield (8%) by aromatic substitution from the reaction of methyl phenyl sulfone (entry 19).

As for the chlorination of alkyl groups adjacent to the functional groups listed in Table 2, the reactions proceeded more easily for anisole and thioanisole which possess electron-donative oxygen and sulfur atoms, respectively (entries 10 and 11). On the other hand, the reactions were quite slow for ketones and sulfones which have electron-withdrawing carbonyl and sulfonyl groups (entries 12–19).

Finally, the reactions of olefins were explored. The results are summarized in Table 3. Interestingly, the coupling adducts **20**,[18] **22**,[19] and **24**[20] between olefins and carbon tetrachloride were obtained (entries 1–3), although the yield of compound **22** was low (12%) because of the production of unidentified complex mixtures. The observed regioselectivites show that the trichloromethyl radical was introduced into olefins first. Compounds **22**[21] and **24** were obtained as a mixture (1:1) and (2:1) of *anti*/*syn* isomers, respectively (entries 2 and 3). The starting material was recovered quantitatively in the case of stilbene (**25**) (entry 4). Because of the steric hindrance between the trichloromethyl radical and the phenyl group on stilbene, the formation of the coupling adduct might be restricted. It was reported that photo-induced chlorination[3] and the use of sulfuryl chloride-BPO[4] resulted in the addition of Cl_2 to the olefinic double bond via radical mechanisms. The BPO-induced addition of sulfuryl chloride to 1-alkenes which affords β-chloro-*n*-alkyl sulfones has been reported by Kharasch et al.[22]

During the reactions, a large amount of Cl_2 was evolved, which was detected by DPD (diethyl-*p*-phenylenediamine) and syringaldazine (3,5-dimethoxy-4-hydroxybenzaldazine) methods. In spite of the considerable stability of carbon tetrachloride at higher temperature (ca. 500 °C),[23] the cleavage of the C–Cl bond to give the chloro radical occurred more easily under subcritical conditions.

In summary, we carried out the chlorination of aliphatic hydrocarbons and side chains of aromatic hydrocarbons in subcritical carbon tetrachloride. In addition, the reactions of a variety of aromatic compounds and olefins were examined. Interestingly, strongly radicalic atmosphere was formed for the chlorination of benzaldehyde, ketones, and sulfones. The addition of carbon tetrachloride to olefins is the characteristic reaction under high temperature conditions.

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8. *A typical experimental procedure*: A mixture of adamantane (**1**) (4.0 mmol) and carbon tetrachloride (15 mL) in a 28 mL Teflon-lined stainless autoclave (purchased from OM Lab-Tech Co. Ltd., Japan)[1f] was heated at 250 °C under nitrogen. The internal pressure reached ca. 7 MPa. The mixture was heated at the same temperature for 4 h. After cooling, the solution was washed with water, dried, and evaporated. The residue was chromatographed (hexane) on silica gel to give **2**, **3**, and **4** in 52, 9, and 3% yields, respectively. Compound **1** was recovered in 15% yield (Table 1, entry 1). *Caution*: Attention should be paid for the leak of the gas, since a large amount of harmful chlorine was evolved during the reactions. It is important to firmly tighten the screw of the stainless autoclave. The operation should be carried out in a well-ventilated fume hood when the autoclave is opened. Many times use of the stainless autoclave should be avoided because of the rust caused by chlorine gas.
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18. *1,1,1,3-Tetrachloroundecane* (**20**). Colorless oil; IR (neat) $\nu_{\max}$ 2932, 1860, 1468, 1380, 1210, 1124, 1050, 962, 788, 701, 574 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 0.89 (3H, t, J = 6.6 Hz, CH$_3$), 1.10–1.70 (12H, m, CH$_2$), 1.70–2.18 (2H, m, CH$_2$), 3.04 (1H, dd, J = 15.0 and 4.8 Hz, CHCCl$_3$), 3.33 (1H, dd, J = 15.8 and 5.1 Hz, CHCCl$_3$), 4.08–4.48 (1H, m, CHCl); ^{13}C NMR (CDCl$_3$) δ 14.1 (q), 22.7 (t), 26.0 (t), 28.9 (t), 29.2 (t), 29.3 (t), 31.8 (t), 39.1 (t), 57.7 (d), 62.3 (t), 97.0 (s). Anal. Calcd for C$_{11}$H$_{20}$Cl$_4$: C, 44.92; H, 6.85. Found: C, 44.83; H, 7.00.
19. *5-Chloro-6-trichloromethyldecane* (**22**).[21] Compound **22** was obtained as a mixture (1: 1) of *anti*/*syn* isomers. Colorless oil; IR (neat) $\nu_{\max}$ 2959, 2872, 1465, 1380, 987, 907, 984, 635 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 0.93 (6H, t, J = 6.6 Hz, CH$_3$), 1.20–2.30 (12H, m, CH$_2$), 2.55 (1H$_{syn}$, td, J = 4.6 and 1.0 Hz, CHCCl$_3$), 2.90–3.15 (1H$_{anti}$, m, CHCCl$_3$), 4.64 (1H, td, J = 6.3 and 1.6 Hz, CHCl); ^{13}C NMR (CDCl$_3$) δ 13.8 (q), 13.9 (q), 22.0 (t), 22.9 (t), 27.5 (C$_{anti}$, t), 28.5 (C$_{syn}$, t), 29.0 (C$_{syn}$, t), 29.4 (C$_{anti}$, t), 31.8 (C$_{anti}$, t), 32.2 (C$_{syn}$, t), 32.7 (C$_{anti}$, t), 39.0 (C$_{syn}$, t), 62.4 (C$_{syn}$, d), 62.7 (C$_{anti}$, d), 63.3 (C$_{syn}$, d), 65.4 (C$_{anti}$, d), 103.1 (C$_{anti}$, s), 104.1 (C$_{syn}$, s). Anal. Calcd for C$_{11}$H$_{20}$Cl$_4$: C, 44.92; H, 6.85. Found: C, 44.64; H, 6.74.
20. *1,3,3,3-Tetrachloro-2-methylpropylbenzene* (**24**). Compound **24** was obtained as a mixture (2:1) of *anti*/*syn* isomers. Colorless oil; IR (neat) $\nu_{\max}$ 3063, 3031, 2998, 2947, 1602, 1495, 1453, 1382, 1309, 1232, 1122, 1076, 1043, 950, 917, 856, 825, 768, 699, 639, 570 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 1.47 (3H$_{syn}$, t, J = 6.8 Hz, CH$_3$), 1.50 (3H$_{anti}$, t, J = 6.6 Hz, CH$_3$), 2.99 (1H$_{anti}$, qd, J = 6.4 and 1.4 Hz, CHCCl$_3$), 3.17–3.50 (1H$_{syn}$, m, CHCCl$_3$), 5.77 (1H$_{syn}$, d, J = 3.6 Hz, CHCl), 5.81 (1H$_{anti}$, d, J = 1.6 Hz, CHCl), 7.17 (5H, m, ArH); ^{13}C NMR (CDCl$_3$) δ 11.4 (C$_{anti}$, q), 12.2 (C$_{syn}$, q), 60.8 (C$_{anti}$, d), 61.2 (C$_{syn}$, d), 61.9 (C$_{syn}$, d), 62.1 (C$_{anti}$, d), 103.2 (s), 126.8 (C$_{anti}$, d) 127.9 (C$_{syn}$, d), 128.2 (C$_{anti}$, d), 128.6 (C$_{anti}$, d), 128.7 (C$_{syn}$, d), 129.3 (C$_{syn}$, d), 136.7 (C$_{syn}$, s), 140.6 (C$_{anti}$, s). Anal. Calcd for C$_{10}$H$_{10}$Cl$_4$: C, 44.16; H, 3.71. Found: C, 44.40; H, 3.73.
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