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Synthesis of Novel Aromatic Isocyanurates by the Fluoride-Catalyzed Selective Trimerization of Isocyanates

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Introduction

Since the aromatic isocyanurate structure produced by trimerization of aromatic isocyanates has been known to improve polyurethanes or coating materials in various properties such as enhanced thermal resistance, flame retardation, chemical resistance, and film-forming characteristics, a number of catalysts for isocyanate trimerization have been reported previously. For example, various metal salts of carboxylic acids,[1] tertiary amines,[2] metal alkoxides,[3] epoxides–pyridine,[4] and metal oxides[5] have been used for this purpose. However, the conventional catalysts for isocyanate trimerization as mentioned above have suffered the following disadvantages: (i) low activity necessitating severe conditions, (ii) poor selectivity accompanied by the formation of byproducts such as dimers and carbodiimides, (iii) difficulty in the removal of catalysts and additives, and (iv) inevitable side reactions due to the attack by the active species of a catalyst upon the functional groups such as esters, amides, and olefins.

Fluoride salts have been widely studied[6,7] as reagents and catalysts for the selective organic reactions. Recently, we have found the new ring-opening reaction of glycidyl ethers by aryl silyl ethers to be catalyzed by cesium fluoride.[8]

We report here a new finding that fluoride salts serve as catalysts for the trimerization of aromatic isocyanates. Synthesis of some new aromatic isocyanurates bearing functional groups by selective trimerization with these new catalysts is also described.

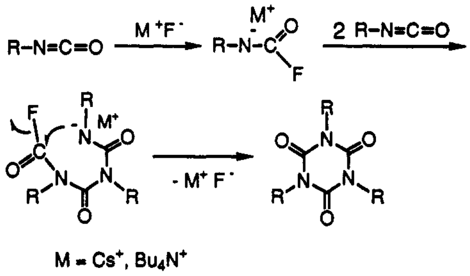
Results and Discussion

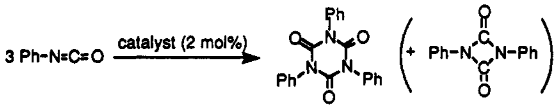
F^--Catalyzed Trimerization of Phenyl Isocyanate. Trimerization of phenyl isocyanate was carried out using cesium fluoride (CsF) or tetrabutylammonium fluoride (**TBAF**) as catalyst under various reaction conditions. The results for a number of catalysts are summarized in Table I. Trimerization of phenyl isocyanate (**1**) catalyzed by CsF proceeded in a heterogeneous system. At room temperature, triphenyl isocyanurate (**2**) was obtained in high yield with the formation of a small amount of its dimer **3**. At elevated temperature, trimerization was attained quantitatively without the formation of any byproducts. CsF was removed easily by filtration of a solution of the product in methylene chloride.

Table I. Trimerization of Phenyl Isocyanate with Various Catalysts

catalyst	temp, °C	time, min	trimer (dimer), %
CsF	rt	20	80.2 (8.8)
CsF	130	5	90.5
Bu_4NF(THF)	rt	1	85.1 (12.7)
Bu_4NF(THF)	rt	5	98.8
KF	rt	20	1.4
Bu_4NCl	rt	20	0
Et_3N	rt	20	0
AcOK	rt	20	0

Scheme I





(1)

1 **2** **3**

On the other hand, KF showed very low activity for the trimerization of phenyl isocyanate.

Trimerization catalyzed by **TBAF** proceeded in a homogeneous system. The activity was much higher than CsF, but the removal of the catalyst was a little tedious. Tetrabutylammonium chloride was soluble in phenyl isocyanate, but no catalytic activity was observed.

When trimerization of phenyl isocyanate was carried out by the commonly used neutral or basic catalysts under similar reaction conditions to the fluoride-catalyzed reaction, trimerization scarcely proceeded as shown in Table I.

The MO calculations have indicated that fluoride anion is the hardest nucleophile.[9] It is suggested that fluoride salts such as CsF and **TBAF**, in which fluoride anion is loosely interacted with a countercation, have high nucleophilicity. They can attack hard heterophiles like isocyanate. Trimerization of isocyanates is therefore suggested to proceed as shown in Scheme I. In the F^--catalyzed cyclization of carbamates, H-bonding of these compounds to F^- plays an important role.[7] Our result provides a new example of a fluoride-ion-promoted cyclization without the participation of H-bonding.

CsF-Catalyzed Selective Trimerization of Reactive Isocyanurates. Various aromatic isocyanates bearing reactive groups were trimerized by using CsF. The isocyanate bearing a reactive group, 4-[(trimethylsilyl)oxy]phenyl isocyanate (**4a**), was trimerized with cesium fluoride at 130 °C for 10 min. The catalyst was removed by filtration of a solution of the product in methylene chloride. The corresponding isocyanurate (**5a**) was obtained in quantitative yield. When isocyanate **4a** was

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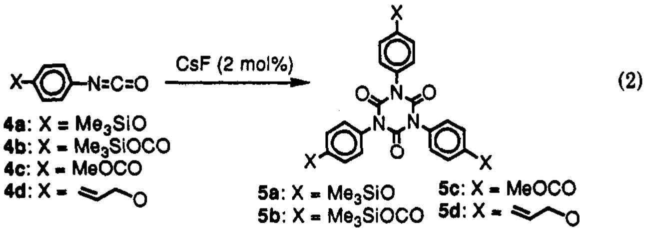
Table II. Selective Trimerization of Reactive Isocyanates 4 by F⁻ Catalysts

X of isocyanate 4	catalyst	temp, °C	time, min	5 (dimer), %
a: Me_3SiO	CsF	130	10	100[a]
b: Me_3SiOCO	Bu_4NF(THF)	70	1	98.0[a]
	CsF	130	10	70.0[a]
c: MeOCO	Bu_4NF(THF)	70	1	65.5 (34.5)
	CsF	130	1	85.8 (13.2)
d: 	CsF	130	10	95.0

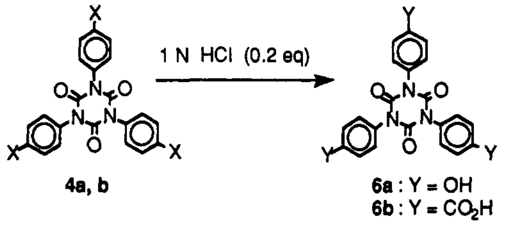
[a] Crude yield.

trimerized with styrene oxide and pyridine following the procedure of Jones et al.[4] at room temperature for 24 h, the partly desilylated product was obtained in 74% yield. New aromatic isocyanurates bearing various reactive groups (5) as shown in eq 2 were obtained by the CsF-catalyzed selective trimerization of reactive isocyanates in high yields without any unfavorable side reactions on the reactive groups of 5 (Table II).



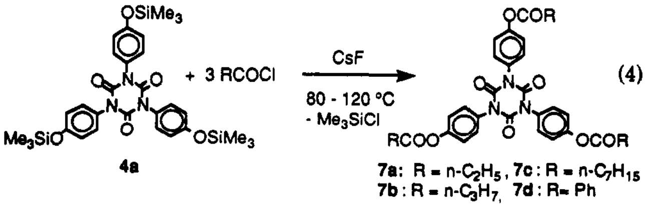
(2)

Chemical Transformation of New Reactive Isocyanurates. Acid hydrolysis of trimethylsilylated isocyanurates **4a** and **4b** gave new aromatic isocyanurates (**6**) bearing free acid and phenol groups, and the products were obtained in quantitative yields. They are attractive as trifunctional aromatic acids or phenols bearing the thermally stable isocyanurate group.



(3)

Mormann et al. reported that the reaction of an aliphatic acid chloride with aryl silyl ether catalyzed with a base proceeded above 80 °C.[10] As another interesting chemical transformation of reactive isocyanurates, isocyanurate **4a** was converted to isocyanurates with various ester groups (**7**) in high yields by the reaction of isocyanurate **4a** with a slight excess of acid chlorides and CsF catalyst at 80–120 °C for 30–180 min, accompanying the evolution of a Me_3SiCl gas (eq 4, Table III).



(4)

Table III. Synthesis of Isocyanurate Esters 7

acid chloride	temp, °C	time, min	isocyanurate	7 (crude), %
C_2H_5COCl	80	30	**7a**	71.5 (100)
n-C_3H_7COCl	95	30	**7b**	71.0 (80)
n-$C_7H_{15}COCl$	120	30	**7c**	54.1 (64)
PhCOCl	120	180	**7d**	71.4 (96)

The existing methods for the introduction of aromatic isocyanurate structures in synthetic polymers are very limited. The reaction of aromatic diisocyanates with polyols produces polyurethanes containing the isocyanurate structure by partial trimerization. Aromatic isocyanurate derivatives having various types of reactive groups synthesized here would be useful as monomers, additives, or cross-linking agents to introduce the thermally stable and highly polar aromatic isocyanurate structure into a wide variety of synthetic polymers.

We found for the first time that neutral salts, CsF and **TBAF**, functioned very effectively as catalysts for the trimerization of aryl and alkyl isocyanates. New aromatic isocyanurates with various functional groups were synthesized by the CsF-catalyzed selective trimerization of reactive isocyanates and chemical transformation of the products. These findings are applicable to the formation of new isocyanurate derivatives as well as polyurethane manufacturing. Characterization and application of new isocyanurate derivatives are now in progress.

Experimental Section

Materials. 4-(Methoxycarbonyl)phenyl isocyanate was obtained from Aldrich. Tetrabutylammonium fluoride (**TBAF**, 1 M tetrahydrofuran solution) was obtained from Tokyo Kasei. Cesium fluoride was obtained from Yoneyama Chemical. 4-[(Trimethylsilyl)oxy]phenyl isocyanate[11] was synthesized by trimethylsilylation of the hydroxyl group of 4-aminophenol with excess hexamethyldisilazane at 120 °C for 2 h followed by isocyanation with diphenylmethane-4,4′-diisocyanate at 150–190 °C for 2.5 h (total yield 88.2%, bp 69–70 °C/0.43 mmHg (lit.[11] bp 52–3 °C/0.24 mmHg); IR (KBr) 2270, 1255, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.25 (s, 9 H, Me_3Si), 6.6–7.1 (m, 4 H, phenylene)). 4-[[(trimethylsilyl)oxy]carbonyl]phenyl isocyanate[11] was synthesized by the trimethylsilylation of the carboxyl group of 4-aminobenzoic acid with excess hexamethyldisilazane at 140 °C for 2 h followed by isocyanation with diphenylmethane-4,4′-diisocyanate at 150–190 °C for 2.5 h (total yield 82.0%, bp 80–82 °C/0.15 mmHg (lit.[11] bp 85 °C/0.027 mmHg); IR (KBr) 2270, 1693, 1298, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.38 (s, 9 H, Me_3Si), 7.0–7.2, 7.9–8.1 (m, 4 H, phenylene)) with the procedure of Mormann et al.[11] 4-(Allyloxy)phenyl isocyanate was synthesized by the reaction of 4-(allyloxy)aniline and trichloromethyl chloroformate (phosgene dimer) in ethylene dichloride at 70 °C for 1 h in 89% yield (bp 101 °C/4 mmHg; IR (KBr) 2280, 1580 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.3–4.5 (m, 2 H, CH_2), 5.1–5.3, 5.7–6.4 (m, 3 H, vinyl), 6.6–7.1 (m, 4 H, phenylene)) following to the similar procedure of Socha.[12] Other chemicals used in this study were purified by distillation.

CsF-Catalyzed Trimerization of Phenyl Isocyanate. Cesium fluoride (128 mg, 0.84 mmol) was dried in vacuo at 130 °C for 30 min. To the salt was added phenyl isocyanate (1) (4.56 mL, 42 mmol) with stirring, and the mixture was heated at 130 °C for 1 min to give a solid. After heating for an additional 9 min, the unreacted phenyl isocyanate was removed by evaporation in vacuo and the residue was dissolved in methylene chloride. The catalyst was removed by filtration, and the solvent was evaporated to obtain triphenyl isocyanurate (2) (4.75 g, 95.0%): mp 282–284 °C (lit.[4] mp 285 °C); IR (KBr), 1710 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.8–7.3 (m, 12 H, phenylene).

TBAF-Catalyzed Trimerization of Phenyl Isocyanate. **TBAF** (1 M, 0.84 mL, 0.84 mmol) was added to isocyanate 1

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(4.56 mL, 42 mmol) at room temperature with vigorous stirring. In 1 min, the reaction mixture almost solidified. The unreacted isocyanate was removed by evaporation under reduced pressure, and the residue was dissolved in methylene chloride and washed with aqueous NaCl. The organic layer was dried over $MgSO_4$ and evaporated to obtain isocyanurate **2** (4.25 g, 85.1%) from the remaining ether-insoluble portion and phenyl isocyanate dimer (**3**) (0.635 g, 12.7%) from the ether-soluble portion. **3**: IR (KBr) 1755, 1775 cm^{-1} (uretidione).[13]

CsF-Catalyzed Selective Trimerization of 4-[(Trimethylsilyl)oxy]phenyl Isocyanate (4a). To dried cesium fluoride (0.61 g, 4.0 mmol) was added isocyanate **4a** (41.4 g, 0.20 mol), and the mixture was vigorously stirred at 130 °C for 5 min. The mixture was solidified completely. The solid was dissolved in methylene chloride, and the catalyst was removed by filtration of the solution. The solvent was evaporated to give tris[4-[(trimethylsilyl)oxy]phenyl] isocyanurate (**5a**) (41.2 g, 98.0%), which was used for further reaction without purification due to its high reactivity: mp 202–204 °C; IR (KBr) 1720 (isocyanurate), 1603 (phenyl), 1270, 1250 cm^{-1} (silyl ether); ^1H NMR ($CDCl_3$) δ 0.25 (s, 27 H, Me_3Si), 6.8–7.3 (m, 12 H, phenylene).

The following compounds were prepared in a similar manner under the conditions of Table II. **Tris[4-(methoxycarbonyl)phenyl] isocyanurate (5c)**: yield 85.8%; mp >320 °C; IR (KBr) 1715 cm^{-1} (isocyanurate); ^1H NMR ($CDCl_3$) δ 3.95 (s, 9 H, Me), 7.4–7.7, 8.1–8.4 (m, 12 H, phenylene). Anal. Calcd for $C_{27}H_{21}N_3O_9$: C, 61.02; H, 3.98; N, 7.91. Found: C, 60.95; H, 3.90; N, 7.93. **Tris[4-(allyloxy)phenyl] isocyanurate (5d)**: yield 95.0%; mp 218–220 °C; IR (KBr) 1710 (isocyanurate), 1650 cm^{-1} (allyl); ^1H NMR ($CDCl_3$) δ 4.5–4.7 (m, 6 H, CH_2), 5.2–5.6, 5.8–6.5 (m, 9 H, $CH_2{=}CH$), 6.9–7.4 (m, 12 H, phenylene). Anal. Calcd for $C_{30}H_{27}N_3O_6$: C, 68.56; H, 5.18; N, 8.00. Found: C, 68.79; H, 5.31; N, 8.06.

TBAF-Catalyzed Selective Trimerization of 4-[[(Trimethylsilyl)oxy]carbonyl]phenyl Isocyanate (4b). TBAF (1 M in THF, 4 mL, 4 mmol) was added to 50.1 g (0.20 mol) of isocyanate **4b**. The mixture was heated to 70 °C with vigorous stirring for 1 min to give a solid. The solid was washed with anhydrous ether to give 45.6 g (crude yield 91.0%) of tris[4-[[(trimethylsilyl)oxy]carbonyl]phenyl] isocyanurate (**5b**) which was used for further reaction without purification due to its high reactivity. **5b**: mp 227–229 °C; IR (KBr) 1720 (isocyanurate), 1705 (ester), 13101, 1295 cm^{-1} (silyl ester); ^1H NMR ($CDCl_3$) δ 0.40 (s, 27 H, Me_3Si), 7.4–7.6, 8.1–8.3 (m, 12 H, phenylene).

Hydrolysis of Tris[4-[(trimethylsilyl)oxy]phenyl] Isocyanurate (4a). Hydrochloric acid (1 N, 10 mL) was added to an acetone solution (200 mL) of isocyanurate **4a** (26.5 g, 20 mmol), the mixture was stirred at room temperature for 10 min, and the solvent was removed by evaporation to give a solid (24.5 g). To the methanol solution (100 mL) of the crude solid was added chloroform (30 mL) gradually to obtain 21.5 g of tris(4-hydroxyphenyl) isocyanurate (**6a**) (21.5 g, 81.0%): mp >320 °C; IR (KBr) 3400 (hydroxyl), 1695 cm^{-1} (isocyanurate); ^1H NMR (acetone-d_6) δ 6.8–7.5 (m, 12 H, phenylene). Anal. Calcd for $C_{21}H_{15}N_3O_6$: C, 62.22; H, 3.73; N, 10.37. Found: C, 61.96; H, 3.64; N, 9.95. Tris[4-[[(trimethylsilyl)oxy]carbonyl]phenyl] isocyanurate (**4b**) was hydrolyzed in the same way to give tris(4-carboxyphenyl) isocyanurate (**6b**) (78.6%): mp >320 °C; IR (KBr) 3000–3500 (carboxyl), 1696–1720 cm^{-1} (isocyanurate, carboxyl); ^1H NMR (DMSO-d_6) δ 7.5–7.8, 8.0–8.3 (m, 12 H, phenylene). Anal. Calcd as methyl ester for $C_{27}H_{21}N_3O_9$: C, 61.02; H, 3.98; N, 7.91. Found: C, 60.95; H, 3.90; N, 7.93.

Synthesis of Esterified Aromatic Isocyanurate (7). General Procedure. An organic acid chloride (22 mmol) was added to isocyanurate **5a** (4.1 g, 20 mmol), and the mixture was stirred at 80–120 °C. The bubbling of trimethylsilyl chloride observed and stopped after heating for 30–180 min, and the solidified product was obtained. The product was dissolved in methylene chloride, and the catalyst was removed by filtration of the solution. The solvent was evaporated to give the corresponding tris[4-(acyloxy)phenyl] isocyanurate **7**, which was purified by the recrystallization with 2-propanol. **7a** (R = C_2H_5): mp 245–247 °C; IR (KBr) 1760 (ester), 1710 cm^{-1} (isocyanurate); ^1H NMR ($CDCl_3$) δ 1.28 (t, 9 H, CH_3), 2.60 (q, 6 H, CH_2), 7.2–7.6 (m, 12 H, phenylene). Anal. Calcd for $C_{30}H_{27}N_3O_9$: C, 62.82; H, 4.74; N, 7.33. Found: C, 62.82; H, 4.74; N, 7.24. **7b** (R = n-C_3H_7): mp 204.5–205.5 °C; IR (KBr) 1760, 1715 cm^{-1} (isocyanurate); ^1H NMR ($CDCl_3$) δ 1.06 (t, 9 H, CH_3), 1.6–2.2 (m, 6 H, CH_2), 2.58 (t, 6 H, CH_2), 7.2–7.6 (m, 12 H, phenylene). Anal. Calcd for $C_{33}H_{33}N_3O_9$: C, 64.38; H, 5.40; N, 6.83. Found: C, 64.17; H, 5.39; N, 6.83. (R = n-C_7H_{15}): mp 125.5–126.5 °C; IR (KBr) 1758, 1738 (ester), 1720, 1690 cm^{-1} (isocyanurate); IR (film) 1755 (ester), 1715 cm^{-1} (isocyanurate); ^1H NMR ($CDCl_3$) δ 0.7–2.1 (m 39 H, C_6H_{13}), 2.57 (t, 6 H, CH_2), 7.2–7.6 (m, 12 H, phenylene). Anal. Calcd for $C_{42}H_{57}N_3O_9$: C, 67.45; H, 7.68; N, 5.62. Found: C, 67.44; H, 7.19; N, 5.45. (R = Ph): mp >320 °C; IR (KBr) 1760, 1742 (ester), 1715, 1698 cm^{-1} (isocyanurate); IR (film) 1755 (ester), 1715 cm^{-1} (isocyanurate); ^1H NMR ($CDCl_3$) δ 0.7–2.1 (m, 27 H, C_4H_9), 2.57 (t, 6 H, CH_2), 7.2–7.6 (m, 12 H, phenylene). Anal. Calcd for $C_{42}H_{27}N_3O_9$: C, 70.29; H, 3.79; N, 5.85. Found: C, 70.02; H, 3.68; N, 5.84.

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