

Incorporation of molecular nitrogen into organic compounds

III. Reaction of titanium–nitrogen complexes with acid halides and acid anhydrides

Miwako Mori ^{*}, Yasuhiro Uozumi and Masakatsu Shibasaki ^{*}

Faculty of Pharmaceutical Sciences, Hokkaido University, Sapporo 060 (Japan)

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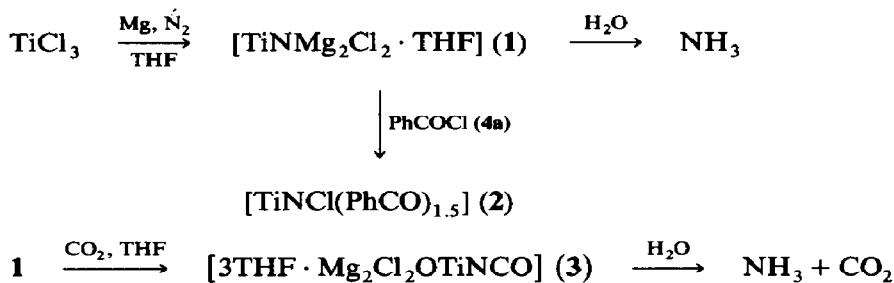
Abstract

The titanium–nitrogen complex **1**, [TiNMg₂Cl₂·THF] prepared from TiCl₃ or TiCl₄ and Mg in THF under nitrogen reacts with acid chloride to give amide and/or imide. The cyclic imides were obtained by the reaction of titanium–isocyanate complex **3**, [3THF·Mg₂Cl₂OTiNCO], made from titanium–nitrogen complex **1** and carbon dioxide, and the corresponding cyclic acid anhydrides. Benzoxazone derivatives afforded the corresponding quinazoline derivatives in a similar procedure. These results indicate that molecular nitrogen was incorporated into organic compounds via titanium nitrogen complexes.

Introduction

Incorporation of molecular nitrogen into organic compounds is a very challenging process. Since Vol'pin and Shur discovered that molecular nitrogen could be fixed by Cp₂TiCl₂ and RMgBr under very mild conditions [1], many transition metal–nitrogen complexes were synthesized from a variety of transition metals [2]. The use of nitrogen–metal complex generated from molecular nitrogen for organic syntheses has been little studied. Yamamoto et al., reported that TiCl₃–Mg–THF system reacts with molecular nitrogen (1 atm) at room temperature to afford a complex formulated as TiNMg₂Cl₂·THF (**1**). This complex further reacts with benzoyl chloride to give the benzoyl–titanium–nitrogen complex [TiNCl(PhCO)_{1.5}] (**2**) [3]. The results indicate that titanium–nitrogen complex **1** prepared from TiCl₃–Mg–THF under nitrogen at room temperature can react with organic compounds. However, whether carbon–nitrogen bond is formed on the titanium complex was not clear.

On the other hand, Sobota et al. reported that titanium–nitrogen complex **1** reacts with carbon dioxide (1 atm) at room temperature to afford titanium–iso-



Scheme 1

cyanate complex $[3\text{THF} \cdot \text{Mg}_2\text{Cl}_2\text{OTiNCO}]$ (3) [4]. They also found that complex 3 further reacts with methyl iodide to give methyl isocyanate. These results prompted us to use titanium–nitrogen complexes 1, 2 and 3 as the reagents for incorporation of molecular nitrogen into organic compounds.

Results and discussion

Reaction of titanium–nitrogen complex with aroyl chloride

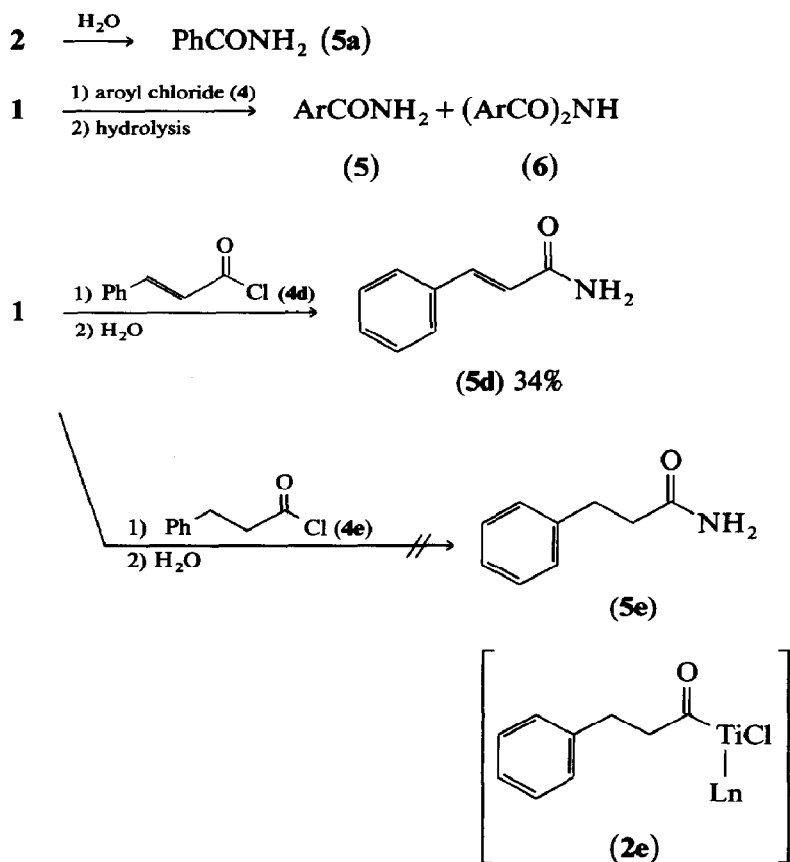
The benzoyl–titanium–nitrogen complex 2 was prepared from titanium–nitrogen complex 1 and benzoyl chloride by use of the procedure reported by Yamamoto [3]. The isolated complex 2 was treated with water at room temperature to give benzamide 5a in 17% yield based on titanium–nitrogen complex 1. The results indicate that a carbon–nitrogen bond was formed by the reaction of complex 1 with benzoyl chloride, and that molecular nitrogen could be incorporated into the organic compound via the transition metal complex. Thus, various aroyl chlorides 4 were allowed to react with titanium–nitrogen complex 1 prepared from TiCl_3 and Mg in THF under nitrogen in situ. The results are summarized in Table 1. It was surprising that benzimide 6a was formed along with benzamide 5a (Table 1, Run 1). The yield of benzimide was raised when THF solution of 1 and benzoyl chloride was refluxed overnight (Run 2). The use of a large amount of benzoyl chloride improved the yields of the desired compounds 5a and 6a (Run 5). Other *para*-sub-

Table 1

Reaction of aroyl chloride with 1

Run	Aroyl chloride		Metal compound	Temperature	Yields ^a		
	R	(eq)			amide	imide	
1	H	(4a)	(1.8)	TiCl_3	rt	11	7
2	H	(4a)	(1.8)	TiCl_3	reflux	–	17
3	H	(4a)	(4.5)	TiCl_3	rt	40	12
4	H	(4a)	(4.5)	TiCl_3	reflux	36	29
5	H	(4a)	(12.0)	TiCl_3	rt	41	24
6	<i>p</i> -Me	(4b)	(4.5)	TiCl_3	rt	34	3
7	<i>p</i> -MeO	(4c)	(4.5)	TiCl_3	rt	49	–
8	H	(4a)	(3.0)	Cp_2TiCl_2	rt	22	12
9	H	(4a)	(3.0)	VCl_3	reflux	4	12

^a Based on titanium complexes.

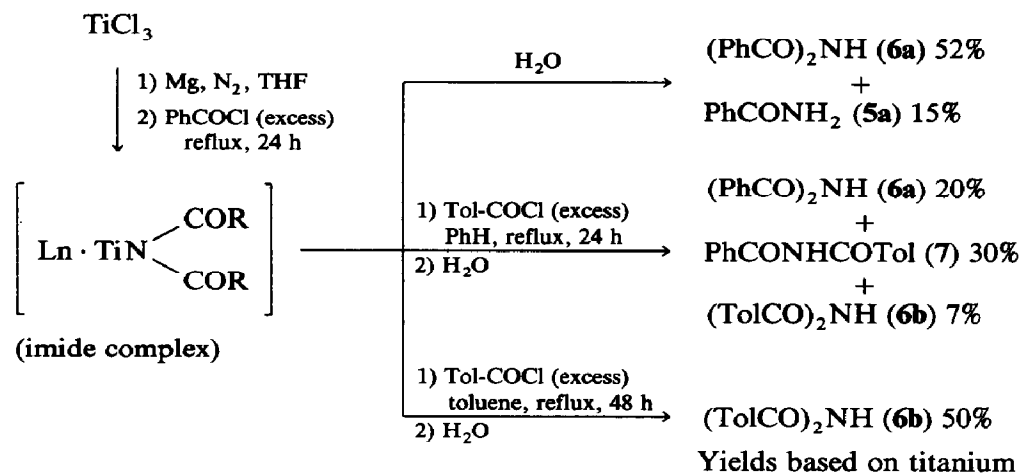


Scheme 2

stituted benzoyl chlorides afforded amide and/or imide in moderate yields (Runs 6 and 7). Titanium–nitrogen complexes prepared from TiCl_4 or Cp_2TiCl_2 , Mg and molecular nitrogen were treated respectively in a similar manner to give the same compounds. The vanadium–nitrogen complex prepared from VCl_3 , Mg and molecular nitrogen also afforded benzamide and benzimide. In some cases, a small amount of benzonitrile was detected on IR spectrum [6*]. The reaction of titanium–nitrogen complex 1 with unsaturated acid chloride 4d gave amide 5d, but when saturated acid chloride was used no 5e was formed, probably because decarbonylation from the acylnitrogen complex 2e followed by β -hydride elimination occurred [7*].

To a benzene solution of titanium–nitrogen complex 1, prepared from TiCl_3 , Mg and N_2 , in THF was added an excess of benzoyl chloride and the solution was refluxed overnight to give a black precipitate, which is insoluble in benzene. The IR spectrum (ν_{max} 1610 cm^{-1}) of the precipitate was clearly different from that of benzoyl–titanium–nitrogen complex 2. Hydrolysis of this complex yields the imide 6a (52% yield) and the amide 5a (15% yield). To a suspension of the black precipitate, prepared from titanium–nitrogen complex 1 and benzoyl chloride, in

* Reference number with asterisk indicates a note in the list of references.

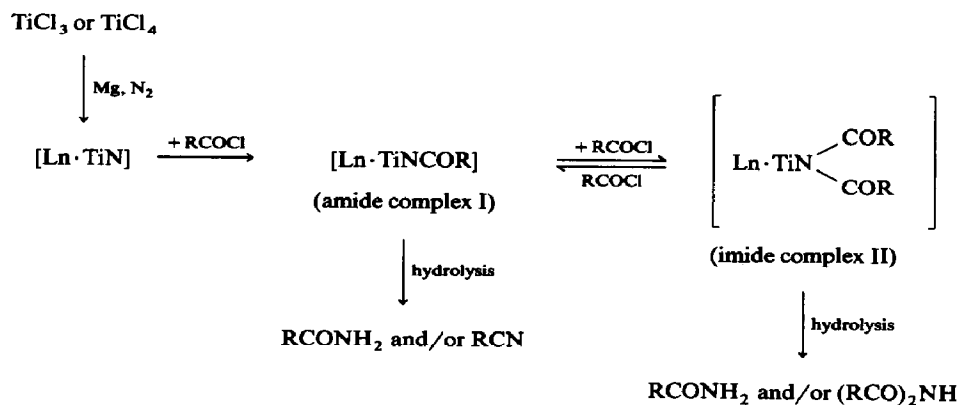


Scheme 3

benzene was added an excess of toluoyl chloride and the solution was further refluxed overnight. The mixture was hydrolysed to give imide **7** in 30% yield along with benzimide **6a** (20% yield) and unexpected toluimide **6b** (7% yield). When the toluene solution was refluxed for 48 h, toluimide **6b** was obtained in 50% yield.

On the basis of these results, it appears that the reaction proceeds by the route depicted in Scheme 4. The reaction of titanium–nitrogen complex **1** with benzoyl chloride affords benzoyl–titanium–nitrogen complex **2** [3a] (amide complex I), which further reacts with benzoyl chloride to give another complex (imide complex II). The amide **5** could have been formed from aroyl–titanium–nitrogen complex (amide complex I) and the imide **6** could have been derived from imide complex II. Interestingly, the aroyl group on the imide complex can be readily exchanged with the other aroyl chloride, probably because imide complex II is in a state of equilibrium with amide complex I and aroyl group.

Low-valent titanium–nitrogen complex, prepared from TiCl₃–Mg–THF system, fixes molecular nitrogen to form titanium–nitrogen complex **1**, whose nitrogen



↓ hydrolysis

RCONH₂ and/or RCN

↓ hydrolysis

RCONH₂ and/or (RCO)₂NH

Scheme 4

Table 2

Reaction of complexes **3** with phthalic anhydride **10**

Run	Temperature	Time/h	Solvent	Yield/% ^a
1	rt	40	pyridine	3
2	reflux	24	pyridine	45
3	reflux	48	pyridine	53
4	reflux	24	mesitylene-Py	28
5	reflux	24	ClCH ₂ CH ₂ Cl-Py	19
6	reflux	24	dioxane-Py	16
7	120 °C	24	DMF	39
8	100 °C	24	NMP	78 ^b

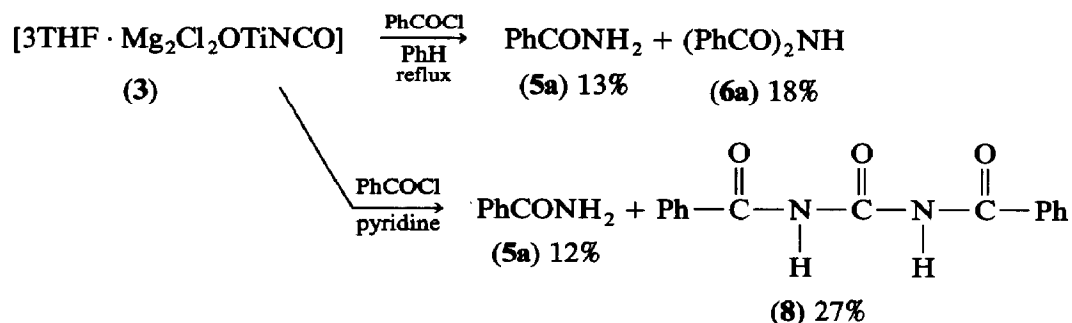
^a Based on complex **3**. ^b Based on phthalic anhydride.

could be incorporated into amides and/or imides by the reaction of an acid chloride with titanium–nitrogen complex **1** under very mild conditions.

Reaction of titanium–isocyanate complex with acid anhydride

Titanium–isocyanate complex [3THF · Mg₂Cl₂OTiNCO] (**3**), which was prepared from titanium–nitrogen complex **1** and carbon dioxide, is very interesting because complex **3** further reacts with methyl iodide to give methyl isocyanate, though the yield was not reported [4]. In order to elucidate the reactivity of this complex **3**, we attempted the reaction of titanium–isocyanate complex **3** with benzoyl chloride. A solution of complex **3** and benzoyl chloride was refluxed overnight, subsequent aqueous workup gave benzamide **5a** (13% yield) and benzimide **6a** (18% yield). The result indicates that the titanium–isocyanate complex **3** has similar reactivity to the benzoyl–titanium–nitrogen complex **2**. However, when a mixture of complex **3** and benzoyl chloride in pyridine was stirred at room temperature, compound **8** (27% yield) was obtained along with benzamide **5a** (12% yield). It is likely that pyridine acts not only as the activating agent of acyl halide but also as a ligand. However, NEt₃ and bipyridine do not affect this reaction. The reaction of phthaloyl dichloride **4f** with complex **3** yielded phthalimide **6f** in 14% yield in place of the expected seven membered ring **9**. When phthalic anhydride **10** was used instead of phthaloyl dichloride **4f** in the expectation that acid anhydride would oxidatively add to the low-valent metal complex, again the same product **6f** was obtained in a low yield (Table 2, Run 1). The yield was improved when a pyridine solution of phthalic anhydride **10** and titanium–isocyanate complex **3** was refluxed overnight (Runs 2 and 3). The use of other pyridine-free solvents such as DMF and NMP (*N*-methyl-2-pyrrolidone) had the same outcome as but solvents such as mesitylene, dichloroethane and dioxane containing pyridine gave poorer results. The use of 3 equivalent of titanium–isocyanate complex **3** raised the yield of the desired product **6f** (Run 8).

Homophthalimide (**12**), tetrahydrophthalimide (**14**) and perhydrophthalimide (**16**) were obtained from the corresponding acid anhydride **11**, **13** and **15** in a similar manner in 10, 16, and 27% yields, respectively. Benzoxazone **17** which is regarded as a kind of mixed anhydride was expected to add oxidatively to the low-valent metal complex. A solution of benzoxazone **17** was heated with titanium–isocyanate complex **3** in NMP at 100 °C for 24 h to produce quinazoline **18** in 55% yield in one step. These results indicate that molecular nitrogen can be incorporated into



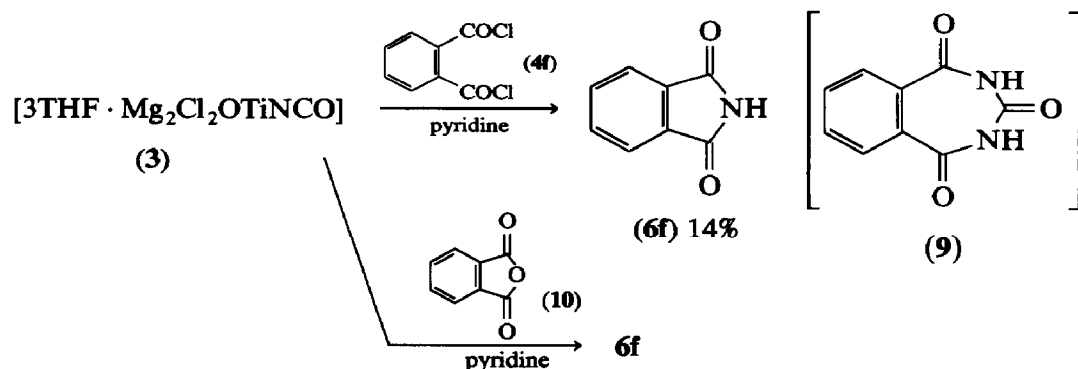
Scheme 5

heterocycles by use of the titanium–isocyanate complex **3**.

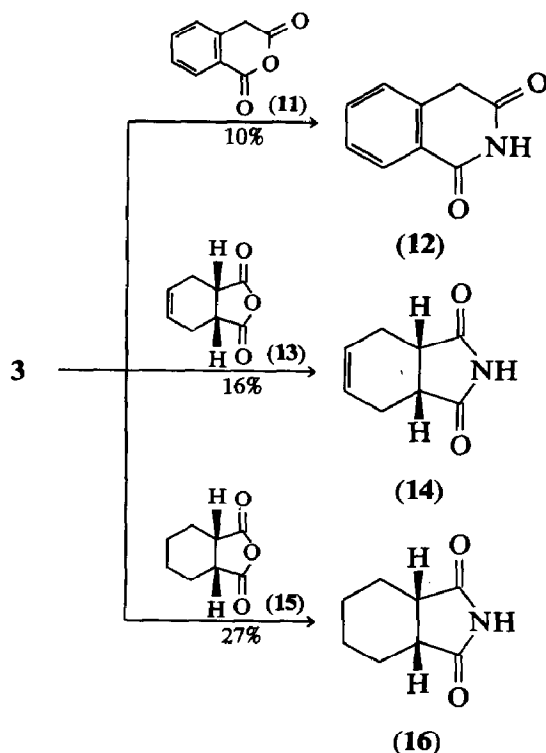
The first step of this reaction is probably the oxidative addition of acid anhydride **10** to titanium–isocyanate complex **3**. Migration of the acyl group in the metalacycle **19** to the nitrogen on the titanium affords the seven membered metalacycle **20**. The nitrogen on complex **20** then attacks the carbonyl group followed by elimination of titanium oxide to give the imide–titanium complex **21**, which upon hydrolysis gives cyclic imide **6f**.

Conversion of aryl halide into amide and/or imide by nitrogenation and palladium-catalyzed carbonylation

The reaction of an aryl halide with carbon monoxide in the presence of a zero-valent palladium complex affords an aroylpalladium complex, **22**. If the aroyl–palladium complex is in a state of equilibrium with an aryl halide and zero-valent palladium complex, the corresponding amides or imides can be obtained from the aryl or vinyl halides by use of nitrogen incorporation followed by palladium-catalyzed carbonylation. When a mixture of bromobenzene (**23a**), an equimolar amount of titanium–isocyanate complex **3** and 10 mol% of $\text{Pd}(\text{PPh}_3)_4$ was heated at 80°C in the presence of diisopropylethylamine in NMP under carbon monoxide for 24 h, benzimide **6a** was obtained in 22% yield. Similarly, *p*-bromotoluene (**23b**) and *p*-iodoanisole (**23c**) were also converted into *p*-toluimide (**6b**) and *p*-anisimide (**6c**) (14% and 28% yields, respectively) along with *p*-toluamide (**5b**) (7%



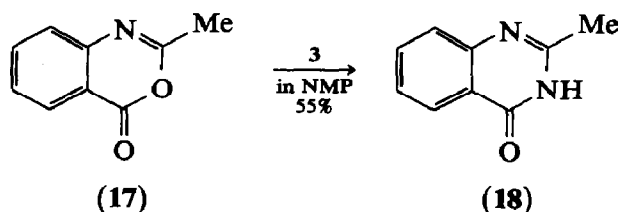
Scheme 6



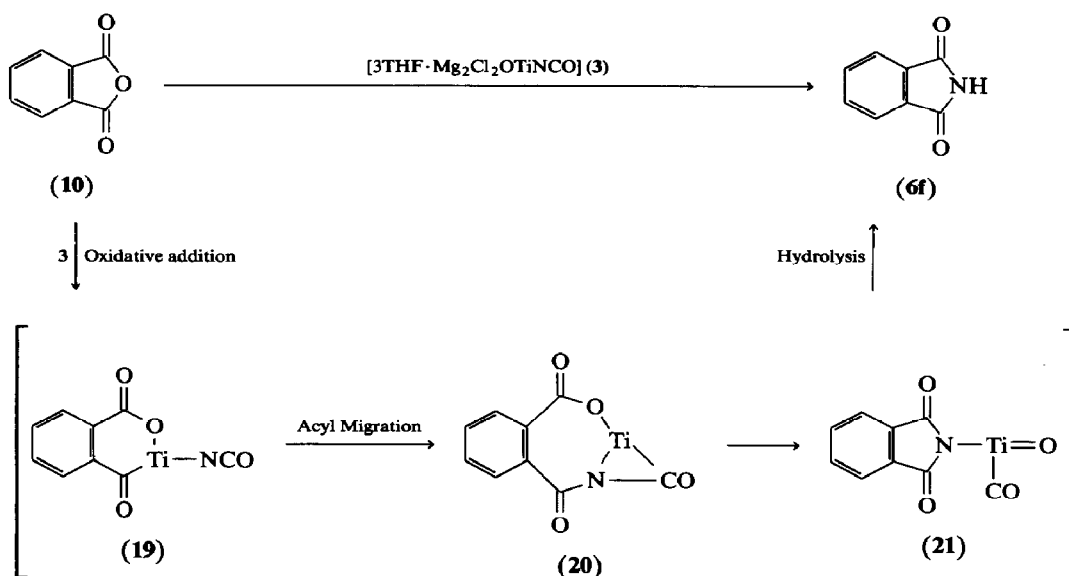
Scheme 7

yield) and *p*-anisamide (5c) (2% yield). *o*-Bromobenzoic acid (24) was treated with complex 3 and Pd(PPh₃)₄ in the presence of K₂CO₃ in NMP under carbon monoxide to give phthalimide (6f) in 22% yield, probably via a phthalic anhydride (10) intermediate. Strikingly, utilization of 3 equivalents of 3 gave the desired imide 6f in 82% yield. The combination system of nitrogenation and palladium catalyzed carbonylation in this system is very interesting because the palladium catalyst can be used together with titanium-isocyanate complex 3.

In conclusion, molecular nitrogen can be incorporated into organic compounds via the titanium–nitrogen complex 1 or the titanium–isocyanate complex 3. This nitrogenation can convert the acid halide and acid anhydride into the amide and/or imide. Moreover, heterocyclic compounds such as cyclic imides and quinazoline



Scheme 8



Scheme 9

derivative are obtained if when the relevant acid anhydrides and benzoxazone are used. In contrast, aryl halide can be converted into aroylamide **5** and/or aroylimide **6** in one step by the combination of nitrogenation and palladium-catalyzed carbonylation in one system [8*].

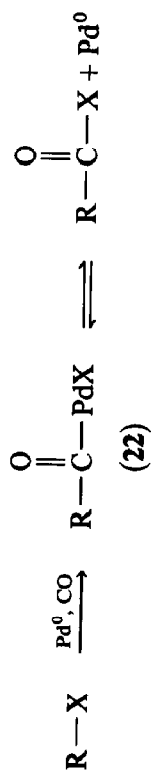
Experimental

All manipulations were performed under nitrogen by standard Schlenk techniques and all the reaction solutions were degassed through freeze-pump-thaw cycle. Solvents were dried by distillation under argon from sodium benzophenone (THF, Et₂O, dioxane), CaH₂ (benzene, toluene, mesitylene, NMP, pyridine) or P₂O₅ (CH₃CN). NMR spectra were recorded on either a JEOL JNM-FX90Q, JEOL JNM-FX100 or JEOL JNM-GX270. IR spectra were recorded on a JASCO A-300 spectrophotometer. Mass spectra were obtained from JEOL JMS-DX303 or JEOL JMS-HX110. Melting points were determined by Yanagimoto Special No. 815 or Isii Melting point Apparatus and are uncorrected. HPLC analysis was performed on Hitachi 635A with RI-detector (ERMA ERC-7520).

The titanium–nitrogen complex [THF · Mg₂Cl₂TiN] (**1**) [3], benzoyl–titanium–nitrogen complex [TiNCl(PhCO)1.5] (**2**) [3] and titanium–isocyanate complex [3THF · Mg₂Cl₂OTiNCO] (**3**) [4] were prepared by the known method.

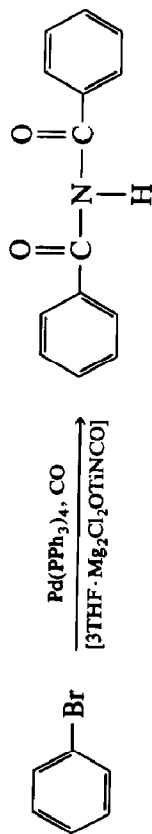
Reaction of benzoyl–titanium complex **2** with water

A 1,4-dioxane suspension of benzoyl–titanium–nitrogen complex **2** (50 mg, 0.2 mmol) was treated with water. The aqueous layer was extracted with ethyl acetate. The organic layer was dried over Na₂SO₄ and evaporated. The residue was purified by column chromatography on silica gel eluted with ethyl acetate to give benzamide (**5a**, 4 mg, 17%); mp. 128 °C (depression of melting point with an authentic sample was not observed.).

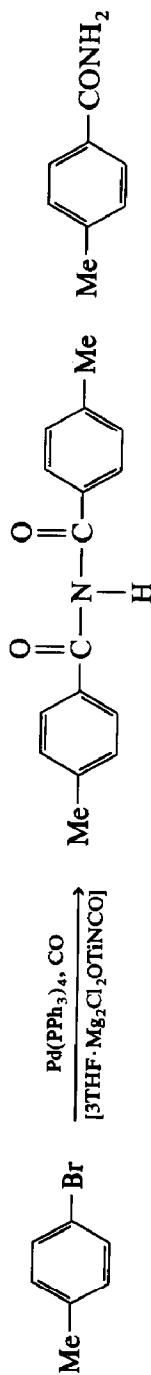


↓₃

5 and/or 6

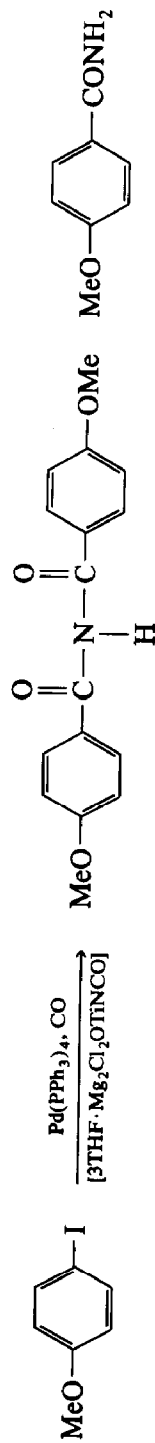


(23a)



(23b)

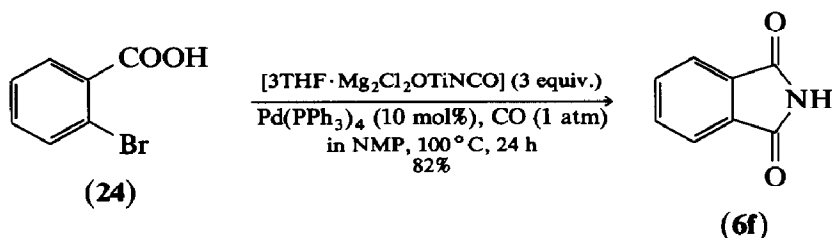
(5b) 7%



(23c)

(5c) 2%

Scheme 10.



Scheme 11

Reaction of **1** with aroyl chloride

General procedure

To a THF solution of **1** (prepared from 1.17 mmol TiCl₃) was added aroyl chloride (3.5 mmol) and the solution was stirred for 24 h. A small quantity of water was added to the reaction mixture and ethyl acetate was added. The organic layer was dried over Na₂SO₄ and evaporated. The residue was purified by column chromatography on silica gel to afford amide and/or imide.

Reaction of **1** with benzoyl chloride (**4a**)

A crude product which was prepared from **1** (prepared from 1.17 mmol TiCl₃) and benzoyl chloride (**4a**, 0.408 ml, 3.5 mmol) was purified by column chromatography on silica gel eluted with ethyl acetate to afford benzamide (**5a**, 56 mg, 40%), and benzimide (**6a**, 312 mg, 12%). Benzamide: mp 128–128.5 °C (no depression of melting point with an authentic sample was observed).; benzimide: IR ν_{\max} (CHCl₃) 3300, 1740, 1680, 1480 cm⁻¹; MS (m/z) 225(M^+), 197($M^+ - \text{CO}$), 105(PhCO, bp), 77.

Reaction of **1** with toluoyl chloride (**4b**)

The crude product that was obtained from the reaction of **1** (prepared from 1.07 mmol TiCl₃) with toluoyl chloride (**4b**, 497 mg, 3.21 mmol) was purified by column chromatography on silica gel eluted with ethyl acetate to afford toluamide (**5b**, 49 mg, 34%) and toluimide (**6b**, 9 mg, 3%). **5b**: mp 161–162 °C (no depression of melting point with an authentic sample was observed).; **6b**: IR ν_{\max} (CHCl₃) 3300, 1740, 1680, 1610, 1460 cm⁻¹; ¹H-NMR (CDCl₃) δ 2.41 (s, 3 H), 7.29(d, $J = 8.8$ Hz, 2 H), 7.77(d, $J = 8.8$ Hz, 2 H), 8.96(brs, 1 H); MS (m/z) 253(M^+), 225($M^+ - \text{CO}$), 119(bp), 91.

Reaction of **1** with anisoyl chloride (**4c**)

A crude product which was prepared from **1** (prepared from 1.02 mmol TiCl₃) and anisoyl chloride (**4c**, 522 mg, 3.06 mmol) was purified by column chromatography on silica gel eluted with ethyl acetate to afford anisamide (**5c**, 76 mg, 49%), mp 164–166 °C. (No depression of melting point with an authentic sample was observed.)

Reaction of **1** with cinnamoyl chloride (**4d**)

A crude product which was prepared from **1** (prepared from 1.30 mmol TiCl₃) and cinnamoyl chloride (**4d**, 649 mg, 3.90 mmol) was purified by column chro-

matography on silica gel eluted with ethyl acetate to afford cinnamamide (**5d**, 65 mg, 34%), mp 145–147°C. (No depression of melting point with an authentic sample was observed.)

Acyl exchange reaction on titanium-nitrogen complex 1

Reaction of imide complex with benzoyl chloride (4a)

A solution of **1** prepared from TiCl_3 (5.525 mmol) and benzoyl chloride (**4a**, 2.40 g, 17.1 mmol) in benzene (10 ml) was refluxed for 24 h. After cooling, the black precipitate was filtered and washed with benzene and dried. IR ν_{max} (Nujol) 1605 cm^{-1} . To a suspension of the black product in benzene (20 ml), was added water (1 ml) and the mixture was stirred for 2 h. Then ethyl acetate was added and the organic layer was dried over Na_2SO_4 . The filtrate was evaporated and the residual oil was purified by column chromatography on silica gel with ethyl acetate–n-hexane(1 : 1–1 : 0) as eluant to give benzimide (**5a**, 646 mg, 52%) and benzamide (**6a**, 100 mg, 15%).

Reaction of imide complex with toluoyl chloride (4b)

To a suspension of the imide complex (1 mmol) in benzene (20 ml) was added toluoylchloride (**4b**, 1.54 g) in benzene (10 ml). After the benzene solution has been refluxed for 24 h, water was added and the solution was stirred for 2 h. After the usual workup, the residue was purified by column chromatography on silica gel with ethyl acetate–n-hexane(1 : 1–1 : 0) as eluant to give a mixture (139.5 mg) of **6a** (7), **6b** (30) and **7** (20%) (the yield was determined by HPLC analysis (column : Cica-Merck RT-250-4; eluent ethyl acetate–n-hexane = 1 : 2)). Similar reaction was carried out in toluene with heating for 48 h to afford toluimide (**6b**, 126 mg, 50%).

Reaction of titanium–isocyanate complex 3 with benzoyl chloride (4a) in pyridine

To a solution of **3** (220 mg, 0.5 mmol) in pyridine (3 ml) was added benzoyl chloride (**4a**, 140 mg, 1.0 mmol) at 0°C and the solution was stirred at room temperature for 24 h. Ethyl acetate was added to the solution and the organic layer was washed with 5% HCl, sat. NaHCO_3 and brine, dried over Na_2SO_4 and evaporated. The residue was purified by column chromatography on silica gel eluted with ethyl acetate–n-hexane(1 : 1) to give benzamide (**5a**, 14 mg, 12%), and colorless crystals of **8** (18 mg, 27%). **8**: mp 235–236°C (from ethyl acetate) IR ν_{max} (Nujol) 3240, 1760, 1660, 1520, 1455 cm^{-1} ; $^1\text{H-NMR}(\text{CDCl}_3)\delta$ 4.28 and 5.60 (brs, and brs, 1 H), 7.46–8.08(m, 10 H), 8.51 and 9.08(brs and brs, 1 H); MS (m/z) 268 (M^+), 121(PhCONH_2), 105(PhCO ,bp), 77; Anal, Found: C, 67.25; H, 4.42; N, 10.30. $\text{C}_{15}\text{H}_{12}\text{N}_2\text{O}_3$ calcd: C, 67.15; H, 4.50; N, 10.44.

Reaction of 3 with cyclic anhydride

General procedure

To a solution of **3** (0.5 mmol) in pyridine was added cyclic anhydride(1.0 mmol) at 0°C and the solution was refluxed for 48 h. Ethyl acetate was added to the reaction mixture and the organic layer was washed with 5% HCl, sat. NaHCO_3 and brine, and dried over Na_2SO_4 . The filtrate was evaporated and the residue was purified by column chromatography on silica gel to give cyclic imide.

Reaction of 3 with phthalic anhydride (10)

A crude product which was prepared from **3** (220 mg, 0.5 mmol) and phthalic anhydride (**10**, 148 mg, 1.0 mmol) was purified by column chromatography on silica gel eluted with n-hexane–ethyl acetate(1 : 1) to give colorless needles of phthalimide (**6f**, 39 mg, 53%: mp 234–237 °C (No depression of melting point with authentic sample was observed).

Reaction of 3 with homophthalic anhydride (11)

A crude product which was prepared from **3** (220 mg, 0.5 mmol) and homophthalic anhydride (**11**, 162 mg, 1 mmol) was purified by column chromatography on silica gel eluted with n-hexane–ethyl acetate (1 : 1) to give colorless crystals of homophthalimide (**12**, 8 mg, 10%): IR ν_{\max} (CHCl₃) 3380, 1720, 1700 cm⁻¹; ¹H-NMR (CDCl₃) δ 4.04(s, 2 H), 7.35–7.71(m, 3 H), 8.23(dd, $J = 1.71, 9.04$ Hz, 1 H), 8.40(brs, 1 H); MS; 161(M^+), 118($M^+ - \text{NHCO}$,bp), 104(PhCO), 90, 76.

Reaction of 3 with tetrahydrophthalic anhydride (13)

A crude product which was prepared from **3** (220 mg, 0.5 mmol), and tetrahydrophthalic anhydride (**13**, 152 mg, 1 mmol) was purified by column chromatography on silica gel eluted with n-hexane–ethyl acetate (1 : 1) to give colorless crystals of tetrahydrophthalic anhydride (**14**, 12 mg, 16%): mp 134–137 °C (no depression of melting point with an authentic sample was observed).

Reaction of 3 with perhydrophthalic anhydride (15)

A crude product, prepared from (**3**, 220 mg, 0.5 mmol) and perhydrophthalic anhydride (**15**, 154 mg, 1 mmol) was purified by column chromatography on silica gel eluted with n-hexane–ethyl acetate(2 : 1) to give colorless crystals of perhydrophthalimide (**16**, 21 mg, 27%). IR ν_{\max} 3450, 1700 cm⁻¹; ¹H-NMR (CDCl₃) δ 2.01–2.99 (m, 10 H); MS (m/z) 153 (M^+), 113(bp).

Synthesis of 2-methyl-4-quinazoline (18)

A solution of **3** (330 mg, 0.75 mmol) and benzoxazone (**15**, 40 mg, 0.25 mmol) in NMP (1 ml) was heated at 100 °C for 24 h. Water was added to the reaction mixture and the solution was filtered through Celite. The aqueous layer was extracted with ethyl acetate. The organic layer was washed with a saturated solution of NaHCO₃ and brine, dried over Na₂SO₄, and evaporated. The residue was purified by column chromatography on silica gel eluted with ethyl acetate to give colorless crystals of quinazoline **18** (22 mg, 55%): mp 230–232 °C (no depression of melting point with an authentic sample was observed).

Nitrogenation–carbonylation reaction by aryl halide**General procedure**

A solution of aryl halide **23** (1 equivalent), **3** (2.5 equivalent), Pd(PPh₃)₄ (5 mol%), and diisopropylethylamine (2.5 eq.) in NMP was heated under carbon monoxide (1 atm) at 80 °C for 24 h. After cooling, 10% HCl was added to the solution and the aqueous layer was extracted with ethyl acetate. The organic layer was washed with brine, dried over Na₂SO₄ and evaporated. The residue was purified by column chromatography on silica gel eluted with n-hexane–ethyl acetate to give the desired product.

Palladium catalyzed carbonylation of bromobenzene (23a) in the presence of 3

The crude product which was prepared from bromobenzene (**23a**, 157 mg, 1 mmol), **3** (1.1 g, 2.5 mmol), diisopropylethylamine (322.5 mg, 2.5 mmol) and Pd(PPh₃)₄ (58 mg, 5 mol%) was purified by column chromatography on silica gel eluted with n-hexane-ethyl acetate (1 : 1) to give benzimide (**6a**, 25 mg, 22%).

Palladium catalyzed carbonylation of p-bromotoluene (23b) in the presence of 3

The crude product which was prepared from *p*-bromotoluene (**23b**, 171 mg, 1 mmol), **3** (1.1 g, 2.5 mmol), diisopropylethylamine (322.5 mg, 2.5 mmol) and Pd(PPh₃)₄ (58 mg, 5 mol%) was purified by column chromatography on silica gel eluted with n-hexane-ethyl acetate (1 : 1) to give *p*-toluimide (**6b**, 18 mg, 14%) and *p*-toluamide (**5b**, 9 mg, 7%).

Palladium catalyzed carbonylation of p-iodoanisole (23c) in the presence of 3

The crude product which was prepared from *p*-iodoanisole (**23c**, 234 mg, 1 mmol), **3** (1.1 g, 2.5 mmol), diisopropylethylamine (322.5 mg, 2.5 mmol) and Pd(PPh₃)₄ (58 mg, 5 mol%) was purified by column chromatography on silica gel eluted with n-hexane-ethyl acetate (1 : 1) to give *p*-anisimide (**6c**, 40 mg, 28%) and *p*-anisamide (**5c**, 3 mg, 2%).

Palladium catalyzed carbonylation of o-bromobenzoic acid (24) in the presence of 3

The crude product which was prepared from *o*-bromobenzoic acid (**24**, 80 mg, 0.4 mmol), **3** (529 mg, 1.2 mmol), K₂CO₃ (110 mg, 0.8 mmol) and Pd(PPh₃)₄ (46 mg, 10 mol%) at 100 °C for 24 h was purified by column chromatography on silica gel eluted with n-hexane-ethyl acetate (1 : 1) to give phthalimide (**6f**, 48 mg, 82%).

References and notes

- 1 M.E. Vol'pin and V.B. Shur, Dokl. Akad. Nauk. SSSR., 156 (1964) 1102.
- 2 Recent review: (a) J.R. Dilworth and R.L. Richards, in G. Wilkinson, F.G.A. Stone and E.W. Abel (Eds.), *Comprehensive Organometallic Chemistry*, Vol. 8, Pergamon Press, 1982, p. 1073; (b) T.A. George in L.H. Pinolet (Ed.), *Homogeneous Catalysis with Metal Phosphine Complexes*, Plenum Press, 1983, p. 405; (c) M. Hidai, in T.G. Spiro (Ed.), *Molybdenum Enzymes*, John Wiley and Sons, 1985, p. 285.
- 3 (a) A. Yamamoto, M. Ookawa and S. Ikeda, *J. Chem. Soc., Chem. Commun.*, (1969) 841. (b) A. Yamamoto, S. Go, M. Ookawa, M. Takahashi, S. Ikeda, and T. Keii, *Bull. Chem. Soc. Jpn.*, 45 (1972) 3110.
- 4 P. Sobota, B. Jeżowska-Trzebiatowska and Z. Janas, *J. Organomet. Chem.*, 118 (1976) 253.
- 5 Preliminary work: M. Mori, Y. Uozumi and M. Shibasaki, *Tetrahedron Lett.*, 28 (1987) 6187.
- 6 Van Tamelen has reported that benzoyl chloride was treated with Cp₂TiCl₂-Mg-N₂ system to afford benzonitrile as a main product. E.E. van Tamelen and H. Rudler, *J. Am. Chem. Soc.*, 92 (1970) 5253.
- 7 The hydrolysis of a mixture of complex **1** and dehydrocinnamoyl chloride **4e**, gave the polymerization product of styrene. The IR spectrum of this compound shows no carbonyl absorption [IR ν_{max}(neat) 1600, 1560 cm⁻¹].
- 8 Novel lactam synthesis from *o*-haloacetophenone derivatives by use of the combination system of nitrogenation and palladium-catalyzed carbonylation in one system has already been reported. Y. Uozumi, N. Kawasaki, E. Mori, M. Mori and M. Shibasaki, *J. Am. Chem. Soc.*, 111 (1989) 3725.