Samarium(II) iodide induced reductive coupling of nitriles with nitro compounds

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The intermolecular and intramolecular reductive coupling of a cyano group with a nitro group induced by SmI_2 was studied. Amidines and 2-aminoquinoline derivatives are prepared in good yields under neutral and mild conditions respectively.

Introduction

Since its introduction by Kagan and his group,[1] SmI_2 has been extensively investigated as a mild, neutral, selective and versatile single electron transfer reductant in synthetic chemistry.[2] Its use in synthesis has been especially advantageous for ring closure reactions, carbon–carbon bond formation and stereocontrol. The reactivity of SmI_2, towards various nitrogen compounds including nitro compounds,[3] azo compounds,[4] hydrazones,[3b,5] oximes,[3b] imines,[3b] azides[6] and hydroxylamines[7] has been examined. Recently, we have reported a novel cyclodimerization of arylidenecyanoacetates promoted by SmI_2.[8]

Amidines are the nitrogen analogues of carboxylic acids and are part of several compounds of biological interest.[9] They can be prepared by reacting aromatic amines with nitriles under intensive reaction conditions,[10] such as high temperature and long reaction times, using sodium or lithium.

2-Aminoquinoline derivatives have attracted strong interest due to their biological properties.[11] For instance, simple molecules such as 2-aminoquinoline have been isolated from a North American mushroom known for its antibacterial and anthelmintic activity.[12] It has been reported that 2-aminoquinoline analogues have antiprotozoal,[13] antidepressant[14] and antihypertensive[15] properties. The syntheses of 2-aminoquinoline derivatives involve: basic condensations of aromatic ketones with (*N*,*N*-dimethylamino)propionitrile,[16a,b] Frielander's approach,[16c] nucleophilic substitution on the previously formed chloroquinoline under strong basic conditions.[16d]

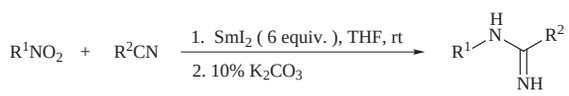
Nitro groups are known to be easily reduced by SmI_2. The cyano group however, is relatively more stable to SmI_2 than the nitro group and could not be coupled by this reagent. Souppe and Kagan[3b] reported that aromatic and aliphatic nitriles are inert in the presence of SmI_2, but *m*- or *p*-nitrobenzonitrile could be selectively reduced to the corresponding cyanoanilines in almost quantitative yields. We considered that the intermediate derived from a more active nitro group by SmI_2 treatment can perhaps attack the more stable cyano group, which does not react with SmI_2. Therefore, we have studied the behaviour of the cyano group and the nitro group when reacted with SmI_2 in THF at room temperature.

Results and discussion

Intermolecular reductive coupling of nitriles with nitro compounds

When aromatic nitro compounds **1** and nitriles **2** were treated with SmI_2 in dry THF, the intermolecular reductive cross coupling products amidines **3** were obtained (Scheme 1).

Table 1 summarizes our results on the reaction of nitro compounds and nitriles with SmI_2. In the reactions, aromatic nitro compounds could react with aromatic or aliphatic nitriles to produce amidines in good yields. However, aliphatic nitro compounds failed to react with aromatic or aliphatic nitriles to give similar amidines as products under the same conditions, under either low temperature or refluxing conditions. Amidines **3** are not derived from reaction between nitriles and the amines produced by the reduction of nitro compounds. On treating nitriles with amines under the same reaction conditions, no reaction took place and no amidines could be detected.



1 **2** **3**

Scheme 1

Table 1 Intermolecular reaction of nitro compounds with nitriles induced by SmI_2[a]

Entry	R^1	R^2	*t*/h	Yield (%)[b]
a	C_6H_5	C_6H_5	2	69
b	*p*-$CH_3C_6H_4$	C_6H_5	4	67
c	*o*-$CH_3C_6H_4$	C_6H_5	1	62
d	C_6H_5	$C_6H_5CH_2$	1	57
e	*p*-$CH_3C_6H_4$	$C_6H_5CH_2$	4	67
f	*p*-ClC_6H_4	$C_6H_5CH_2$	4	59
g	*p*-ClC_6H_4	*p*-ClC_6H_4	2	70
h	*p*-$CH_3C_6H_4$	*p*-ClC_6H_4	2	82
i	C_6H_5	*p*-ClC_6H_4	2	87
j	*p*-ClC_6H_4	C_6H_5	1	78
k	*P*-ClC_6H_4	*m*-$CH_3C_6H_4$	4	74
l	*p*-$CH_3C_6H_4$	*m*-$CH_3C_6H_4$	3	71
m	C_6H_5	*m*-$CH_3C_6H_4$	1	72
n	CH_3	C_6H_5	2	0[c]
o	CH_3	$C_6H_5CH_2$	2	0[c]

[a] 1 equiv. nitro compounds, 1.2 equiv. nitriles and 6 equiv. SmI_2 were used. [b] Isolated yield. [c] The reaction was studied under 0 °C, 25 °C and refluxing conditions respectively.

Though the detailed mechanism of the above reaction has not been clarified yet, the amidine formation could be explained by the possible mechanism presented in Scheme 2.

Intramolecular reductive coupling of cyano group with nitro group

On the other hand, the intramolecular reductive coupling of **4** is similar to the intermolecular one. When a solution of 1 equiv. of substrate **4** in anhydrous THF was allowed to react with 6 equiv. in dry THF under the same reaction conditions, the intramolecular reductive cyclization of a nitro group with a cyano group took place and gave the cyclic amidines 2-aminoquinoline-3-carboxylates **5** (Scheme 3), which differ from the products of cyclodimerization of arylidenecyanoacetates.[8]

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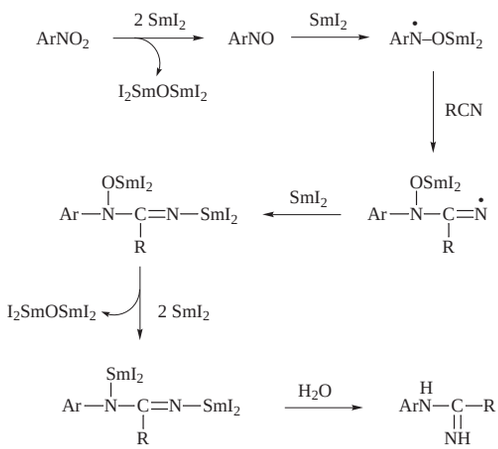
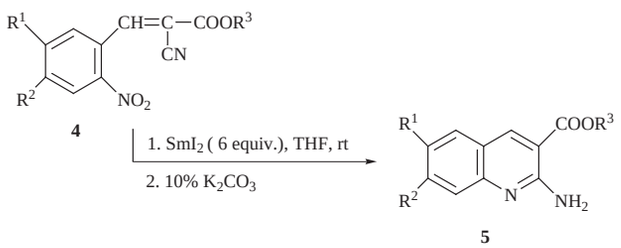
Table 2 Intramolecular reductive coupling of nitro group with nitrile group induced by SmI_2

Entry	R^1,R^2	R^3	*t*/h	Isolated yield (%)
a	H,H	CH_3	1	90
b	H,H	C_2H_5	1	91
c	H,H	i-C_3H_7	1.5	85
d	H,H	*n*-C_3H_7	1	78
e	H,H	*n*-C_4H_9	2	83
f	OCH_2O	CH_3	1	87
g	OCH_2O	C_2H_5	2	86
h	OCH_2O	i-C_3H_7	2	82
i	OCH_2O	*n*-C_3H_7	1.5	75
j	OCH_2O	*n*-C_4H_9	2	82



Scheme 2



Scheme 3

Cyclic amidines may tautomerize and exist in the amino form.[17]

Table 2 summarizes the results on the intramolecular reductive cyclization of a nitro group with a nitrile group induced by SmI_2. In contrast with the intermolecular reductive coupling of a nitro group and a nitrile group, the intramolecular reactions have higher yields. However, treating aminocyano olefins derived from nitrocyano olefins **4** under the same reaction conditions, products **5** could not be detected.

In conclusion, with high yields, mild and neutral conditions as well as a straightforward procedure, we think that the work described herein provides a useful method for the preparation of amidines and 2-aminoquinoline-3-carboxylates. Further studies to develop other new uses of SmI_2 are now in progress.

Experimental

General

Tetrahydrofuran was distilled from sodium–benzophenone immediately prior to use. All reactions were conducted under a nitrogen atmosphere. Melting points are uncorrected. Infrared spectra were recorded on FTIR-8101 or Perkin-Elmer 683 spectrometers in KBr with absorptions in cm^{-1}. ^1H NMR spectra were determined in Bruker AC-80 or JEOL PMX 60 SI spectrometers as $CDCl_3$ solutions. *J* Values are in Hz. Chemical shifts are expressed in ppm downfield from internal tetramethylsilane. Mass spectra were recorded on ZAB-HS or Finnigan MAT GC–MS spectrometers. Microanalysis were carried out on Perkin-Elmer 240C or Carlo-Erba 1106 instruments.

General procedure for the synthesis of amidines 3

A solution of nitro compound **1** (1 mmol) and nitrile **2** (1.2 mmol) in anhydrous THF (3 ml) was added dropwise to a solution of SmI_2 (6 mmol) in THF (40 ml) at room temperature under a dry nitrogen atmosphere. The reaction was continued with stirring under N_2. After the reaction was complete, the reaction mixture was poured into 10% K_2CO_3 (50 ml) and extracted with diethyl ether (3 × 30 ml). The combined extracts were washed with saturated aqueous $Na_2S_2O_3$ (15 ml), saturated aqueous NaCl (15 ml), and dried over anhydrous Na_2SO_4. After evaporating the solvent under reduced pressure, the crude product was purified by preparative TLC on silica gel using ethyl acetate–cyclohexane (1 : 3) as eluent.

***N*^{1}-Phenylbenzamidine 3a.** Mp 115–117 °C (lit.,[18] 112 °C); ν_{max}/cm^{-1} 3500, 3380, 1630, 1600, 1580, 1490, 1450, 1380, 1240, 1170, 1080, 1020, 835, 770, 750, 700; δ_H 5.30 (2H, br s, NH, C=NH), 6.87–7.83 (10H, m, ArH).

4-Methyl-*N*^{1}-phenylbenzamidine 3b. Mp 99–100 °C (lit.,[19] 100.5–101 °C); ν_{max}/cm^{-1} 3470, 3310, 1640, 1610, 1580, 1510, 1380, 1235, 860, 790; δ_H 2.30 (3H, s, CH_3), 5.23 (2H, br s, NH, C=NH), 6.70–7.95 (9H, m, ArH).

***N*^{1}-(2-Methylphenyl)benzamidine 3c.** Mp 102–104 °C (lit.,[19] 105 °C); ν_{max}/cm^{-1} 3470, 3320, 1640, 1575, 1490, 1390, 1240, 740, 720 cm^{-1}; δ_H 2.15 (3H, s, CH_3), 4.90 (2H, br s, NH, C=NH), 6.68–7.90 (9H, m, ArH); *m*/*z* 211 (M + 1, 45), 210 (M^+, 100), 107 (78), 106 (88), 104 (88), 91 (36), 77 (86), 76 (22) (Calc. for $C_{14}H_{14}N_2$: C, 79.97; H, 6.71; N, 13.32; Found: C, 79.81; H, 6.83; N, 13.40%).

***N*^{1}-Phenylphenylacetamidine 3d.** Mp 128–130 °C (lit.,[19] 127–130 °C); ν_{max}/cm^{-1} 3470, 3320, 1650, 1610, 1490, 1400, 1070, 860, 790; δ_H 3.63 (2H, s, CH_2), 4.80 (2H, br s, NH, C=NH), 6.80–7.73 (10H, m, ArH).

***N*^{1}-(*p*-Tolyl)phenylacetamidine 3e.** Mp 118–119 °C (lit.,[19] 119 °C); ν_{max}/cm^{-1} 3480, 3320, 1650, 1510, 1390, 1290, 1250, 850, 740, 700; δ_H 2.27 (3H, s, CH_3), 3.60 (2H, s, CH_2), 4.73 (2H, br s, NH, C=NH), 6.70–7.55 (9H, m, ArH).

***N*^{1}-(*p*-Chlorophenyl)phenylacetamidine 3f.** Mp 114–116 °C (lit.,[20] 114–116 °C); ν_{max}/cm^{-1} 3450, 3320, 1650, 1590, 1490, 1430, 1400, 1300, 1230, 1090, 835, 750, 720, 700; δ_H 3.57 (2H, s, CH_2), 7.40 (2H, br s, NH, C=NH), 6.67–7.50 (9H, m, ArH).

4-Chloro-*N*^{1}-(4-chlorophenyl)benzamidine 3g. Mp 177–179 °C (lit.,[21] 179 °C); ν_{max}/cm^{-1} 3530, 3430, 1650, 1590, 1495, 1410, 1380, 1240, 1085, 1010, 860, 840, 790; δ_H 5.17 (2H, br s, NH, C=NH), 6.80–7.73 (8H, m, ArH).

4-Chloro-*N*^{1}-(4-methylphenyl)benzamidine 3h. Mp 129–131 °C; ν_{max}/cm^{-1} 3500, 3360, 1640, 1565, 1510, 1380, 1240, 1110, 1090, 1010, 860, 840, 795; δ_H 2.30 (3H, s, CH_3), 5.07 (2H, br s, NH, C=NH), 6.70–8.00 (8H, m, ArH); *m*/*z* 246 (M + 2, 32), 245 (M + 1, 21), 244 (M^+, 100), 229 (15), 138 (88), 111 (44), 107 (94), 91 (36) (Calc. for $C_{14}H_{12}ClN_2$: C, 69.00; H, 4.96; N, 11.49; Found: C, 69.30; H, 4.81; N, 11.59%).

4-Chloro-*N*^{1}-phenylbenzamidine 3i. Mp 107–109 °C (lit.,[22] 106–110 °C); ν_{max}/cm^{-1} 3480, 3350, 1640, 1600, 1565, 1500, 1440, 1380, 1230, 1180, 1090, 1010, 840, 825, 760; δ_H 5.10 (2H, br s, NH, C=NH), 6.80–7.90 (9H, m, ArH).

***N*^{1}-(4-Chlorophenyl)benzamidine 3j.** Mp 114–116 °C (lit.,[23] 112–115 °C); ν_{max}/cm^{-1} 3500, 3380, 1630, 1610, 1575, 1490, 1450, 1380, 1240, 1100, 1010, 860, 755, 700; δ_H 5.00 (2H, br s, NH, C=NH), 6.70–8.00 (9H, m, ArH).

3-Methyl-*N*^{1}-(4-chlorophenyl)benzamidine 3k. Mp 98–100 °C; ν_{max}/cm^{-1} 3490, 3340, 1630, 1590, 1495, 1380, 1250, 1100, 1010, 855, 810, 790, 760, 720; δ_H 2.33 (3H, s, CH_3), 4.90 (2H, br s, NH, C=NH), 6.68–7.80 (8H, m, ArH); *m*/*z* 246 (M + 2, 32), 245 (M + 1, 35), 244 (M^+, 100), 229 (9), 127 (97), 118 (60), 111 (35),

91 (58) (Calc. for $C_{14}H_{12}ClN_2$: C, 69.00; H, 4.96; N, 11.49; Found: C, 69.23; H, 5.12; N, 11.37%).

3-Methyl-*N*^{1}-(4-methylphenyl)benzamidine 3l. Mp 88–90 °C; ν_{max}/cm^{-1} 3490, 3300, 1650, 1580, 1510, 1380, 1240, 1100, 1020, 920, 860, 790, 710; δ_H 2.26 (3H, s, CH_3), 2.33 (3H, s, CH_3), 5.00 (2H, br s, NH, C=NH), 6.75–7.85 (8H, m, ArH); *m*/*z* 225 (M + 1, 27), 224 (M$^+$, 94), 209 (11), 133 (9), 118 (30), 107 (100), 106 (75), 91 (66), 77 (23) (Calc. for $C_{15}H_{16}N_2$: C, 80.32; H, 7.19; N, 12.49; Found: C, 80.54; H, 7.03; N, 12.52%).

3-Methyl-*N*^{1}-phenylbenzamidine 3m. Mp 104–106 °C; ν_{max}/cm^{-1} 3460, 3320, 1640, 1590 1490, 1390, 1240, 1170, 1020, 840, 800, 770, 720, 695; δ_H 2.37 (3H, s, CH_3), 5.20 (2H, br s, NH, C=NH), 6.90–7.80 (9H, m, ArH); *m*/*z* 211 (M + 1, 19), 210 (M$^+$, 100), 195 (10), 194 (29), 118 (33), 93 (92), 91 (42), 77 (8) (Calc. for $C_{14}H_{14}N_2$: C, 79.97; H, 6.71; N, 13.32; Found: C, 79.86; H, 6.87; N, 13.38%).

General procedure for the synthesis of 2-aminoquinoline-3-carboxylic acid derivatives 5

A solution of nitrocyano olefins **4** (1 mmol) in THF (3 ml) was added carefully to SmI_2 (6 mmol) at room temperature under nitrogen atmosphere. The mixture was stirred at room temp. under N_2 atmosphere until the reaction was complete. The reaction mixture was poured into 10% K_2CO_3 (50 ml) and extracted with $CHCl_3$ (4 × 30 ml). The combined extracts were washed with saturated aqueous $Na_2S_2O_3$ (15 ml), saturated aqueous NaCl (15 ml), and dried over anhydrous Na_2SO_4. After evaporating the solvent under reduced pressure, the crude product was purified by preparative TLC on silica gel using ethyl acetate–cyclohexane (1 : 1) as eluent.

Methyl 2-aminoquinoline-3-carboxylate 5a. Mp 139–140 °C (from EtOH, lit.,[24] 140–141 °C); ν_{max}/cm^{-1} 3380 (NH_2), 3200 (NH_2), 1700 (CO); δ_H 3.93 (3H, s, OCH_3), 6.80 (2H, br s, NH_2), 7.03–7.68 (4H, m, ArH), 8.66 (1H, s, hetero ArH).

Ethyl 2-aminoquinoline-3-carboxylate 5b. Mp 134–135 °C (from EtOH, lit.,[24] 135 °C); ν_{max}/cm^{-1} 3450 (NH_2), 3180 (NH_2), 1700 (CO); δ_H 1.41 (3H, t, *J* 7.2, CH_3), 4.40 (2H, q, *J* 7.2, OCH_2), 6.68 (2H, br s, NH_2), 7.10–7.82 (4H, m, ArH), 8.69 (1H, s, hetero ArH); *m*/*z* 217 (M + 1, 14), 216 (M$^+$, 100), 171 (18), 170 (32), 144 (75), 143 (65), 116 (36), 89 (23).

Isopropyl 2-aminoquinoline-3-carboxylate 5c. Mp 160–161 °C (from EtOH); ν_{max}/cm^{-1} 3415 (NH_2), 3150 (NH_2), 1690 (CO); δ_H 1.41 (6H, d, *J* 6.2, 2 × CH_3), 5.28 (1H, *J* 6.2, OCH), 6.66 (2H, br s, NH_2), 7.24–7.70 (4H, m, ArH), 8.65 (1H, s, hetero ArH); *m*/*z* 231 (M + 1, 15), 230 (M$^+$, 81), 188 (5), 171 (14), 144 (100), 143 (51), 117 (21), 116 (32) (Found: C, 67.62; H, 6.20; N, 12.25. $C_{13}H_{14}N_2O_2$ requires C, 67.78; H, 6.13; N, 12.16%).

***n*-Propyl 2-aminoquinoline-3-carboxylate 5d.** Mp 114–115 °C (from EtOH); ν_{max}/cm^{-1} 3400 (NH_2), 3280 (NH_2), 1690 (CO); δ_H 1.01 (3H, t, *J* 7.2, CH_3), 1.40–1.88 (2H, m, CH_2), 4.29 (2H, t, *J* 6.6, OCH_2), 6.86 (2H, br s, NH_2), 7.24–7.69 (4H, m, ArH), 8.65 (1H, s, hetero ArH); *m*/*z* 231 (M + 1, 17), 230 (M$^+$, 73), 188 (5), 171 (13), 144 (100), 143 (48), 117 (23), 116 (34) (Found: C, 67.52; H, 6.21; N, 12.30. $C_{13}H_{14}N_2O_2$ requires C, 67.78; H, 6.13; N, 12.16%).

Butyl 2-aminoquinoline-3-carboxylate 5e. Mp 104–106 °C (from EtOH); ν_{max}/cm^{-1} 3380 (NH_2), 3150 (NH_2), 1690 (CO); δ_H 1.00 (3H, t, *J* 6.9, CH_3), 1.44–1.68 (4H, m, CH_2CH_2), 4.35 (2H, t, *J* 6.4, OCH_2), 6.79 (2H, br s, NH_2), 7.20–7.71 (4H, m, ArH), 8.66 (1H, s, hetero ArH); *m*/*z* 245 (M + 1, 11), 244 (M$^+$, 68), 188 (6), 171 (15), 144 (100), 143 (52), 117 (23), 116 (35) (Found: C, 68.95; H, 6.70; N, 11.38. $C_{14}H_{16}N_2O_2$ requires C, 68.83; H, 6.60; N, 11.47%).

Methyl 2-amino-6,7-methylenedioxyquinoline-3-carboxylate 5f. Mp 225–227 °C (from EtOH); ν_{max}/cm^{-1} 3400 (NH_2), 3150 (NH_2), 1680 (CO); δ_H 3.93 (3H, s, OCH_3), 6.05 (2H, s, OCH_2O), 6.67 (2H, br s, NH_2), 6.92 (1H, s, ArH), 6.99 (1H, s, ArH), 8.49 (1H, s, hetero ArH); *m*/*z* 247 (M + 1, 21), 246 (M$^+$, 44), 215 (27), 214 (45), 188 (44), 187 (100), 161 (12), 160 (30) (Found: C, 58.37; H, 4.22; N, 11.54. $C_{12}H_{10}N_2O_4$ requires C, 58.54; H, 4.09; N, 11.38%).

Ethyl 2-amino-6,7-methylenedioxyquinoline-3-carboxylate 5g. Mp 204–205 °C (from EtOAc); ν_{max}/cm^{-1} 3440 (NH_2), 3280 (NH_2), 1680 (CO); δ_H 1.41 (3H, t, *J* 7.1, CH_3), 4.38 (2H, q, *J* 7.1, OCH_2), 6.03 (2H, s, OCH_2O), 6.56 (2H, br s, NH_2), 6.90 (1H, s, ArH), 6.95 (1H, s, ArH), 8.46 (1H, s, hetero ArH); *m*/*z* 261 (M + 1, 20), 246 (M$^+$, 100), 232 (6), 215 (9), 214 (11), 188 (72), 161 (7), 160 (20) (Found: C, 60.25; H, 4.51; N, 10.66. $C_{13}H_{12}N_2O_4$ requires C, 60.00; H, 4.64; N, 10.76%).

Isopropyl 2-amino-6,7-methylenedioxyquinoline-3-carboxylate 5h. Mp 215–217 °C (from EtOH); ν_{max}/cm^{-1} 3380 (NH_2), 3200 (NH_2), 1680 (CO); δ_H 1.38 (6H, d, *J* 6.2, 2 × CH_3), 5.26 (1H, *J* 6.2, OCH), 6.03 (2H, s, OCH_2O), 6.54 (2H, br s, NH_2), 6.91 (1H, s, ArH), 6.95 (1H, s, ArH), 8.44 (1H, s, hetero ArH); *m*/*z* 275 (M + 1, 6), 274 (M$^+$, 94), 232 (9), 215 (11), 214 (9), 188 (100), 187 (38), 161 (6), 160 (25) (Found: C, 61.42; H, 5.07; N, 10.32. $C_{14}H_{14}N_2O_4$ requires C, 61.31; H, 5.14; N, 10.21%).

***n*-Propyl 2-amino-6,7-methylenedioxyquinoline-3-carboxylate 5i.** Mp 157–158 °C (from EtOH); ν_{max}/cm^{-1} 3400 (NH_2), 3150 (NH_2), 1690 (CO); δ_H 1.03 (3H, t, *J* 7.2, CH_3), 1.25–1.65 (2H, m, CH_2), 4.26 (2H, t, *J* 6.6, OCH_2), 6.01 (2H, s, OCH_2O), 6.50 (2H, br s, NH_2), 6.88 (1H, s, ArH), 6.92 (1H, s, ArH), 8.42 (1H, s, hetero ArH); *m*/*z* 275 (M + 1, 6), 274 (M$^+$, 92), 232 (10), 215 (12), 214 (10), 188 (100), 187 (39), 161 (6), 160 (25) (Found: C, 61.51; H, 5.03; N, 10.31. $C_{14}H_{14}N_2O_4$ requires C, 61.31; H, 5.14; N, 10.21%).

Butyl 2-amino-6,7-methylenedioxyquinoline-3-carboxylate 5j. Mp 148–149 °C (from EtOH); ν_{max}/cm^{-1} 3480 (NH_2), 3200 (NH_2), 1680 (CO); δ_H 1.00 (3H, t, *J* 6.8, CH_3), 1.21–1.78 (4H, m, CH_2CH_2), 4.32 (2H, t, *J* 6.4, OCH_2), 6.02 (2H, s, OCH_2O), 6.55 (2H, br s, NH_2), 6.89 (1H, s, ArH), 6.93 (1H, s, ArH), 8.42 (1H, s, hetero ArH); *m*/*z* 289 (M + 1, 17), 288 (M$^+$, 90), 232 (11), 216 (7), 215 (11), 188 (100), 187 (31), 161 (8), 160 (23) (Found: C, 62.37; H, 5.68; N, 9.60. $C_{15}H_{16}N_2O_4$ requires C, 62.49; H, 5.59; N, 9.72%).

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References

1 (*a*) P. Girard, J. L. Namy and H. B. Kagan, *J. Am. Chem. Soc.*, 1980, **102**, 2693; (*b*) J. L. Namy, P. Girard and H. B. Kagan, *Nouv. J. Chim.*, 1977, **1**, 5; (*c*) H. B. Kagan, *New J. Chem.*, 1990, **14**, 453.

2 For reviews see: (*a*) G. A. Molander and C. R. Harris, *Chem. Rev.*, 1996, **96**, 307; (*b*) F. Matsuda, *Synth. Org. Chem. Jpn.*, 1995, **53**, 987; (*c*) G. A. Molander, *Org. React.*, 1994, **46**, 221; (*d*) T. Imamota, *Lanthanides in Organic Synthesis*, Academic Press, London, 1994; ch. 4; (*e*) M. Shibasaki and H. Sasai, *Synth. Org. Chem. Jpn.*, 1993, **51**, 972; (*f*) G. A. Molander, *Chem. Rev.*, 1992, **92**, 29; (*g*) D. P. Curran, T. L. Fevig, C. P. Jasperse and M. J. Totleben, *Synlett*, 1992, 943; (*h*) J. A. Soderquist, *Aldrichim. Acta*, 1991, **24**, 15; (*i*) G. A. Molander, *Comprehensive Organic Synthesis*, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, vol. 1, 1991, 251; (*j*) H. B. Kagan, *New J. Chem.*, 1990, **14**, 453; (*k*) G. A. Molander, in *The Chemistry of the Metal-Carbon Bond*; ed. F. R. Hartly, Wiley, Chichester, 1989, vol. 5, ch. 8; (*l*) H. B. Kagan, M. Sasaki and J. Collin, *Pure Appl. Chem.*, 1988, **60**, 1725; (*m*) H. B. Kagan and J. L. Namy, *Tetrahedron*, 1986, **42**, 6573.

3 (*a*) Y. Zhang and R. Lin, *Synth. Commun.*, 1987, **17**, 329; (*b*) J. Souppe, L. Danon, J. L. Namy and H. B. Kagan, *J. Organomet. Chem.*, 1983, **250**, 227; (*c*) T. Mukaiyama, K. Yoyozu, K. Kato and T. Yamada, *Chem. Lett.*, 1992, 181.

4 A. S. Kende and J. S. Mendoza, *Tetrahedron Lett.*, 1991, **32**, 1699.

5 M. J. Burk and J. E. Feaster, *J. Am. Chem. Soc.*, 1992, **114**, 6266.

6 (*a*) N. R. Natale, *Tetrahedron Lett.*, 1982, **23**, 5009; (*b*) L. Benati, P. C. Monievecohi, D. Nanni, P. Spagnolo and M. Volta,

Tetrahedron Lett., 1995, **36**, 7313; (*c*) C. Goulaouic-Dubois and M. Hesse, *Tetrahedron Lett.*, 1995, **36**, 7427.
7 G. E. Keck, S. F. McHardy and T. T. Wager, *Tetrahedron Lett.*, 1995, **36**, 7419.
8 L. Zhou and Y. Zhang, *Tetrahedron Lett.*, 1997, **38**, 8063.
9 (*a*) S. Patai and Z. Rappoport, *The Chemistry of Amidines and Imidates*, Wiley, New York, 1991, **27**, 226; (*b*) A. Kreutzberger, *Progress in Drug Research*, ed. E. Jucker, Birklauser Verlag, Basel, 1968, pp. 356–445.
10 (*a*) Lottermoser, *J. Prakt. Chem.*, 1896, **54**, 116; (*b*) F. C. Cooper and M. W. Partridge, *J. Chem. Soc.*, 1953, 255; (*c*) N. A. Kalashnikova, G. N. Kul′bitskii, B. V. Passet and B. Z. Askinazi, *Zh. Org. Khim.*, 1974, **10**, 1529.
11 (*a*) T. Matsumoto, D. Yoshida, S. Mitzusaki and H. Tomita, *Agric. Biol. Chem.*, 1978, **42**, 861; (*b*) I. Arai and I. Nakayama, *J. Pharm. Soc. Jpn.*, 1952, **72**, 167; (*c*) N. Yoshiola and S. Ishii, *J. Biochem.*, 1972, **71**, 185.
12 J. R. Pfister, *J. Nat. Prod.*, 1988, **51**, 969.
13 D. G. Markees, V. C. Dewey and G. W. Kidder, *J. Med. Chem.*, 1970, **13**, 324.
14 (*a*) A. A. Alhaider, M. A. Abdelkader and E. J. Lien, *J. Med. Chem.*, 1985, **28**, 1398; (*b*) K. Hino, Y. Nagai and H. Uno, *Chem. Pharm. Bull.*, 1987, **35**, 2819.
15 S. F. Campbell, J. D. Hardstone and M. J. Palmer, *J. Med. Chem.*, 1988, **31**, 1031.
16 (*a*) S. Chorbadjiev, Ch. Ivanov and B. Moskova, *Synth. Commun.*, 1985, **15**, 451; (*b*) S. Corbadjiev, Ch. Ivanov and B. Moskova, *Synth. Commun.*, 1987, **17**, 1363; (*c*) A. A. Sayed, *Synth. Commun.*, 1991, **21**, 749; (*d*) F. Korodi, *Synth. Commun.*, 1991, **21**, 1841.
17 H. U. Sieveking and W. Lutte, *Liebigs Ann. Chem.*, 1977, 189.
18 P. Oxley, M. W. Partridge and W. F. Short, *J. Chem. Soc.*, 1947, 1110.
19 P. Oxley and W. F. Short, *J. Chem. Soc.*, 1946, 147.
20 O. Motoi, T. Shigeo and O. Ryohei, *Yuki Gosei Kagaku Kyokai Shi.*, 1966, **24**, (7), 562.
21 *Beilstein* I (12), 611.
22 N. A. Kalashnikova, G. N. Kul′bitskii, B. V. Passet and B. Z. Askinazi, *Zh. Org. Khim.*, 1974, **10**, 1529.
23 L. Citero, M. L. Saccarello and R. Stradi, *Synthesis*, 1979, 594.
24 J. M. Tyleer, *J. Chem. Soc.*, 1955, 203.

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