Supplementary Information for

Highly enantioselective hydroaminoalkylation of secondary amines catalyzed by group 5 metal amides with chiral biaryldiamidate ligands

Guofu Zi,* Furen Zhang and Haibin Song

Experimental

General methods

Group 5 complexes and catalytic reactions were performed under an atmosphere of dry dinitrogen with rigid exclusion of air and moisture using standard Schlenk or cannula techniques, or in a glovebox. All organic solvents used for the synthesis of complexes were freshly distilled from sodium benzophenone ketyl immediately prior to use. (*R*)-2,2'-Bis(mesitoylamino)-1,1'-binaphthyl (**1**),[1] (*R*)-5,5',6,6',7,7',8,8'-octahydro-2,2'-bis(mesitoylamino)-1,1'-binaphthyl (**2**),[1] (*R*)-6,6'-dimethyl-2,2'-bis(mesitoylamino)-1,1'-biphenyl (**3**),[2] and $M(NMe_2)_5$[3] were prepared according to literature methods. All chemicals were purchased from Aldrich Chemical Co. and Beijing Chemical Co. used as received unless otherwise noted. Infrared spectra were obtained from KBr pellets on an Avatar 360 Fourier transform spectrometer. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AV 400 spectrometer at 400 and 100 MHz, respectively. All chemical shifts are reported in δ units with reference to the residual protons of the deuterated solvents for proton and carbon chemical shifts. HPLC analyses were conducted on a Shimadzu Series SPD-20A with UV/VIS detector using a Chiralcel OD-H or AS-H column (length: 25 cm, inner diameter: 4.6 mm, particle size: 5 μm). Retention time was given in minutes. Melting points were measured on an X-6 melting point

apparatus and were uncorrected. Elemental analyses were performed on a Vario EL elemental analyzer.

Syntheses

Preparation of 4. A toluene solution (10 mL) of **1** (0.28 g, 0.5 mmol) was slowly added to a toluene solution (10 mL) of $Nb(NMe_2)_5$ (0.16 g, 0.5 mmol) with stirring at room temperature. After this mixture was stirred at room temperature for one day, the solution was filtered and the solvent was removed under reduced pressure. The resulting orange solid was recrystallized from a benzene solution to give **4** as orange crystals. Yield: 0.36 g (90%) (Found: C, 69.15; H, 6.63; N, 8.72. $C_{46}H_{52}N_5NbO_2$ requires C, 69.08; H, 6.55; N, 8.76%). M.p.: 131-133 ^oC (dec.). ^1H NMR (C_6D_6): δ 7.73 (d, J = 8.2 Hz, 2H, aryl), 7.64 (d, J = 7.8 Hz, 1H, aryl), 7.51 (m, 4H, aryl), 6.83 (s, 1H, aryl), 6.74 (s, 2H, aryl), 6.60 (s, 2H, aryl), 6.36 (s, 1H, aryl), 6.28 (s, 2H, aryl), 6.12 (d, J = 8.0 Hz, 1H, aryl), 3.38 (s, 18H, $Nb(NMe_2)_3$), 2.22 (s, 3H, CH_3), 2.01 (s, 3H, CH_3), 1.93 (d, J = 6.2 Hz, 6H, CH_3), 1.86 (s, 3H, CH_3), 1.62 (s, 3H, CH_3). ^{13}C NMR (C_6D_6): δ 178.2, 159.4, 149.7, 138.9, 137.3, 136.3, 135.6, 131.8, 130.2, 129.7, 129.5, 128.9, 126.5, 125.7, 124.5, 121.7, 47.8, 25.6, 21.7. IR (KBr, cm^{-1}): v 2962 (m), 2912 (m), 1589 (s), 1464 (s), 1422 (s), 1260 (s), 1089 (s), 1018 (s), 799 (s).

Preparation of 5. This compound was prepared as pale yellow crystals from the reaction of **1** (0.28 g, 0.5 mmol) with $Ta(NMe_2)_5$ (0.20 g, 0.5 mmol) in toluene (20 mL) and recrystallization from a benzene solution by a similar procedure as in the synthesis of **4**. Yield: 0.41 g (92%) (Found: C, 62.08; H, 5.86; N, 7.78. $C_{46}H_{52}N_5O_2Ta$ requires C, 62.23; H, 5.90; N, 7.89%). M.p.: 140-142 ^oC (dec.). ^1H NMR (C_6D_6): δ 7.77 (m, 3H, aryl), 7.52 (m, 6H, aryl), 6.94 (s, 2H, aryl), 6.82 (s, 2H, aryl), 6.65 (m, 1H, aryl), 6.47 (m, 1H, aryl), 6.31 (m, 1H, aryl), 3.58 (s, 18H, $Ta(NMe_2)_3$), 2.27 (s, 3H, CH_3), 2.13 (s, 9H, CH_3), 1.89 (s, 3H, CH_3), 1.66 (s, 3H, CH_3). ^{13}C NMR (C_6D_6): δ 179.5, 156.5, 147.8, 142.4, 139.2, 138.6, 138.0, 136.0, 135.2, 134.0, 133.5, 133.1, 130.6, 128.5, 127.9, 125.2, 124.3, 120.6, 118.9, 44.5, 24.5, 20.4. IR (KBr, cm^{-1}): v 2962 (m), 1588 (s), 1464 (s), 1422 (s), 1260 (s), 1090 (s), 1017 (s), 799 (s).

Preparation of 6. This compound was prepared as orange crystals from the reaction of **2** (0.29 g, 0.5 mmol) with $Nb(NMe_2)_5$ (0.16 g, 0.5 mmol) in toluene (20 mL) and recrystallization from an *n*-hexane solution by a similar procedure as in the synthesis of **4**. Yield: 0.36 g (89%) (Found: C, 68.42; H, 7.36; N, 8.58. $C_{46}H_{60}N_5NbO_2$ requires C, 68.39; H, 7.49; N, 8.67%). M.p.: 118-120 ^oC (dec.). ^1H NMR (C_6D_6): δ 6.80 (m, 4H, aryl), 6.70 (s, 2H, aryl), 6.55 (s, 2H, aryl), 3.06 (s, 18H, $Nb(NMe_2)_3$), 2.73-2.56 (m, 4H, CH_2), 2.35 (s, 6H, CH_3), 2.30 (m, 4H, CH_2), 2.24 (s, 6H, CH_3), 2.01 (s, 6H, CH_3), 1.55 (m, 8H, CH_2). ^{13}C NMR (C_6D_6): δ 176.4, 158.9, 148.3, 141.8, 138.3, 135.1, 134.1, 133.0, 129.6, 125.0, 120.2, 48.2, 30.2, 29.7, 28.3, 27.0, 26.4, 23.5, 23.2, 22.8, 22.4, 22.1, 21.5. IR (KBr, cm^{-1}): *v* 2969 (s), 2924 (s), 1607 (s), 1454 (s), 1368 (s), 1260 (s), 1089 (s), 1020 (s), 938 (s), 796 (s).

Preparation of 7. This compound was prepared as pale yellow crystals from the reaction of **2** (0.29 g, 0.5 mmol) with $Ta(NMe_2)_5$ (0.20 g, 0.5 mmol) in toluene (20 mL) and recrystallization from an *n*-hexane solution by a similar procedure as in the synthesis of **4**. Yield: 0.39 g (87%) (Found: C, 61.58; H, 6.86; N, 7.88. $C_{46}H_{60}N_5O_2Ta$ requires C, 61.67; H, 6.75; N, 7.82%). M.p.: 178-180 ^oC (dec.). ^1H NMR (C_6D_6): δ 6.80 (m, 4H, aryl), 6.66 (s, 2H, aryl), 6.53 (s, 2H, aryl), 3.59 (s, 18H, $Ta(NMe_2)_3$), 2.71-2.56 (m, 4H, CH_2), 2.36 (s, 6H, CH_3), 2.55 (m, 4H, CH_2), 2.06 (s, 6H, CH_3), 1.91 (s, 6H, CH_3), 1.58 (m, 8H, CH_2). ^{13}C NMR (C_6D_6): δ 175.4, 156.8, 146.7, 135.7, 134.9, 134.3, 133.4, 128.7, 123.7, 121.6, 119.1, 44.6, 29.0, 28.5, 27.1, 25.8, 25.4, 22.3, 21.9, 20.3, 19.7. IR (KBr, cm^{-1}): *v* 2962 (m), 2923 (m), 1586 (s), 1465 (s), 1422 (s), 1260 (s), 1090 (s), 1018 (s), 798 (s).

Preparation of 8. This compound was prepared as orange microcrystals from the reaction of **3** (0.25 g, 0.5 mmol) with $Nb(NMe_2)_5$ (0.16 g, 0.5 mmol) in toluene (20 mL) and recrystallization from an *n*-hexane solution by a similar procedure as in the synthesis of **4**. Yield: 0.32 g (88%) (Found: C, 66.12; H, 7.14; N, 9.58. $C_{40}H_{52}N_5NbO_2$ requires C, 66.01; H, 7.20; N, 9.62%). M.p.: 168-170 ^oC (dec.). ^1H NMR (C_6D_6): δ 7.03 (m, 1H, aryl), 6.98 (m, 2H, aryl), 6.87 (s, 4H, aryl), 6.66 (m, 2H, aryl), 6.51 (m, 1H, aryl), 3.42 (s, 18H, $Nb(NMe_2)_3$), 2.27 (s, 6H, CH_3), 2.16 (s, 6H, CH_3), 2.09 (s, 6H, CH_3), 2.02 (s, 3H, CH_3), 1.99 (s, 3H, CH_3). ^{13}C NMR (C_6D_6): δ 172.3, 156.8, 148.2, 137.2, 135.4, 135.2, 134.8, 132.2, 125.9, 125.5, 124.3, 46.1, 25.9, 19.7, 19.2, 19.0, 18.8. IR (KBr,

cm^{-1}): *v* 2954 (m), 1538 (s), 1504 (s), 1417 (s), 1361 (s), 1256 (s), 1084 (s), 1014 (s), 959 (s), 793 (s). Few orange crystals suitable for X-ray diffraction analysis were picked up from the mixture.

Preparation of 9. This compound was prepared as pale yellow microcrystals from the reaction of **3** (0.25 g, 0.5 mmol) with $Ta(NMe_2)_5$ (0.20 g, 0.5 mmol) in toluene (20 mL) and recrystallization from an *n*-hexane solution by a similar procedure as in the synthesis of **4**. Yield: 0.35 g (85%) (Found: C, 58.72; H, 6.66; N, 8.48. $C_{40}H_{52}N_5O_2Ta$ requires C, 58.89; H, 6.42; N, 8.58%). M.p.: 126-128 ^oC (dec.). ^1H NMR (C_6D_6): δ 6.85 (m, 1H, aryl), 6.81 (m, 2H, aryl), 6.76 (s, 4H, aryl), 6.64 (m, 2H, aryl), 6.54 (m, 1H, aryl), 3.52 (s, 18H, $Ta(NMe_2)_3$), 2.19 (s, 3H, CH_3), 2.09 (s, 3H, CH_3), 2.08 (s, 3H, CH_3), 2.05 (s, 3H, CH_3), 2.00 (s, 3H, CH_3), 1.98 (s, 3H, CH_3), 1.86 (s, 3H, CH_3), 1.84 (s, 3H, CH_3). ^{13}C NMR (C_6D_6): δ 179.1, 157.1, 149.1, 143.9, 141.0, 138.8, 136.5, 135.9, 131.7, 127.6, 125.0, 118.5, 44.7, 25.8, 24.4, 20.9, 20.5, 19.6, 19.5, 18.8, 17.2. IR (KBr, cm^{-1}): *v* 2962 (m), 2910 (m), 1578 (s), 1508 (s), 1458 (s), 1260 (s), 1091 (s), 1018 (s), 797 (s). Few pale yellow crystals suitable for X-ray diffraction analysis were picked up from the mixture.

General procedure for asymmetric hydroaminoalkylation

In a nitrogen-filled glove box, precatalyst (0.005 mmol), C_7D_8 (0.7 mL), amine (0.10 mmol), and alkene (0.15 mmol) were introduced sequentially into a J. Young NMR tube equipped with Teflon screw cap. The reaction mixture was subsequently kept at 130 ˚C or 160 ˚C to achieve hydroaminoalkylation, and the reaction was monitored periodically by ^1H NMR spectroscopy. The mixture was added to a CH_2Cl_2 solution (5 mL) of benzoylchloride (140 mg, 116μL, 1.0 mmol) and Et_3N (152 mg, 1.5 mmol) with stirring at room temperature, and stirred continuously for 2 h. Removal of the solvent, diethyl ether (10 mL) and 2M NaOH (10 mL) were added and stirred for 0.5 h, then extracted with diethyl ether (20 mL x 3) and washed with brine (20 mL). The combined organic layers were dried with anhydrous Na_2SO_4, then filtered. The solvent was removed, and the resulting residue was further purified by flash column chromatography. The enantiomeric excesses

of benzamide derivative were determined by HPLC analysis using a Chiralcel AS-H or OD-H column.

***N*-(bicyclo[2.2.1]heptan-2-ylmethyl)-*N*-phenylbenzamide.**[4] HPLC (AS-H, 254 nm, hexane/2-propanol 98:2, 1.0 mL/min): t_R 37.9 (minor), 49.9 (major). ^{1}H NMR ($CDCl_3$): δ 7.18 (d, J = 6.9 Hz, 2H, aryl), 7.13 (d, J = 7.2 Hz, 3H, aryl), 7.05 (d, J = 7.7 Hz, 3H, aryl), 6.95 (d, J = 7.6 Hz, 2H, aryl), 3.86 (m, 1H, C*H*N), 3.61 (m, 1H, C*H*N), 2.16 (s, 1H, C*H*), 2.03 (s, 1H, C*H*), 1.60 (m, 1H, C*H*), 1.39 (m, 3H, CH_2), 1.22 (m, 1H, CH_2), 1.21 (m, 2H, CH_2), 1.09 (m, 2H, CH_2). Colorless crystals suitable for X-ray structural analysis were grown from an ethyl acetate solution at room temperature.

***N*-(2-cyclohexylpropyl)-*N*-phenylbenzamide.**[4] HPLC (OD-H, 254 nm, hexane/2-propanol 99:1, 0.5 mL/min): t_R 36.7 (minor), 40.1 (major). ^{1}H NMR ($CDCl_3$): δ 7.16 (d, J = 7.6 Hz, 2H, aryl), 7.12 (d, J = 7.7 Hz, 3H, aryl), 7.06 (t, J = 7.8 Hz, 3H, aryl), 6.94 (d, J = 7.6 Hz, 2H, aryl), 3.91 (m, 1H, C*H*N), 3.76 (m, 1H, C*H*N), 1.72 (s, 1H, C*H*), 1.66-1.56 (m, 5H, CH_2), 1.46 (d, J = 12.2 Hz, 1H, C*H*), 1.23-1.04 (m, 5H, CH_2), 0.83 (d, J = 6.9 Hz, 3H, CH_3).

***N*-(2-methyloctyl)-*N*-phenylbenzamide.**[4] HPLC (AS-H, 254 nm, hexane/2-propanol 98.5:1.5, 1.0 mL/min): t_R 26.1 (minor), 30.8 (major). ^{1}H NMR ($CDCl_3$): δ 7.18 (d, J = 5.7 Hz, 2H, aryl), 7.12 (d, J = 7.5 Hz, 3H, aryl), 7.03 (t, J = 7.5 Hz, 3H, aryl), 6.95 (d, J = 7.6 Hz, 2H, aryl), 3.77 (m, 2H, C*H*N), 1.68 (m, 1H, C*H*), 1.32 (m, 10H, CH_2), 0.87 (d, J = 6.7 Hz, 3H, CH_3), 0.79 (t, J = 6.7 Hz, 3H, CH_3).

X-Ray crystallography

Single-crystal X-ray diffraction measurements were carried out on a Rigaku Saturn CCD diffractometer at 113(2) K using graphite monochromated Mo Kα radiation (λ = 0.71075 Å) or Cu Kα radiation (λ = 1.54187 Å). An empirical absorption correction was applied using the SADABS

program.[5] All structures were solved by direct methods and refined by full-matrix least squares on F^2 using the SHELXL-97 program package.[6] All the hydrogen atoms were geometrically fixed using the riding model. The absolute configuration of **10** was determined according to the literature method.[7] The crystal data and experimental data for **4**-**10** are summarized in Tables 1 and 2. Selected bond lengths and angles are listed in Table 3.

References

1. G. Zi, F. Zhang, L. Xiang, Y. Chen, W. Fang and H. Song, *Dalton Trans.* 2010, **39**, 4048-4061.

2. M. C. Wood, D. C. Leitch, C. S. Yeung, J. A. Kozak and L. L. Schafer, *Angew. Chem.*, *Int. Ed.* 2007, **46**, 354-358.

3. X.-H. Zhang, S.-J. Chen, H. Cai, H.-J. Im, T. Chen, X. Yu, X. Chen, Z. Lin, Y.-D. Wu and Z.-L. Xue, *Organometallics* 2008, **27**, 1338-1341.

4. P. Eisenberger, R. O. Ayinla, J. M. P. Lauzon and L. L. Schafer, *Angew. Chem. Int. Ed.* 2009, **48**, 8361-8365.

5. G. M. Sheldrick, *SADABS*, *Program for Empirical Absorption Correction of Area Detector Data*; University of Göttingen, Göttingen, Germany, 1996.

6. G. M. Sheldrick, *SHELXL-97*, *Program for the Refinement of Crystal Structure from Diffraction Data*; University of Göttingen, Göttingen, Germany, 1997.

7. H. D. Flack, *Acta Cryst.* 1983, **A39**, 876-881.

Table 1 Crystal data and experimental parameters for compounds **4-7**

compound	**4**	**5**	**6**	**7**
formula	$C_{46}H_{52}N_5NbO_2$	$C_{46}H_{52}N_5O_2Ta$	$C_{46}H_{60}N_5NbO_2$	$C_{46}H_{60}N_5O_2Ta$
formula weight	799.84	887.88	807.90	895.94
crystal system	monoclinic	monoclinic	monoclinic	monoclinic
space group	$P2_1$	$P2_1$	$P2_1$	$P2_1$
a (Å)	11.680(2)	11.687(2)	11.934(2)	11.832(2)
b (Å)	13.465(2)	13.451(3)	14.079(3)	14.325(3)
c (Å)	13.696(2)	13.686(3)	13.534(2)	13.481(3)
α (deg)	90	90	90	90
β (deg)	108.56(1)	108.63(3)	111.01(1)	111.28(3)
γ (deg)	90	90	90	90
V (Å^3)	2041.9(5)	2038.8(7)	2122.8(6)	2129.1(7)
Z	2	2	2	2
$D_{calc.}$ (g/cm^3)	1.301	1.446	1.264	1.398
size (mm)	0.42 x 0.38 x 0.36	0.22 x 0.18 x 0.14	0.22 x 0.20 x 0.20	0.32 x 0.30 x 0.28
F(000)	840	904	856	920
2θ range (deg)	3.14 to 55.76	3.14 to 55.84	7.00 to 144.18	3.24 to 55.76
no. of reflections collected	26215	18042	21782	22072
no. of unique reflections [$R_{(int)}$]	9650 (0.0402)	9255 (0.0397)	6900 (0.0448)	9882 (0.0529)

no. of observed reflections	8460	9010	6542	7509
absorbed corrections (T_{max}, T_{min})	0.89, 0.87	0.70, 0.58	0.62, 0.60	0.53, 0.49
R	0.030	0.035	0.037	0.035
R_w	0.067	0.084	0.100	0.085
$wR2$ (all data)	0.068	0.085	0.124	0.086
gof	1.01	1.12	1.18	0.94

Table 2 Crystal data and experimental parameters for compounds **8-10**

compound	**8**	**9**	**10**
formula	$C_{40}H_{52}N_5NbO_2$	$C_{40}H_{52}N_5O_2Ta$	$C_{21}H_{23}NO$
formula weight	727.78	815.82	305.40
crystal system	triclinic	triclinic	triclinic
space group	*P*(-1)	*P*(-1)	*P*1
a (Å)	9.757(2)	9.761(2)	9.39(2)
b (Å)	12.302(3)	12.259(2)	9.44(2)
c (Å)	15.936(3)	15.969(3)	9.48(2)
α (deg)	98.09(1)	82.37(1)	88.28(9)
β (deg)	103.42(1)	77.15(1)	81.19(5)
γ (deg)	90.47(1)	89.89(1)	89.14(9)
V (Å^3)	1840.3(6)	1845.7(1)	830(3)
Z	2	2	2
$D_{calc.}$ (g/cm^3)	1.313	1.468	1.222
size (mm)	0.26 x 0.22 x 0.20	0.24 x 0.22 x 0.20	0.22 x 0.16 x 0.12
F(000)	768	832	328
2θ range (deg)	3.34 to 55.76	2.64 to 55.78	9.38 to 145.08
no. of reflections collected	31741	22062	11805
no. of unique reflections [$R_{(int)}$]	8743 (0.0402)	8670 (0.0344)	4974 (0.0458)
no. of observed reflections	7881	8385	4582
absorbed corrections (T_{max}, T_{min})	0.93, 0.91	0.58, 0.53	0.93, 0.88
R	0.031	0.035	0.042
R_w	0.081	0.086	0.111
*wR*2 (all data)	0.083	0.089	0.128
gof	1.09	1.21	1.12

Table 3 Selected bond distances (Å) and bond angles (deg) for compounds **4**-**9**

compound	**4** (Nb)	**5** (Ta)	**6** (Nb)	**7** (Ta)	**8** (Nb)	**9** (Ta)
M-N (av.)	2.064(2)	2.064(3)	2.073(4)	2.062(5)	2.053(1)	2.054(3)
M-N(3)	1.974(2)	1.963(3)	2.024(4)	1.960(5)	2.000(1)	1.979(2)
M-N(4)	1.962(2)	1.983(3)	1.972(4)	2.031(5)	1.961(1)	2.002(3)
M-N(5)	2.020(2)	2.017(3)	1.996(4)	1.977(4)	1.972(1)	1.968(2)
M-O(1)	2.185(2)	2.155(3)	2.186(3)	2.163(4)	2.180(1)	2.164(2)
M-O(2)	2.082(2)	2.062(3)	2.076(3)	2.065(4)	2.069(1)	2.051(2)
M-C	2.675(2)	2.656(4)	2.658(5)	2.655(6)	2.652(2)	2.645(3)
sum angle of N(3)	360.0(2)	357.5(4)	359.4(5)	359.1(5)	159.2(1)	359.8(3)
sum angle of N(4)	356.3(2)	359.8(4)	357.0(4)	359.2(5)	158.9(1)	359.2(3)
sum angle of N(5)	359.7(2)	359.9(4)	359.9(4)	360.0(5)	159.8(1)	359.2(2)
torsion (aryl-aryl)	74.1(2)	75.0(4)	77.9(5)	78.9(5)	77.4(1)	77.0(3)

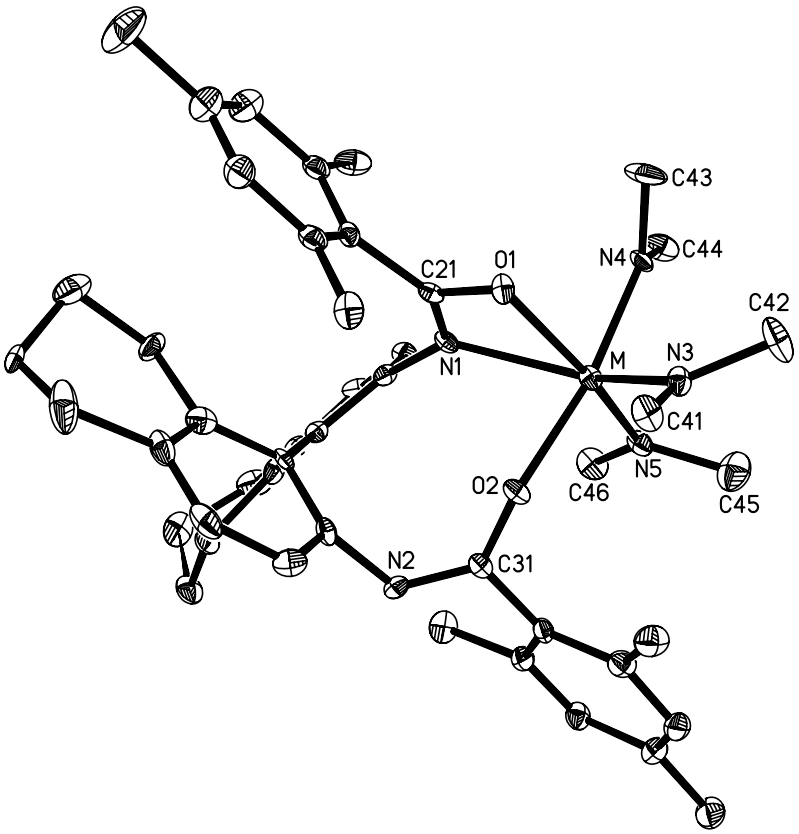

Fig. 1 Molecular structures of **6** (M = Nb) and **7** (M = Ta) (thermal ellipsoids drawn at the 35% probability level).

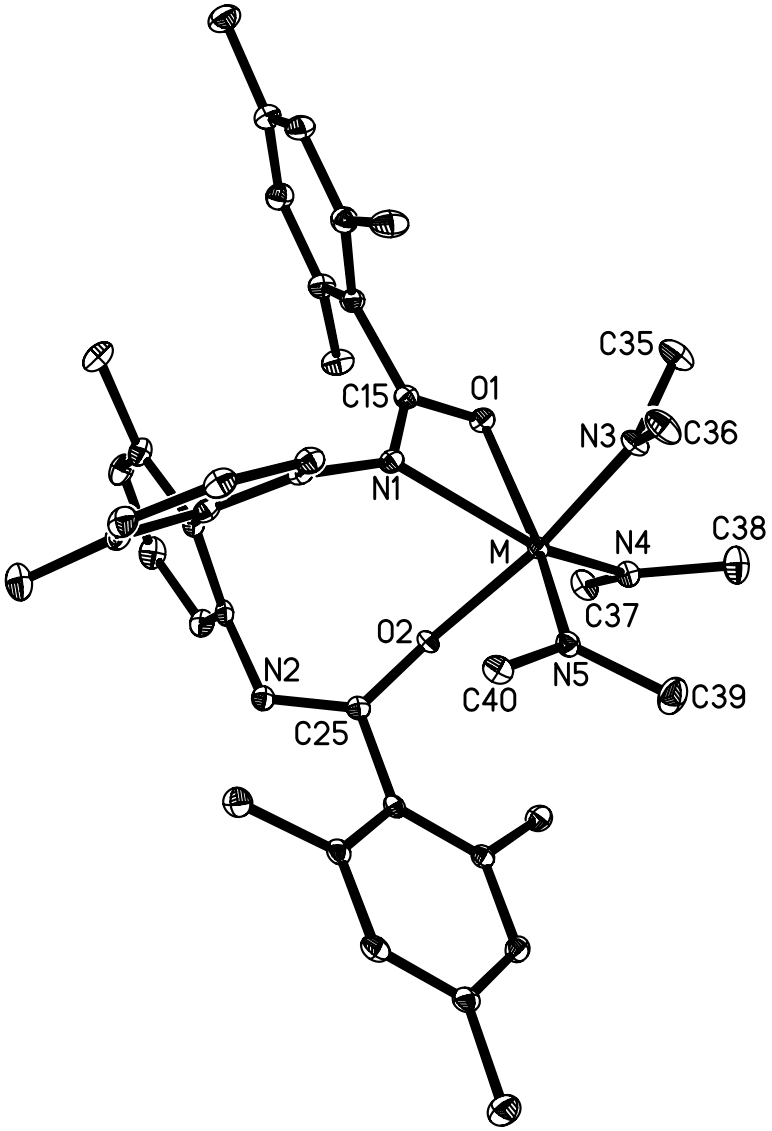

Fig. 2 Molecular structures of **8** (M = Nb) and **9** (M = Ta) (thermal ellipsoids drawn at the 35% probability level).

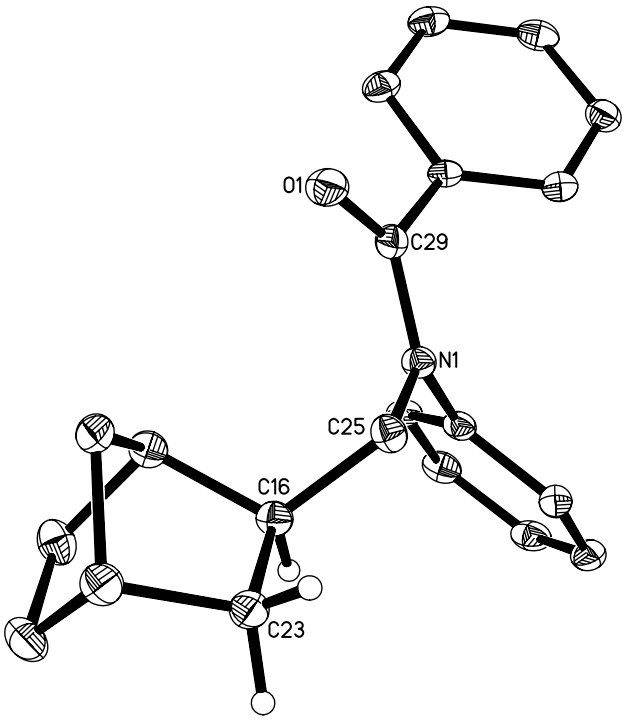

Fig. 3 Molecular structure of benzamide derivative of **10** (thermal ellipsoids drawn at the 35% probability level).