Synthesis, Characterization and Catalytic Activity of Tetradentate Ligands

Haleden Chiririwa, and Champakla T. Parekh

Abstract**—**The synthesis and characterization of novel tetradentate ligands is described. The ligands were characterized by elemental analysis, IR, ^{1}H, ^{13}C NMR, X-ray crystallography and mass spectrometry. Single-crystal X-ray diffraction analysis for ligand **2** revealed that the structure exists as discrete molecules. Furthermore, the ligands 1-4 were tested as potential catalysts.

Keywords**—**Heck reaction, Tetradentate ligands, X-ray crystal structure

I. INTRODUCTION

THE chemistry of bidentate compounds (i.e α-diimines and β-diimines) has been well explored [1]-[2]. A few reports on unconjugated diimines describing their use as catalysts [3] and in bio-inorganic chemistry [4] have appeared in literature. Westcott and co-workers have prepared unconjugated diimines with boronate esters, and complexed them with platinum, to synthesise platinum complexes which can be used as anticancer agents [5]. Here, we report the synthesis and characterization of four new tetradentate ligands obtained by the reaction of terephthalaldehyde with two equivalents of the appropriate amine. These ligands show moderate catalytic activity in the Heck coupling of bromobenzene with acrylic acid.

II. EXPERIMENTAL

All manipulations were carried out under an atmosphere of nitrogen or argon using standard Schlenk techniques unless otherwise stated. All other glassware was thoroughly dried at 210 ° C for at least four hours prior to use.

All reagents were purchased from Aldrich and used without further purification. Anhydrous magnesium sulphate or sodium sulphate were used for drying reaction solutions. Melting points were determined on the Kofler hotstage microscope (Reichart Thermovar) and are uncorrected. Microanalysis data was obtained from the University of Cape Town's Microanalytical Laboratory using a Carlo Erba EA1108 elemental analyser. Infrared Spectra were recorded on a Perkin-Elmer 1000 FT-IR spectrometer, at the University of Cape Town, as KBr discs for solids. All data are given in wavenumbers (cm^{-1}). ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded on either a Varian Unity-400 ^{1}H: 400 MHz; ^{13}C: 100.6 MHz) or Varian Mercury-300 (^{1}H: 300 MHz; ^{13}C: 75.5 MHz) spectrometer at ambient temperatures. ^{1}H NMR spectra were referenced internally using residual protons in the deuterated solvent ($CDCl_3$: δ 7.27; DMSO: δ 2.50 ppm) and values reported relate to tetramethylsilane (δ 0.00). ^{13}C NMR were similarly referenced internally to the solvent resonance $CDCl_3$: δ 77.0; DMSO: δ 39.4 and with values reported relative to tetramethylsilane (δ 0.00). ^{31}P NMR spectra were referenced externally to H_3PO_4. All chemical shifts are quoted in δ (ppm) and coupling constants, *J*, in Hertz (Hz). Mass spectra (EI) were recorded using a JEOL-MATE(II) GC-MS.

General procedure for the synthesis of ligands **1- 4**

The tetradentate ligands were prepared by the addition of one equivalent of aromatic dialdehyde (terephthalaldehyde) to two equivalents of the appropriate amine previously dissolved in methanol and the mixture stirred at room temperature for *ca* 36 hours. The formed compound precipitated out alone without adding any solvent, washed with dry Et_2O and dried under vacuum for 4 hours.

Preparation of **1**

$C_{18}H_{16}N_2S_2$ pale white microcrystalline powder. Yield: 80 %. M.p.: 180-182 °C. Anal.: found, C, 66.59 %; H, 4.62 %; N, 8.72 %; S, 19.65 Calc. for $C_{18}H_{16}N_2S_2$, C, 66.63 %; H, 4.97 %; N, 8.63 %; S, 19.77. ^{1}H NMR ($CDCl_3$) δ_H (ppm): 8.38 (t, 2H, *J* = 1.3 Hz) 7.82 (s, 2H) 7.25 (m, 4H) 7.00 (d, 4H, *J* = 3.4 Hz) 5.00 (d, 4H, *J* = 1.3 Hz). ^{13}C NMR ($CDCl_3$) δ 161.54, 141.72, 138.10, 128.55,126.88, 125.11, 124.80, 59.28. IR (KBr): 1612 cm^{-1} (C=N, imine). EI-MS: *m/z* 103.30 $[M - 2C_5H_5SN]^+$.

Preparation of **2**

$C_{20}H_{20}N_2S_2$ white shiny crystals. Yield: 75 %. M.p.: 240-242 °C. Anal.: found, C, 68.19 %; H, 5.52 %; N, 7.72 %; S, 18.44. Calc. for $C_{20}H_{20}N_2S_2$, C, 68.14 %; H, 5.72 %; N, 7.95 %; S, 18.19 C 43.1, H 5.7, N 7.2 %. ^{1}H NMR ($CDCl_3$) δ_H (ppm): 8.23 (d, 2H, *J* = 1.3Hz, 7.76 (s, 2H) 7.13 (dd, 2H, *J* = 3.4 Hz, *J* = 5.1Hz) 6.92 (dd, 2H, *J* = 1.1 Hz, *J* = 5.1 Hz) 6.84 (dd, 4H, *J* = 1.3 Hz, *J* = 2.1Hz) 3.91 (dt, 4H, *J* = 1.1 Hz, *J* = 7.0Hz) 3.25 (t, 4H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ 161.27, 142.28, 138.15, 128.34, 126.72, 125.18, 123.61, 62.90, 31.42. IR (KBr): 1613 cm^{-1} (C=N, imine), EI-MS: *m/z* 351.76 $[M]^+$.

Preparation of **3**

H. Chiririwa was with Department of Chemistry, University of Johannesburg, P.O. Box 524, Auckland Park, Johannesburg 2006 South Africa. He is now with the Department of Chemistry, National University of Science & Technology, P.O Box AC939 Ascot Bulawayo, Zimbabwe (phone: +263-9- 2828442 ext 2445; fax: +263-9-286803; e-mail: (harrychiririwa@yahoo.com).

C. T. Parekh is with the Department of Chemistry, National University of Science & Technology, P.O Box AC939 Ascot Bulawayo, Zimbabwe. (e-mail: champaklal.parekh@nust.ac.zw).

$C_{20}H_{18}N_4$ white solid. Yield: 85 %. M.p.: does not melt below 260 °C. Anal.: found, C, 76.19 %; H, 5.52 %; N, 17.72 %; Calc. for $C_{20}H_{18}N_4$, C, 76.41 %; H, 5.77%; N, 17.82 %; ^1H NMR ($CDCl_3$) δ_H (ppm): 8.57 (d, 2H, *J* = 4.8 Hz, H_i) 8.50 (s, 2H, H_c) 7.86 (s, 2H, H_a) 7.68 (dt, 2H, *J* = 1.8 Hz, *J* = 7.7 Hz, H_g) 7.44 (d, 2H, *J* = 7.8 Hz, H_f) 7.26 (m, 2H, H_h) 7.18 (dd, 2H, *J* = 4.6 Hz, *J* = 7.2 Hz, H_f) 4.97 (s, 4H, H_d) ^{13}C NMR ($CDCl_3$) δ 162.67, 159.2, 149.54, 138.43, 136.90, 128.78, 122.56, 122.29, 67.12. IR (KBr): 1605 cm^{-1} (C=N, imine), EI-MS: *m/z* 221.84 $[M – C_6H_6N]^+$.

Preparation of **4**

$C_{22}H_{22}N_4$ white solid. Yield: 85 %. M.p.: does not melt below 260 °C. Anal.: found, C, 77.19 %; H, 6.22 %; N, 16.52 %; Calc. for $C_{22}H_{22}N_4$, C, 77.16 %; H, 6.48 %; N, 16.36 %; ^1H NMR ($CDCl_3$) δ_H (ppm): 8.55 (ddd, 2H, *J* =0.8 Hz, *J* = 1.7Hz, J = 4.8 Hz) 8.21 (t, 2H, *J* = 1.3Hz) 7.69 (s, 2H) 7.55 (dt, 2H, *J* = 1.9Hz, *J* = 7.7Hz) 7.11 (m, 2H) 4.03 (dt, 8H, *J* = 1.2 Hz, *J* = 7.2Hz) 3.19 (t, 4H, *J* = 7.2Hz), ^{13}C NMR ($CDCl_3$) δ 161.05, 159.45, 149.37, 138.88, 136.13, 128.21, 123.67, 121.24, 61.18, 39.61.IR (KBr): 1610 cm^{-1} (C=N, imine). EI-MS: *m/z* 249.90 $[M – C_6H_6N]^+$.

Catalytic reactions

A mixture of bromobenzene (1.0 mmol), acrylic acid (1.3 mmol), triethylamine (2.0 mmol), DMF (6 mL) and 0.5 mol % of catalyst was stirred at 80 °C under air. Following the reaction, the catalyst was separated by filtration. The filtrate was dried over Na_2SO_4 and filtered. The products were quantified by GC–MS analysis. The typical GC–MS analysis program was as follows: initial column temperature 100 °C, hold 2 min, ramp temperature to 280 °C at 15 °C /min, and hold for 5 min.

X-ray crystal structure determination

Recrystallisation by slow diffusion of Et_2O into a concentrated CH_2Cl_2 of the solution gave crystals of **2** suitable for X-ray structure determination.. X-ray intensity data were collected on a Nonius Kappa-CCD diffractometer with 1.5 kW graphite monochromated Mo-Kα radiation.

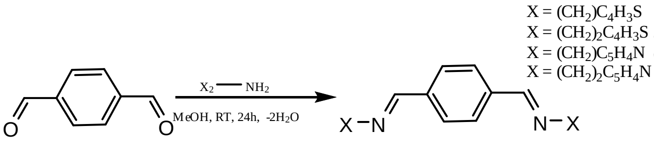
The structure was solved by direct methods using SHELXS-97 and refined employing full-matrix least-squares with the program SHELXL-97 refining on F^2. Packing diagrams were produced using the program PovRay and graphic interface X-seed [6]. Crystallographic data for the structure determinations are listed in Table I.

TABLE I
CRYSTAL DATA AND STRUCTURE REFINEMENT PARAMETERS FOR LIGAND 2

Ligand	**2**
Empirical formular	$C_{20}H_{20}N_2S_2$
Formular weight	352.52
T/K	173
λ/Å	0.7103
Space group	Monoclinic
a	9.8592(10)
b	7.1533(3)
c	25.678(2)
α(deg)	90
β(deg)	96.646(5)
γ(deg)	90
V($Å^3$)	1798.8(3)
Z	8
$Density_{calc}$(mg/ml)	1.302
Absorption coefficient (mm^{-1})	0.299
F(000)	744
Crystal size (mm)	0.04x0.20x0.22
Theta range for data collection (deg)	3.2 – 28.3
Limiting indices	-13<=h<=13, -9<=k<=9, -34<=1<=34
Reflections Collected/ Unique	16248 / 2230 [R(int) = 0.045]
Completeness of theta max. and min. transmission	28.3 (99.8%)
Refinement method	Full-matrix least-squares on F^2
Data / Restraints/ Parameters	2230/0/109
Goodness-of-fit on F^2	1.06

III. RESULTS AND DISCUSSION

Symmetrical ligands **1-4** are usually prepared upon condensation of dialdehydes with amines [7] as shown in Scheme I. The ligands were characterised by IR spectroscopy as well as ^1H, ^{13}C NMR, X-ray crystallography and mass spectrometry.



In the ^1H NMR spectra of the tetradentate ligands **1-4**, the imine protons appear as singlets in the range 8.23 – 8.57 ppm, the chemical shifts for the methylene ($-CH_2-$) protons appear at 5.00 ppm for **1** and **3** but at *ca* 3 - 4 ppm for **2** and **4**. The ^1H NMR spectra of the ligands **1** to **3** displayed peaks for the aromatic protons in the region of 7.45 - 7.95 ppm. The signals for the pyridyl and thiophenyl rings occur at between 6.9 – 7.2 ppm for all the ligands respectively. The NMR spectra of the ligands indicate that each half of the ligand is equivalent due to the presence of internal symmetry. In view of the observed NMR pattern, it may be considered that the *trans* configuration of the ligands is predominant in solution or that there is a fast equilibrium between the *cis* and *trans* isomers of the ligands.

The mass spectral data of the tetradentate ligands are given in Table II. The molecular ion peaks are in good agreement with their empirical formula as indicated from elemental analysis. The other peaks represent fragments of the molecular ion.

TABLE II
MASS SPECTRA DATA OF THE LIGANDS 1-4

Ligand	Calculated molar mass (g/mol)	Molecular fragment	Assignment
1	324.47	103.30	$[M\text{-}2C_5H_5SN]^+$
2	352.52	254.89	$[M\text{-}C_5H_8S]^+$
3	314.38	221.84	$[M\text{-}C_6H_6N]^+$
4	342.44	249.90	$[M\text{-}C_6H_6N]^+$

Single crystal X-ray determination of ligand 2

The selected bond lengths and angles for ligand **2** are summarized in Table III, and the molecular structure is shown in Fig. 1.

TABLE III
SELECTED BOND DISTANCES AND ANGLES FOR LIGAND 2

Bond Distances (Å)		Bond Angles(°)	
S(1)-C(2)	1.691(3)	C(2)-S(1)-C(5)	93.56(12)
S(1)-C(5)	1.693(2)	C(7)-N(8)-C(9)	117.3(2)
N(8)-C (7)	1.455(3)	S(1)-C(2)-C(3)	111.6(2)
N(8)-C(9)	1.266(3)	S(1)-C(5)-C(6)	121.91(17)
C(5)-C(6)	1.502(3)	N(8)-C(9)-C(10)	122.84(19)
C(6)-C(7)	1.520(3)		
C(9)-C(10)	1.473		

The crystal structure reveals that ligand **2** exists as discrete molecules. The N(8)-C(9) distance of 1.266 Å is consistent with a C=N double bonding. The C=N-C angle in the ligand of 117.3°, is slightly less than the idealised angle of 120°, as is seen in other structurally characterised imines [8]-[9]. Bond distances and angles around the sulphur atoms are also similar to those in related compounds [10]-[11].

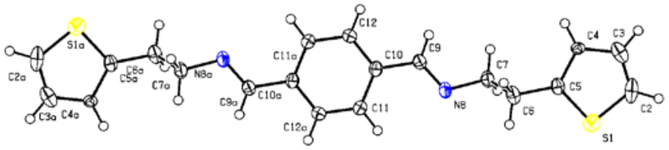


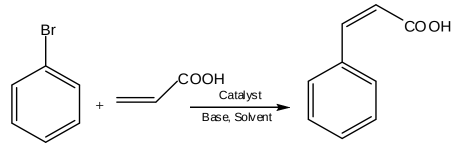
Fig. 1 Molecular structure of ligand showing the atomic numbering scheme. All non-hydrogen atoms were presented with ellipsoidal model with probability level 40%.

Heck reaction of bromobenzene with acrylic acid

The tetradentate ligands **1-4** were evaluated as catalyst precursors for the Heck reaction of bromobenzene with acrylic acid. In the present work, the ligands gave reasonably active catalysts, (Table IV).

The base and solvent for the Heck reaction greatly influences catalytic activity. The results for these complexes are summarized in Table IV. DMF is the best solvent for this catalytic system. In other organic solvents, e.g., methanol, or toluene, low yields of coupling products were obtained. Among four different bases investigated for these reactions Et_3N was found to be the most effective K_2CO_3 and Na_2CO_3 were substantially less effective and KF failed to promote the reaction.

TABLE IV
THE EFFECT OF BASE AND SOLVENT ON THE LIGANDS 1-4 CATALYSED HECK REACTION OF BROMOBENZENE WITH ACRYLIC ACID



Entry	Base	Solvent	Atmosphere	T (°C)	T (hr)	Yields
1	Et_3N	DMF	Air	100	12	52/42/36
2	Et_3N	MeOH	Air	75	12	35/25/15
3	Et_3N	Toluene	Air	80	12	25/20/15
4	K_2CO_3	DMF	Air	80	12	18/16/14
5	Na_2CO_3	DMF	Air	80	12	14/12/10
6	KF	DMF	Air	80	12	-/-/-

Supplementary materials

Supplementary data and figures for this paper are available from the IUCr electronic archives (Reference: GO2007) [12].

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