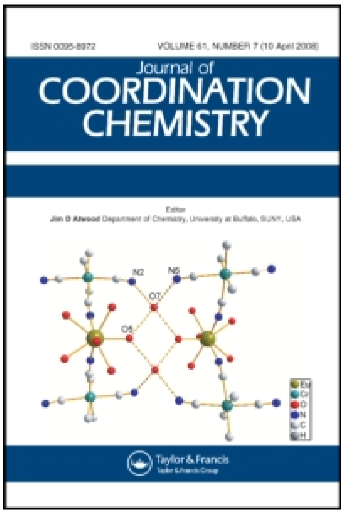

**Journal of Coordination Chemistry**
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455674

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**To cite this Article** Patel, K. S. and Kolawole, G. A.(1982) 'MAGNETIC AND SPECTRAL PROPERTIES OF OXOVANADIUM(IV) COMPLEXES OF QUADRIDENTATE NAPHTHALDIMINE LIGANDS', Journal of Coordination Chemistry, 11: 4, 231 — 237

**To link to this Article: DOI:** 10.1080/00958978208079742

**URL:** http://dx.doi.org/10.1080/00958978208079742

*J. Coord. Chem.*, 1982, Vol. 11, pp. 231–237
0095-8972/82/1104-0231$06.50/0

# MAGNETIC AND SPECTRAL PROPERTIES OF OXOVANADIUM(IV) COMPLEXES OF QUADRIDENTATE NAPHTHALDIMINE LIGANDS

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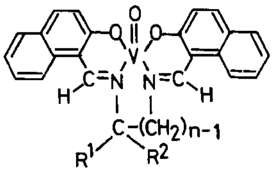
(*Received September 9, 1981*)

Oxovanadium(IV) complexes of 2-hydroxy-1-naphthaldehyde and the Schiff-base complexes [$VO\{OC_{10}H_8CH{=}N{-}CR^1R^2{-}(CH_2)_{n-1}{-}N{=}CHC_{10}H_8O\}$] where $n = 2$ ($R^1 = R^2 = H$ or $CH_3$) and $n = 3$–$8$ ($R^1 = R^2 = H$) along with the corresponding ligands have been synthesised and characterised by elemental analysis, i.r. and electronic spectral and magnetic susceptibility measurements. There is evidence that the conversion of the bis-napthaldehyde complex to the Schiff-base complexes is accompanied by an inversion of the $e_\pi^*$ and $b_1^*$ energy levels. Moreover, the introduction of a second phenyl ring results in a reduction of the in-plane ligand field. The $\nu(V{=}O)$ frequencies suggest that the complexes are five-coordinate, except VO(naph$_2$-tn) which is likely to be six-coordinate and polymeric. Although the magnetic moments at room temperature for the complexes vary between 1.59 and 1.77 B.M. the variation of the moments with temperature is not appreciable.

## INTRODUCTION

Although the magnetic and spectral properties of the oxovanadium(IV) Schiff-base complexes derived from salicylaldehyde and polymethylenediamines have very recently been reported,[1] it appears from the literature that similar studies have not been made on the corresponding complexes of 2-hydroxy-1-naphthaldehyde. Moreover, there have been speculation about the possibility of the inversion of the ordering of the $e_\pi^*$ and $b_1^*$ energy levels[2] in such systems.[1] As the $pK_a$ of 2-hydroxy-1-naphthaldehyde is lower than that of salicylaldehyde,[3] one would expect that the oxovanadium(IV) complex of the naphthaldehyde would be more stable than that of salicylaldehyde[4] and this provides an opportunity of following the stereochemical changes accompanying the conversion of the $O_4$ chromophore around V=O in the bis-aldehyde complex to $O_2N_2$ in the quadridentate Schiff-base complexes. Furthermore, it would be of interest to investigate the effect of the additional benzene ring on the stereochemistry of the oxovanadium(IV) Schiff-base complexes, I.



| Compound | $R^1$ | $R^2$ | n | Abbreviation |
|---|---|---|---|---|
| 1 | H | H | 2 | VO(naph$_2$-en) |
| 2 | H | $CH_3$ | 2 | VO(naph$_2$-pn) |
| 3 | $CH_3$ | $CH_3$ | 2 | VO(naph$_2$-Mepn) |
| 4 | H | H | 3 | VO(naph$_2$-tn) |
| 5 | H | H | 4 | VO(naph$_2$-tm) |
| 6 | H | H | 5 | VO(naph$_2$-ptn) |
| 7 | H | H | 6 | VO(naph$_2$-hxm) |
| 8 | H | H | 7 | VO(naph$_2$-hpm) |
| 9 | H | H | 8 | VO(naph$_2$-ocm) |

The bis-aldehyde complex, VO(naph)$_2$·$H_2O$ is given number 0.

## EXPERIMENTAL

### *Preparation of ligands*

The ligands were isolated by dropwise addition of

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TABLE I
Analytical data for the Schiff-base ligands

| Compound | Molecular formula | M.P. (°C) | %C Found (Calc.) | %H Found (Calc.) | %N Found (Calc.) |
|---|---|---|---|---|---|
| $H_2$naph$_2$-en | $C_{24}H_{20}N_2O_2$ | 318[a] | 78.15<br>(78.24) | 5.55<br>(5.47) | 7.80<br>(7.60) |
| $H_2$naph$_2$-pn | $C_{25}H_{22}N_2O_2$ | 181.6 | 78.65<br>(78.51) | 6.00<br>(5.80) | 7.30<br>(7.32) |
| $H_2$naph$_2$-Mepn | $C_{26}H_{24}N_2O_2$ | 146.0 | 78.40<br>(78.76) | 6.30<br>(6.10) | 6.85<br>(7.07) |
| $H_2$naph$_2$-tn | $C_{25}H_{22}N_2O_2$ | 214.8 | 78.40<br>(78.51) | 6.00<br>(5.80) | 7.15<br>(7.32) |
| $H_2$naph$_2$-tm | $C_{26}H_{24}N_2O_2$ | 229.0 | 78.35<br>(78.76) | 6.25<br>(6.10) | 7.00<br>(7.07) |
| $H_2$naph$_2$-ptn | $C_{27}H_{26}N_2O_2$ | 157.7 | 79.00<br>(79.00) | 6.40<br>(6.38) | 7.50<br>(6.82) |
| $H_2$naph$_2$-hxm | $C_{28}H_{28}N_2O_2$ | 170.0 | 78.95<br>(79.22) | 6.70<br>(6.65) | 6.50<br>(6.60) |
| $H_2$naph$_2$-hpm | $C_{29}H_{30}N_2O_2$ | 141.3 | 79.20<br>(79.42) | 6.70<br>(6.90) | 6.40<br>(6.39) |

[a] Decomposition temperature.

0.05 mol of the aliphatic diamines (Aldrich) in 40 cm$^3$ methanol to a warm 80 cm$^3$ methanolic solution of 0.1 mol of 2-hydroxy-1-naphthaldehyde while stirring. The reaction mixture was refluxed for 15 min. and yellow crystals of Schiff-bases separated while cooling except those of octamethylene diamine and methylpropylene derivatives. $H_2$naph$_2$-ocm formed an oily product while $H_2$naph$_2$-Mepn was precipitated by the addition of petroleum ether. The products were recrystallised from methanol. The analytical data for the ligands are given in Table I. They were found to be relatively less soluble in organic solvents and possess higher melting points compared with those of the corresponding salicylaldimine and 3-methoxysalicylaldimine Schiff-bases.[5]

### *Preparation of bis(naphthaldehyde)oxovanadium(IV) monohydrate*

34.4 g (0.2 mol) of 2-hydroxy-1-naphthaldehyde was added in bits to a solution of 20.0 g (0.1 mol) of $VOSO_4 \cdot 2H_2O$ dissolved in 800 cm$^3$ of 60% ethanol while stirring. The pH of the resultant mixture was adjusted to 6 by addition of an aqueous solution of sodium acetate whereby the complex was precipitated. The product was filtered, washed with 40% ethanol and digested thrice with 60% ethanol. It was finally washed twice with absolute ethanol and dried in vacuo over $CaCl_2$—$P_2O_5$, and finally at 100° in a drying pistol over $P_2O_5$ for 8 h.

### *Preparation of N,N'-bis(naphthalidene)(polymethylenediiminato)oxovanadium(IV) complexes*

Complexes (1)–(5), and (7) were obtained by refluxing a suspension of VO(naph)$_2$$\cdot H_2O$ in ethanol with ethanolic solutions of the appropriate amines in mole ratio 2 : 1. Complexes (6), (8), and (9) were isolated by the reaction of equimolar (6 mmol) methanolic solutions of $VOSO_4 \cdot 2H_2O$ with preformed Schiff-bases buffered with triethylamine (14 mmol).[1] All the reactions required refluxing for 1 h except complexes (5) and (7) which required 2 h and 18 h respectively.

### *Physical measurements*

Elemental analysis was performed by the Microanalytical Laboratories of the Universities of Ibadan and Leeds. Vanadium was estimated as vanadium(V) oxide. Melting points were determined using the Reichert Austria Instrument equipped with a digital thermometer. The analytical results along with colours, melting points and yields are presented in Table II. The i.r. spectra were recorded on a Perkin-Elmer 457 Grating Infrared spectrophotometer in the range 250–4000 cm$^{-1}$, using pressed KBr discs, and a Grubb-Parsons DM4 spectrophotometer equipped with a CsI prism was also used for recording the spectra in Nujol mulls in the range 200–500 cm$^{-1}$. The frequencies are believed to be accurate within ±2 cm$^{-1}$. The diffuse-reflectance electronic spectra were

TABLE II
Analytical results of the oxovanadium(IV) complexes

| Compound | Colour | M.P. (°C) | Yield (%) | %C Found (Calc.) | %H Found (Calc.) | %N Found (Calc.) | %V Found (Calc.) |
|---|---|---|---|---|---|---|---|
| $VO(naph)_2 \cdot H_2O$ | green | 226[a] | 90 | 62.35<br>(61.84) | 3.80<br>(3.77) | —<br>— | 11.81<br>(11.92) |
| $VO(naph_2\text{-}en)$ | light-green | 310[a] | 70 | 66.65<br>(66.52) | 4.25<br>(4.19) | 6.70<br>(6.46) | 11.50<br>(11.75) |
| $VO(naph_2\text{-}pn)$ | light-green | 270[a] | 70 | 67.35<br>(67.12) | 4.75<br>(4.51) | 6.30<br>(6.26) | 11.26<br>(11.39) |
| $VO(naph_2\text{-}Mepn)$ | green | 278.8 | 66 | 67.60<br>(67.68) | 4.95<br>(4.81) | 6.25<br>(6.07) | 10.90<br>(11.02) |
| $VO(naph_2\text{-}tn)$ | orange-yellow | 292.0 | 95 | 66.95<br>(67.12) | 4.60<br>(4.51) | 6.25<br>(6.26) | 11.39<br>(11.39) |
| $VO(naph_2\text{-}tm)$ | light-green | 246[a] | 80 | 67.00<br>(67.68) | 5.00<br>(4.81) | 6.25<br>(6.07) | 10.66<br>(11.02) |
| $VO(naph_2\text{-}ptn) \cdot H_2O$ | light-green | 224[a] | 82 | 65.50<br>(65.72) | 5.15<br>(5.31) | 5.45<br>(5.68) | 10.52<br>(10.32) |
| $VO(naph_2\text{-}hxm)$ | light-green | 247[a] | 82 | 68.55<br>(68.71) | 5.60<br>(5.35) | 5.70<br>(5.72) | 10.25<br>(10.41) |
| $VO(naph_2\text{-}hpm)$ | light-green | 210[a] | 83 | 69.80<br>(69.18) | 5.75<br>(5.61) | 5.60<br>(5.56) | 10.35<br>(10.12) |
| $VO(naph_2\text{-}ocm) \cdot H_2O$ | greyish-green | 162[a] | 80 | 67.95<br>(67.28) | 5.90<br>(6.02) | 5.80<br>(5.23) | 9.41)<br>(9.51) |

[a] Decomposition temperatures.

measured in the range 335–1000 nm on an SP 500 spectrophotometer using LiF as a reference, while the solution electronic spectra in chloroform and pyridine ($10^{-3}$–$10^{-4}$ mol dm$^{-3}$) were recorded on an Applied Physics Cary 14H spectrophotometer. The magnetic susceptibility measurements were carried out by the Gouy method over the temperature range 84–320K using a Newport Instruments Gouy balance. The samples were packed into flat-bottomed silica tubes and were sealed via graded seals under vacuum. The samples were free from ferromagnetic impurities and the diamagnetic corrections were calculated from tables of Pascal's constants.

## RESULTS AND DISCUSSION

The relevant i.r. band positions are given in Table III. The $\nu$(C=O) mode shifts from 1645 cm$^{-1}$ in the 2-hydroxy-1-naphthaldehyde to 1596 cm$^{-1}$ in $VO(naph_2 \cdot H_2O$, indicating that the carbonyl oxygen is involved in bonding to V. The band in the range 1620–1638 cm$^{-1}$ in the Schiff-base ligands which shifts to 1600–1620 cm$^{-1}$ in the complexes is assigned to $\nu$(C=N). This observation suggests the weakening of the C=N bond due to coordination of the azomethine N to V. The splitting of this band suggests that the two azomethine groups may be more distorted below and above the horizontal plane than in the salicylaldimine analogues.[1] The $\nu$(C=C) stretching frequency (1538–1548 cm$^{-1}$) is not significantly changed from the ligands (1540 cm$^{-1}$). However, the position of this band is lower than in the corresponding bands in the salicylaldimines.[1] The —$CH_2$— deformation modes are expected at 1450–1503 cm$^{-1}$ but it seems there is a considerable coupling with C—C modes.[6] On the basis of previous assignments[1,6–8] the band at 1301 cm$^{-1}$ in the complexes has been assigned to $\nu$(C—O).

The $\nu$(V=O) mode in $VO(sal)_2 \cdot H_2O$[4] which is at 965 cm$^{-1}$ is found to be normal[9] (980 cm$^{-1}$) in $VO(naph)_2 \cdot H_2O$ suggesting that the water is present as lattice water[10] and the complex itself is five-coordinate. In the Schiff-base complexes $\nu$(V=O) vibrations are sharp and normal (975–980 cm$^{-1}$) except for complex (4) ($R^1 = R^2 = H$; $n = 3$), where a band at 860 cm$^{-1}$ is diagnostic for V—O—V polymerisation.[11,12] The bands at 560–580 cm$^{-1}$ and 420–460 cm$^{-1}$, absent in $VO(naph)_2 \cdot H_2O$, are assigned to $\nu$(V—N) while the bands at 480–530 cm$^{-1}$ and 290–340 cm$^{-1}$ are assigned to (V—O) in both $VO(naph)_2 \cdot H_2O$ and the Schiff-base complexes.

The electronic spectral band position along with molar absorptivities (where solution measurements were taken) and the diffuse-reflectance spectra of the complexes are given in Table IV and Fig. 1 respectively. The most intense band in $VO(naph)_2 \cdot H_2O$ observed at 741 nm is assigned to $b_2(d_{xy}) \rightarrow e_\pi^*(d_{xy}, d_{yz})$.[2] Two relatively weak bands are also observed at 667–625 nm

TABLE III

Some relevant infrared frequencies[a,b] for the oxovanadium(IV) complexes

| (0) | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | Tentative assignment |
|---|---|---|---|---|---|---|---|---|---|---|
|  | $\left.\begin{matrix}1614\\1600\end{matrix}\right\}\mathrm{vs}$ | $\left.\begin{matrix}1614\\1600\end{matrix}\right\}\mathrm{vs}$ | $\left.\begin{matrix}1618\\1602\end{matrix}\right\}\mathrm{vs}$ | 1615vs | $\left.\begin{matrix}1618\\1601\end{matrix}\right\}\mathrm{vs}$ | $\left.\begin{matrix}1620\\1607\end{matrix}\right\}\mathrm{vs}$ | $\left.\begin{matrix}1620\\1605\end{matrix}\right\}\mathrm{vs}$ | $\left.\begin{matrix}1616\\1603\end{matrix}\right\}\mathrm{vs}$ | $\left.\begin{matrix}1616\\1603\end{matrix}\right\}\mathrm{vs}$ | ν(C=N) |
|  | (1638vs) | (1625vs) | (1620vs) | (1632vs) | (1632vs) | (1630vs) | (1628vs) | (1634vs) |  |  |
| 1596m |  |  |  |  |  |  |  |  |  | ν(C=O) |
| 1534s | 1538s | 1540s | 1540s | 1540s | 1542s | 1548s | 1546s | 1542s | 1543s | ν(C=C) |
|  | (1540s) | (1541m) | (1540m) | (1540m) | (1540m) | (1540m) | (1538m) | (1543m) |  |  |
|  | 1503m | 1505m | 1510m | 1500m | 1505m | 1501w | 1509m | 1505m | 1505m | $-CH_2$-deformation |
|  | (1490m) | (1490w) | (1490w) | (1488w) | (1488w) | (1490w) | (1490w) | (1490w) |  |  |
| 1452s | 1450m | 1452s | 1455s | 1455m | 1453m | 1456m | 1456m | 1453m | 1454m | ν(C—C) + $-CH_2$-deformation |
|  | (1447m) | (1440w) | (1440w) | (1442w) | (1438w) | (1437w) | (1445w) | (1445m) |  |  |
| 1422s | 1438m | 1428m | 1434m | 1430m | 1429m | 1432m | 1432m | 1430m | 1430m |  |
| 1407vs | 1408m | 1410m | 1416w | 1410m | 1412m | 1416m | 1416m | 1414m | 1412m |  |
|  | (1402m) | (1400m) | (1395w) | (1399w) | (1400w) | (1398w) | (1400w) | (1400m) |  |  |
|  | 1389m | 1390m | 1393m | 1396sh | 1393w | 1391w | 1394vw | 1391w | 1390w | ν(C—N) |
| 1365sh | 1355m | 1357m | 1359m | 1360m | 1356m | 1360m | 1360m | 1356m | 1357m |  |
|  | (1350s) | (1350m) | (1350s) | (1360m) | (1353m) | (1350m) | (1360m) | (1364m) |  |  |
| 1305m | 1298s | 1300s | 1301m | 1302s | 1300s | 1303m | 1302s | 1301s | 1300s | ν(C—O) |
|  | (1310w) | (1314vw) | (1320sh) | (1310w) | (1305m) | (1305w) | (1316w) | (1311m) |  |  |
| 1250m | 1247m | 1248m | 1250m | 1245m | 1249m | 1250m | 1250m | 1251m | 1250m | δ(C—H) |
|  | (1256m) | (1252w) | (1250w) |  | (1254w) | (1255w) | (1250vw) | (1258m) |  |  |
| 1190s | 1187m | 1190s | 1186s | 1187s | 1185m | 1189m | 1188m | 1190m | 1188m |  |
|  | (1180m) | (1182m) | (1184w) | (1180w) | (1191m) | (1178m) | (1179m) | (1184m) |  |  |
| 980vs | $\left.\begin{matrix}989\\982\end{matrix}\right\}\mathrm{vs}$ | 986vs | 984vs | $\left.\begin{matrix}987\\965\end{matrix}\right\}\mathrm{vs}$ | 985vs | 987s | 987s | 981s | 983s | ν(V=O) |
|  |  |  |  | 860vs |  |  |  |  |  | V—O—V |
|  | 573s | 571vs | 579s | 575m | 560sh | 550w | 552w | 260w |  | ν(V—N) |
| 524m | 528m | 522m | 520m | 533m | 520s | 524m | 523m | 522m | 522m | ν(V—O) |
| 479m | 460w | 460m | 462w | 462m |  | 468s |  |  |  | ν(V—N) |
|  | (455m) | (448w) | (460w) |  |  |  |  | (440m) |  |  |
|  | 420w | 420m | 423m | 420m | 420m | 417m | 421w | 422w | 420w | + ν(V—O) |
| 410s | 411w |  |  | 400m |  | 400 |  | 404w | 403w | + Ligand vibrations |
|  | 390w | 388w |  |  |  |  |  |  |  |  |
|  | 356m | 350m | 364m | 364m |  |  | 398m |  |  |  |
|  |  |  |  |  |  |  | 351w |  | 348w |  |
| $\left.\begin{matrix}339\\325\end{matrix}\right\}\mathrm{w}$ | 334m | 330w | 329vw | 337w |  |  | 346 |  |  |  |
|  | 308w | 310w |  | 320m |  |  | 326w |  |  |  |
| 299w | 301w |  | 291w | 291m |  |  |  |  |  |  |
|  | 277w | 275w | 276w | 273w |  |  |  |  |  |  |

[a] vs = very strong, s = strong, m = medium, w = weak.

[b] Corresponding ligand frequencies in parentheses.

TABLE IV
Electronic spectral data of oxovanadium(IV) complexes. Band maxima/nm ($\varepsilon/m^2\ mol^{-1}$)

| Compound | Medium[a] | Band I $b_2 \rightarrow b_1^*$ | Band II $b_2 \rightarrow e_\pi^*$ | Band III $b_2 \rightarrow a_1^*$ | Band IV | Band V |
|---|---|---|---|---|---|---|
| | | | | | Charge | Transfer |
| (0) | R | 610 | 740 | 510 | 395 | 350 |
| | C[b] | | 630 | | | |
| | P | 761(10) | 557(23) | | | |
| (1) | R | 800sh | 630 | | 385 | |
| | | | 595 | | | |
| | C | | 639(116) | | | |
| | P | 762(23) | 606(40) | | | |
| (2) | R | 800sh | 620 | | 405 | 365 |
| | | | 600? | | | |
| | C | | 652(190) | 478(157) | | |
| | P | 758(10) | 621(20) | | | |
| (3) | R | 800sh | 645 | | 405 | 362 |
| | | | 600sh | | | |
| | C | | 645(81) | | | |
| | P | | 615(17) | 511(9) | | |
| (4) | R | 890br | | 540sh | 400 | 370 |
| | C | | 795(161) | | 417(237) | |
| | P[c] | | 558 | 494 | | |
| (5) | R | 800 | 625 | 505 | 382 | |
| (6) | R | 806br | 617 | 533 | 380 | |
| (7) | R | 815br | 615 | 570 | 400 | 375 |
| (8) | R | 825 | 615 | 550 | 380 | 365 |
| (9) | C | | 670(35) | 525(61) | | |

[a] R = reflectance; C = chloroform; P = pyridine.
[b] Unresolved spectrum sh = shoulder; br = broad.
[c] $0.98 \times 10^{-3}$ mol dm$^{-3}$ solution gave one band at 494 nm; $0.17 \times 10^{-3}$ mol dm$^{-3}$ solution gave an additional band at 558 nm.

along with a shoulder at 526–500 nm. The bands at 610 nm and 510 nm are assigned to $b_2(d_{xy}) \rightarrow b_1^*(d_{x^2-y^2})$ and $b_2(d_{xy}) \rightarrow a_1^*(d_{z^2})$ respectively. The observation of four likely *d*—*d* transitions may suggest a distortion of the square-pyramidal geometry around V in support of the i.r. results. The reflectance spectra of the Schiff-base complexes are, however, different from that of $VO(naph)_2 \cdot H_2O$ where the most intense band shifts to 667–588 nm and the band at 770 cm$^{-1}$ reduces to either a shoulder [complexes (1)–(3)] or a broad low-intensity band [complexes (4)–(9)] at 910–770 nm. Similar trends are observed in cases where measurements were taken in chloroform solutions. These results support our earlier speculation[1] about the possibility of an inversion[9,13] of the $e_\pi^*$ and $b_1^*$ energy-levels in the quadridentate Schiff-base complexes. The weak splitting of Band II (667–588 nm) in the reflectance-spectra of complexes (1)–(3), and (5)–(9) is interpreted as arising from the removal of the degeneracy of the $e_\pi^*$ levels[9] as a result of lowering of symmetry of the complexes by the introduction of the alkyl bridge. The absence of this band in the spectra of (4), similar to $VO(sal_2\text{-}tn)$,[1,11,12] suggests that (4) is also likely to be polymeric, with a distorted octahedral geometry.[11]

Although the electronic spectra of the Schiff-base complexes are similar to those observed for corresponding complexes of the salicylaldimine series,[1] the energies of Bands I, II, and III tend to be lower in the present series. The lowering of the energies of the *d*—*d* transitions appears to be due to the introduction of the benzene ring into the salicylaldehyde and this observation is consistent with the effect of phenyl substitution observed in the β-ketimine complexes.[14]

The magnetic data for seven of the complexes are tabulated in Table V. The room temperature magnetic moments are 'normal'[15] for $VO(naph)_2 \cdot H_2O$ and complexes (1)–(3), and (7), higher for (4), and lower for (5). However, the variation of the moments with temperature is not appreciable and the compounds follow the Curie-Weisslaw giving small θ-values. A θ-value of −4K obtained for (4) indicates some very weak ferromagnetic interaction, similar to that reported for $VO(sal_2\text{-}tn)$.[16,17]

The magnetic moment at room temperature for (5) (1.59 B.M.) is very close to that reported for $(VO)_2$

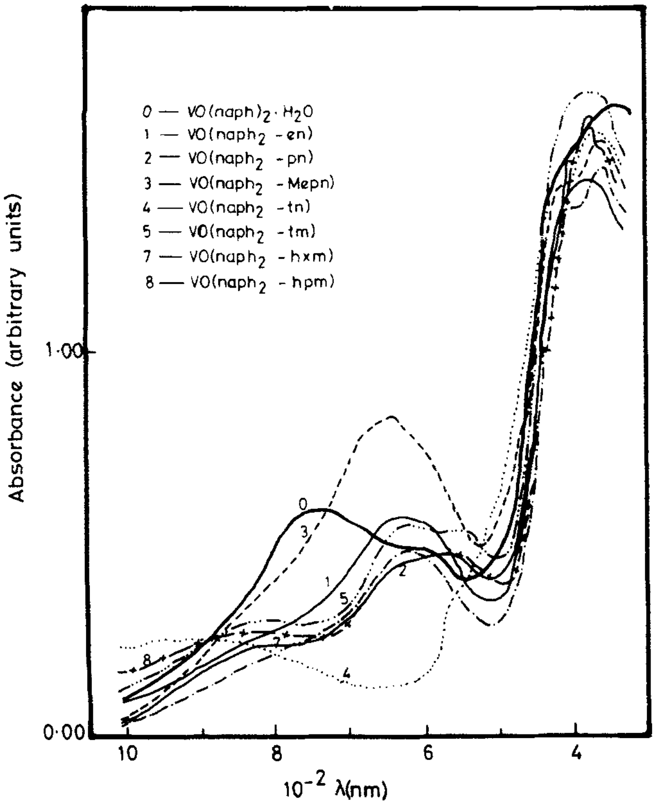

FIGURE 1 Reflectance spectra of the naphthaldimine complexes.

(triketone)$_2$,[18] however, in the absence of anticipated direct V—V coupling the origin of the subnormal moment is unknown.

## ACKNOWLEDGEMENTS

We are very grateful to Dr. Earnshaw and Mr. Hedley for their technical assistance and useful suggestions.

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TABLE V
Variation of magnetic moments ($\mu_{eff}{}^a$/B.M.) with temperature

| Compound<br>T(K) | 0 | 1 | 2 | 3 | 4 | 5 | 7 |
|---|---|---|---|---|---|---|---|
| 320.0 | 1.725 | 1.725 | 1.72 | 1.715 | 1.77 | 1.60 | 1.73 |
| 300.0 | 1.72 | 1.72 | 1.71 | 1.71 | 1.76 | 1.59 | 1.74 |
| 280.0 | 1.725 | 1.72 | 1.71 | 1.71 | 1.75 | 1.59 | 1.74 |
| 260.0 | 1.72 | 1.715 | 1.70 | 1.71 | 1.755 | 1.59 | 1.74 |
| 240.0 | 1.72 | 1.71 | 1.69 | 1.70 | 1.76 | 1.58 | 1.73 |
| 220.0 | 1.71 | 1.71 | 1.70 | 1.69 | 1.76 | 1.58 | 1.745 |
| 200.0 | 1.71 | 1.70 | 1.69 | 1.69 | 1.75 | 1.58 | 1.74 |
| 180.0 | 1.71 | 1.70 | 1.69 | 1.685 | 1.76 | 1.58 | 1.71 |
| 160.0 | 1.70 | 1.69 | 1.68 | 1.68 | 1.76 | 1.58 | 1.70 |
| 140.0 | 1.70 | 1.685 | 1.67 | 1.68 | 1.76 | 1.57 | 1.70 |
| 120.0 | 1.69 | 1.68 | 1.66 | 1.68 | 1.77 | 1.56 | 1.69 |
| 100.0 | 1.67 | 1.67 | 1.65 | 1.67 | 1.77 | 1.56 | 1.67 |
| 84.0 | 1.685 | 1.67 | 1.65 | 1.65 | 1.77 | 1.55 | 1.67 |
| $\theta$/K | 7 | 10 | 13 | 9 | −4 | 8 | 14 |
| $-\chi_L \times 10^6$ ($cm^3$ $mol^{-1}$) | 238 | 245 | 257 | 268 | 257 | 268 | 292 |

[a] The moments are calculated from the expression $\mu_e = 2.828(X_A \cdot T)^{1/2}$ and the Curie-Weiss law $\chi_A^{-1} \propto (C + \theta)$. $X_A$ = Molar magnetic susceptibility, C = Curie constant, 1 B.M. = $0.927 \times 10^{-23}$ Am$^2$.

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