Inorganica Chimica Acta, 45 (1980) L139–L141
© Elsevier Sequoia S.A., Lausanne – Printed in Switzerland

Rates of Incorporation of Nickel(II) into Linear and Macrocyclic Tetra-amines in Acetonitrile Solvent, and Comments on the Macrocyclic Effect

ROBERT W. HAY and PAUL R. NORMAN

Department of Chemistry, University of Stirling, Stirling FK9 4LA, U.K.

Received May 13, 1980

Although a number of investigations of the rates of incorporation of metal ions into tetra-aza macrocycles have appeared [1–3], these studies have dealt with aqueous solutions where both protonation and solvation of the ligand leads to problems of interpretation. The macrocyclic effect, in which the thermodynamic stability of metal complexes is enhanced by coordination to macrocyclic as opposed to analogous noncyclic ligands of the same denticity was first reported in 1969 [4]. A great deal of interest has been shown in the thermodynamic origins of this additional stability. Early conflicting studies assigned the additional stability to wholly entropic [5] or wholly enthalpic [6] factors. More recent investigations [7–11] have shown that the entropy term is always favourable and that the enthalpy term is dependent on the matching size of the macrocyclic ligand aperture to that of the metal ion. The macrocyclic effect can also be considered in kinetic terms, as the formation constant for the equilibrium (1) is given by

$$\mathrm{Ni^{2+}(solv) + MAC(solv)} \underset{k_r}{\overset{k_f}{\rightleftharpoons}} \mathrm{Ni(MAC)^{2+}(solv)} \qquad (1)$$

$K = k_f/k_r$. The macrocyclic effect can be considered to arise predominantly from the slower dissociation rate of the macrocyclic complex compared with the linear analogue. The present paper discusses the values of k_f for a variety of linear and macrocyclic ligands in acetonitrile as solvent. The use of a dipolar aprotic solvent removes the problems of ligand protonation and solvation which occurs in polar hydrogen-bonding solvents such as methanol or water.

Experimental

The various ligands employed were prepared by reported methods, 1,4,8,11-tetra-azacyclotetradecane (cyclam) [12], C-*meso*-5,12-dimethyl-1,4,8,11-tetra-azacyclotetradecane (Me_2cyclam) [13] C-*meso*-5,7,12,14-tetramethyl-1,4,8,11-tetra-azacyclotetradecane (Me_4cyclam) [14], C-*meso*-5,7,7,12,14,14-hexamethyl-1,4,8,11-tetra-azacyclotetradecane (tet *a*) [15], C-*racemic*-5,7,7,12,14,14-hexamethyl-1,4,8,11-tetra-azacyclotetradecane (tet *b*), 1,10-diamino-4,7-diazadecane (3,2,3-tet) [12] and 1,9-diamino-3,7-diazanonane (2,3,2-tet) [16]. The ligands were purified by vacuum distillation or recrystallisation as appropriate.

The nickel(II) salts employed were $Ni(NO_3)_2 \cdot 6H_2O$, $Ni(ClO_4)_2 \cdot 6H_2O$ or anhydrous $NiCl_2$ prepared from the hydrate by treatment with thionyl chloride [17]. Ionic strengths were maintained (where practical) using either $NaNO_3$ or anhydrous $NaClO_4$. Analar grade acetonitrile was dried as described in the literature [18] and stored over type 4A molecular sieves. The nickel(II) solutions were prepared by dissolving $Ni(ClO_4)_2 \cdot 6H_2O$ in the solvent, followed by succesive decantation over molecular sieves (type 4A) to remove water; a modification of the procedure used by Kratochevil and Long [19]. Anhydrous $NaClO_4$ proved to be insoluble in 'dry' CH_3CN and it was impracticable to maintain constant ionic strength. Ionic strength considerations should be of limited importance as reaction occurs between a neutral and a charged species. Methanol was dried as described in the literature [20] and nickel(II) solutions prepared in this solvent using anhydrous nickel(II) chloride.

The kinetics of incorporation of nickel(II) were studied using a Durrum-Gibson stopped-flow spectrometer (U.V. measurements) and a Canterbury SF-3A instrument (for reactions monitored at 450 nm). Kinetic data was stored on a Datalab DL901 transient recorder with output to a chart recorder. All reactions were carried out using at least a ten-fold excess of nickel(II) over the ligand, and all measurements were made at 25 °C. For acetonitrile solutions the reactions were monitored using the absorbance increase at 255 nm. Values of k_{obs} were obtained from plots which were linear for at least two half-lives.

Results and Discussion

In all cases, it proved impossible to isolate one 'clean' metal incorporation reaction. At least two reactions were always apparent and in many cases three reactions could be detected, particularly when the solutions were monitored at 450 nm. In all cases the initial rapid reaction showed a first order dependence on the nickel(II) concentration and is thus assigned to the incorporation step. The subsequent slower reactions are independent of the concentration of nickel(II), and are presumably isomerisation reactions which may involve inversion

TABLE I. Incorporation of Nickel(II) into cyclam in Acetonitrile at 25 °C.

10^3 [Ni^{2+}] (M)	k_{obs} (s^{-1})	10^{-2} k_{obs}/[Ni^{2+}] (M^{-1} s^{-1})
4.13[a]	3.36	8.1
3.09[a]	2.67	8.6
2.06[a]	1.49	7.2
7.50[b]	4.90	6.6
7.50[b]	5.40	7.2
7.50[c]	5.85	7.8

[a] In Analar CH_3CN, [cyclam] = 1×10^{-4} M ($I = 2.48 \times 10^{-2}$ M). [b] In Analar CH_3CN, [cyclam] = 2.5×10^{-4} M ($I = 2.50 \times 10^{-2}$ M). [c] In dry CH_3CN, [cyclam] = 2.5×10^{-4} M (I not maintained).

TABLE II. Rate Constants for the Incorporation of Nickel(II) into Various Ligands at 25 °C in Acetonitrile.

Ligand	10^{-2} $k_{Ni^{2+}}$ (M^{-1} s^{-1})
cyclam[a]	7.6
Me_2cyclam[b]	7.3
Me_2cyclam[c]	6.1
Me_4cyclam[b]	7.9
Me_4cyclam[c]	9.3
Tet *a*[b]	9.2
Tet *b*[b]	8.3
Tet *b*[d]	6.5
3,2,3-tet[b]	10.0
trien[b]	10.0
2,3,2-tet[b]	10.0

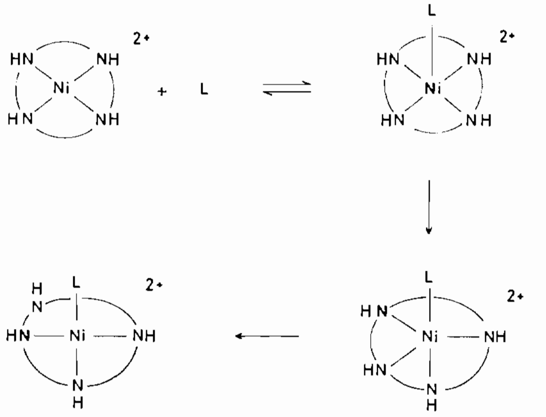
[a] Average of results quoted in Table I. [b] [Ligand] = 1×10^{-4} M, $I = 2.48 \times 10^{-2}$ M. [c] [Ligand] = 2.5×10^{-4} M, I not maintained. [d] [Ligand] = 0.5×10^{-2} M.

of the chiral nitrogen centres of the complex. Semi-quantitative experiments in CH_3CN showed that this second reaction was accelerated by the presence of a non-coordinating base such as triethylamine. For example, 1% (v/v) triethylamine increased the rate constant of the second step for the reaction of nickel(II) with cyclam from 0.20 s^{-1} to 0.31 s^{-1}. Formation of such intermediates with copper(II) is well established [21, 22] and in some cases they have been isolated and characterised [23]. Their isomerisation is catalysed by base [21, 24]. The third step which was most readily detectable in the visible region may involve interconversions of the blue (octahedral) species and the yellow (planar) species. Such equilibria are well established for complexes such as $[Ni(cyclam)]^{2+}$ and $[Ni(2,3,2\text{-tet})]^{2+}$ in coordinating solvents [25–27].

Thus for the equilibrium,

$$[Ni(cyclam)]^{2+} + 2\ CH_3CN \rightleftharpoons [Ni(cyclam)(CH_3CN)_2]^{2+}$$

K is 8.85 at 25 °C with $\Delta H = -28.9$ kJ mol^{-1} and $\Delta S^{\ddagger} = -79$ JK^{-1} mol [26]. The metal incorporation reaction was at least 20 times faster than any subsequent reaction and as a result could be considered in isolation. Typical results for the incorporation of nickel(II) into cyclam are shown in Table I. Values of $k_{Ni} = k_{obs}/[Ni^{2+}]$ are sensibly constant indicating a first-order dependence on $[Ni^{2+}]$. The rates of incorporation of nickel(II) into a variety of other macrocyclic and linear tetraamines were also studied and values of k_{Ni} are summarised in Table II. Solubility problems occurred with some of these systems and as a result it was necessary to operate the instrumentation at the limits of its capabilities. The rate constants summarised in Table II are subject to some error, but establish that the incorporation rates for both linear and macrocyclic tetra-amines are essentially identical within experimental error at *ca.* 900 M^{-1} s^{-1} at 25 °C. Any macrocyclic effect in acetonitrile must therefore be the result of marked differences in dissociation rates of the complexes of cyclic and non-cyclic ligands. Ligand dissociation from a macrocyclic complex is difficult as the ligand has no free end, so that the "unzipping mechanism" [28] observed with non-cyclic ligands cannot occur. Busch *et al.* [28] have suggested that macrocycle dissociation involves prior attack of an appropriate ligand at one of the axial sites of the planar nickel(II) complex, followed by ligand folding. The donor atom then readily moves away in the folded configuration (Scheme). There is some evidence that the incorporation of metal ions into macrocycles proceeds *via* folded intermediates so that this sug-



Scheme. Possible mechanism for macrocycle dissociation.

TABLE III. Rate Constants for the Incorporation of Nickel(II) into cyclam in Various Solvents at 25 °C.

Solvent	$k_{Ni^{2+}}$ (M^{-1} s^{-1})
CH_3CN	760
CH_3OH	54
$CH_3OH + 1\% H_2O$ (v/v)	25
$CH_3OH + 5\% H_2O$ (v/v)	1.5
$CH_3OH–H_2O$ (1/1, v/v)	0.5

gestion is supported by the principle of microscopic reversibility.

There are indications that the Eigen–Wilkins mechanism (2) for complex formation applies in non-aqueous solvents [29].

$$M(CH_3CN)_x^{n+} + L \overset{K_{os}}{\rightleftharpoons} M(CH_3CN)_x^{n+}, L \xrightarrow{k_i} M(CH_3CN)_{x-1}L^{n+} + CH_3CN \qquad (2)$$

For this scheme, rate = $K_{os}k_i[M^{n+}][L]$ if K_{os} and/or [L] are relatively low, so that $k_f = K_{os}k_i$. For solvent exchange of acetonitrile on nickel(II) $k_i \sim 2 \times 10^3$ s^{-1} [30] giving a value of K_{os} of *ca.* 0.45 M^{-1} if k_f = 900 M^{-1} s^{-1}. Such a value for the outer sphere ion pair constant seems reasonable for uncharged ligands, thus for nickel(II) and NH_3 in aqueous solution, K_{os} = 0.15 M^{-1} at 25 °C [31].

The incorporation rates are very dependent on the solvent employed, and some results obtained in different solvents for the incorporation of nickel(II) into cyclam are summarised in Table III. The reaction is considerably slower in dipolar hydrogen-bonded solvents such as methanol, and addition of water leads to a marked decrease in rate. In methanol–water solvents, the ligand will be partially protonated and also solvated (due to hydrogen bonding) thus leading to a marked rate decrease.

Acknowledgement

We wish to thank the Science Research Council for financial support.

References

1 W. Steinmann and T. A. Kaden, *Helv. Chim. Acta, 58,* 1358 (1975).
2 A. D. Zuberbuhler and T. A. Kaden, *Helv. Chim. Acta,* 57, 1897 (1974).
3 A. P. Leuger, L. Hertli and T. A. Kaden, *Helv. Chim. Acta, 61,* 2296 (1978).
4 S. K. Cabbiness and D. W. Margerum, *J. Am. Chem. Soc., 91,* 6540 (1969).
5 M. Kodama and E. Kimura, *J. Chem. Soc. Dalton Trans.,* 2341 (1976).
6 F. P. Hinz and D. W. Margerum, *Inorg. Chem., 13,* 2941 (1974).
7 A. Anichini, L. Fabbrizzi, P. Paoletti and R. M. Clay, *J. Chem. Soc. Chem. Commun.,* 244 (1977).
8 A. Anichini, L. Fabbrizzi, P. Paoletti and R. M. Clay, *Inorg. Chim. Acta, 22,* L25 (1977).
9 A. Anichini, L. Fabbrizzi and P. Paoletti, *J. Chem. Soc. Dalton Trans.*
10 L. Fabbrizzi, P. Paoletti and R. M. Clay, *Inorg. Chem., 17,* 1042 (1978).
11 R. M. Clay, M. Micheloni, P. Paoletti and W. V. Steele, *J. Am. Chem. Soc., 101,* 4119 (1979).
12 E. K. Barefield, F. Wagner, A. W. Herlinger and A. R. Dahl, *Inorg. Synth., 16,* 220.
13 R. A. Kolinski, B. Korybut-Daszkiewicz, *Bull. Acad. Pol. Sci., 17,* 13 (1969).
14 R. W. Hay and B. Jeragh, *J. Chem. Soc. Dalton Trans.*
15 R. W. Hay, G. A. Lawrance and N. F. Curtis, *J. Chem. Soc., Perkin I Trans.,* 591 (1975).
16 F. Hinz and D. W. Margerum, *Inorg. Chem., 13,* 2941 (1974).
17 *Inorg. Synth., 5,* 153.
18 A. Gordon and R. Ford, 'The Chemists Companion', John Wiley, London (1972) p. 431.
19 B. Kratochevil and R. Long, *Canad. J. Chem., 48,* 1414 (1970).
20 A. Vogel, 'Practical Organic Chemistry', Longmans, London (1951).
21 T. A. Kaden, Helv. Chim. Acta, 54, 2307 (1971).
22 R. W. Hay and C. R. Clark, *J. Chem. Soc. Dalton Trans.,* 1148 (1977).
23 R. Clay, J. Murray-Rust and P. Murray-Rust, *J. Chem. Soc. Dalton Trans.,* 1135 (1979).
24 B-F. Liang, D. W. Margerum and C-S. Chung, *Inorg. Chem.,* 2001 (1979).
25 N. Herron and P. Moore, *Inorg. Chim. Acta, 36,* 89 (1979).
26 G. S. Vigel, C. L. Watkins and H. F. Brown, *Inorg. Chim. Acta, 35,* 255 (1979).
27 A. Anichini, L. Fabbrizzi and P. Paoletti, *Inorg. Chim. Acta, 24,* L21 (1977).
28 D. H. Busch, K. Farmery, V. Goedken, V. Katovic, A. C. Melnyk, C. R. Spearti and N. Tokel, 'Bioinorganic Chemistry', Adv. Chem. *Ser., 100,* ACS Washington D.C. (1971) p. 44.
29 J. Burgess, 'Metal Ions in Solution', Ellis Horwood, Chichester (1978), p. 388.
30 See ref. 29, page 314.
31 See ref. 29, page 352.