Mixed-ligand Complexes of Palladium(II). Part 3.† Diaqua(ethylenediamine)palladium(II) Complexes of L-Amino-acids

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The reactions of $[Pd(en)(OH_2)_2]^{2+}$ (en = ethylenediamine) with the amino-acids glycine, L-alanine, sarcosine, *NN*-dimethylglycine, L-leucine, L-phenylalanine, L-proline, L-tryptophan, L-methionine, and *S*-methyl-L-cysteine have been studied by potentiometric titrations. For L-methionine and *S*-methyl-L-cysteine, equilibria (i) and (ii)

$$[Pd(en)(OH_2)_2]^{2+} + L^- \overset{K_1}{\rightleftharpoons} [Pd(en)L]^+ + 2H_2O \quad \text{(i)}$$

$$[Pd(en)(OH_2)_2]^{2+} + HL \overset{K_1^H}{\rightleftharpoons} [Pd(en)(HL)]^{2+} + 2H_2O \quad \text{(ii)}$$

hold in solution, where $L^- = MeS[CH_2]_nCH(NH_2)CO_2^-$ (n = 1 or 2). For the remaining amino-acids only equilibrium (i) is significant.

THERE are very few stability-constant data for palladium(II) complexes. As pointed out by Anderegg and Malik,[1] one of the major difficulties in studying the equilibrium chemistry of palladium is the ease with which the Pd^{2+} ion undergoes hydrolysis even in strongly acidic media.

In a recent article we have shown that the species $[Pd(en)(OH_2)_2]^{2+}$ (en = ethylenediamine) exists in rapid equilibrium with its dimer in solution according to (1).

$$2[Pd(en)(OH_2)_2]^{2+} \overset{K_d}{\rightleftharpoons} [Pd_2(en)_2(OH)_2]^{2+} + 2H^+ \quad (1)$$

At pH $\leqslant$4, the species in solution is practically entirely in the form of $[Pd(en)(OH_2)_2]^{2+}$ which is quite stable against hydrolysis.[2] Moreover, the two co-ordinated water molecules in $[Pd(en)(OH_2)_2]^{2+}$ can be easily replaced by suitable ligands. It can therefore serve as a convenient starting material for studying mixed-ligand complexes of Pd^{II}. Its reactions with glycylglycine, glycinamide, asparagine, and glutamine have already been described and the stability constants of the various species determined.[3,4]

Extending the study to other ligands of biological interest, we now report a potentiometric titration study of the reactions of $[Pd(en)(OH_2)_2]^{2+}$ with a series of L-amino-acids in solution.

EXPERIMENTAL

Materials.—The preparation of crystalline $[PdCl_2(en)]$ and $[Pd(en)(OH_2)_2][NO_3]_2$ in solution therefrom has been reported previously.[2,5] The amino-acids glycine (Gly),

† Part 2 is ref. 4.

[1] G. Anderegg and S. C. Malik, *Helv. Chim. Acta*, 1976, **59**, 1498.

[2] M. C. Lim and R. B. Martin, *J. Inorg. Nuclear Chem.*, 1976, **38**, 1911.

[3] M. C. Lim, *J.C.S. Dalton*, 1977, 15.

[4] M. C. Lim, *J.C.S. Dalton*, 1977, 1398.

[5] H. D. K. Drew, F. W. Pinkard, G. H. Preston, and A. W. Wardlaw, *J. Chem. Soc.*, 1932, 1895.

L-alanine (Ala), and L-phenylalanine (Phe) were obtained from B.D.H.; *NN*-dimethylglycine hydrochloride (Me_2-Gly·HCl), L-methionine (Met), *S*-methyl-L-cysteine (Me-Cys), L-proline (Pro), L-leucine (Leu), and L-tryptophan (Trp) were from Sigma, and sarcosine (Sar) from Tokyo Kasei. All were used without further purification. *NN*-Dimethylglycine hydrochloride was converted into the nitrate by stirring it with 1 equivalent of $Ag[NO_3]$ in water, filtering, and adjusting the filtrate to the desired volume in a standard flask. All the other chemicals used were of AnalaR grade.

Potentiometric Titrations.—(*a*) $[Pd(en)(OH_2)_2][NO_3]_2$ + *ligands*. The potentiometric titrations were carried out on solutions containing 1 : 1 mol ratios of $[Pd(en)(OH_2)_2][NO_3]_2$ and the respective ligands at a constant ionic strength of 0.5 mol dm^{-3} $K[NO_3]$ at 25 °C. The apparatus and procedure have been described previously.[3]

(*b*) *Free ligands.* The pK_A and pK_B of the free ligands, *i.e.* the dissociation constants of the carboxyl and amino-groups respectively, were determined under the same conditions of ionic strength and temperature by titrating weighed samples of the ligands with standard HNO_3 and Na[OH] respectively.

Dissociation constants of L-amino-acids and stability constants of their complexes with $[Pd(en)(OH_2)_2]^{2+}$ at I = 0.5 mol dm^{-3} $K[NO_3]$ and 25 °C

Ligand	pK_A	pK_B	log K_1	log K_1^H
Glycine	2.49 ± 0.01	9.72 ± 0.01	11.21 ± 0.01	
L-Alanine	2.48 ± 0.01	9.77 ± 0.01	11.22 ± 0.01	
Sarcosine	2.29 ± 0.01	10.16 ± 0.01	11.28 ± 0.01	
NN-Dimethylglycine	2.14 ± 0.01	9.88 ± 0.01	11.02 ± 0.01	
L-Leucine	2.42 ± 0.01	9.75 ± 0.01	11.41 ± 0.01	
L-Phenylalanine	2.32 ± 0.01	9.05 ± 0.01	10.86 ± 0.01	
L-Proline	2.13 ± 0.02	10.63 ± 0.02	12.16 ± 0.03	
L-Tryptophan	2.38 ± 0.02	9.47 ± 0.02	10.83 ± 0.03	
S-Methyl-L-cysteine	2.14 ± 0.01	8.89 ± 0.01	9.38 ± 0.01	1.18 ± 0.01
L-Methionine	2.25 ± 0.02	9.22 ± 0.02	9.14 ± 0.03	0.74 ± 0.02
L-Asparagine *	2.26 ± 0.01	8.79 ± 0.01	10.46 ± 0.01	
L-Glutamine *	2.29 ± 0.01	9.09 ± 0.01	10.76 ± 0.02	

* From ref. 4.

RESULTS AND DISCUSSION

The ionisation of the free amino-acids may be represented as in (2), where L^- = anionic form of the amino-acid. The reactions of $[Pd(en)(OH_2)_2]^{2+}$ with the various amino-acids, except methionine and *S*-methylcysteine, can be described by (3). For Met and Me-Cys the additional equilibrium (4) is involved, where HL = $MeS[CH_2]_nCH(NH_2)CO_2H$ (n = 1 or 2).

$$H_2L \overset{K_A}{\rightleftharpoons} H^+ + HL \overset{K_B}{\rightleftharpoons} H^+ + L^- \qquad (2)$$

$$[Pd(en)(OH_2)_2]^{2+} + L^- \overset{K_1}{\rightleftharpoons} [Pd(en)L]^+ + 2H_2O \qquad (3)$$

$$[Pd(en)(OH_2)_2]^{2+} + HL \overset{K_1^H}{\rightleftharpoons} [Pd(en)(HL)]^{2+} + 2H_2O \qquad (4)$$

The values of pK_A, pK_B, log K_1, and log K_1^H were evaluated by considering the mass-balance and electroneutrality conditions in the solutions. All the numerical calculations were made with the aid of an IBM 1130 computer. The values are summarised in the Table.

The values of log K_1 for $[Pd(en)L]^+$ are all very large indeed; in fact they are larger than those reported for the same ligands with other metal ions, whether in simple or mixed-ligand complexes. For instance, log K_1 for $[Pd(en)(GlyO)]^+$ is 11.21, whereas the corresponding value for $[Cu(en)(GlyO)]^+$ is only 7.47 (GlyO = glycinate).[6]

It was pointed out earlier that stability-constant data for palladium(II) complexes are scarce, but the palladium(II)–glycine system is an exception. Maley and Mellor [7] reported values of log K_1 9.12 and log K_2 8.43 for $[Pd(GlyO)]^+$ and $[Pd(GlyO)_2]$ based on pH titration of $[PdCl_x]^{(2-x)+}$ with glycine at I = 0.01 mol dm^{-3} and 25 °C. More recently, Anderegg and Malik reported log K_1 15.25 and log K_2 12.25 for the same complexes at I = 1 mol dm^{-3} $Na[ClO_4]$ and 20 °C, using both ligand-exchange and spectrophotometric methods. The former set of values are much smaller than the log K_1 for $[Pd(en)(GlyO)]^+$ reported here. This is unexpected because, for the analogous system involving Cu^{II}, log K_1 and log K_2 for $[Cu(GlyO)]^+$ and $[Cu(GlyO)_2]$ are 8.37 and 6.87 respectively whereas for $[Cu(en)(GlyO)]^+$ log K_1 is 7.47.[6,8] The binary complex is more stable than the ternary complex. This trend can be expected to hold for the palladium complexes. Anderegg pointed out that the values reported by Maley and Mellor were not meaningful because certain species such as $[PdCl_x]^{(2-x)+}$ present were not taken into account in their evaluations.

The value of log K_1 for $[Pd(en)(GlyO)]^+$ reported here compares favourably with those for $[Pd(GlyO)]^+$ and $[Pd(GlyO)_2]$ obtained by Anderegg and Malik. It is smaller than log K_1 for $[Pd(GlyO)]^+$ and is comparable in magnitude to log K_2 for $[Pd(GlyO)]_2$, if one takes into account the different experimental conditions and techniques used. The effect of a ligand attached to the metal ion on the incoming ligand is of current interest and, except for Cu^{II}, few systems have been studied. However, from available data for the analogous copper(II)

[6] H. Sigel, R. Caraco, and B. Prijs, *Inorg. Chem.*, 1974, **13**, 462.

[7] L. E. Maley and D. P. Mellor, *J. Austral. Sci. Res.*, 1949, **A2**, 579.

[8] ' Stability Constants of Metal–Ion Complexes,' *Special Publ.*, The Chemical Society, London, 1964, no. 17.

system, the similarity of log K_1 for $[Pd(en)(GlyO)]^+$ and log K_2 for $[Pd(GlyO)_2]$ is not at all unreasonable.

The similarity in log K_1 for $[Pd(en)(GlyO)]^+$, $[Pd(en)(SarO)]^+$, $[Pd(en)(Me_2\text{–}GlyO)]^+$, $[Pd(en)(AlaO)]^+$, and $[Pd(en)(LeuO)]^+$ shows that alkyl substituents on the amino-nitrogen as well as on the α-carbon atom have very little effect on the stability of the complexes. Aromatic substituents on the α-carbon atom on the other hand tend to decrease the stability of the complexes. This may well be due to the smaller pK_B values of such amino-acids. In general, the trend in log K_1 for $[Pd(en)L]^+$ is similar to that of pK_B of the ligands. This suggests a common mode of co-ordination in these complexes, which is most likely through the amino- and the carboxyl groups of the ligands, forming a stable five-membered chelate ring.

The log K_1 values for methionine and *S*-methylcysteine are abnormally small. It has been shown, both in the solid state as well as in solution, that in $[PdCl_2(MetO)]$ and $[PdCl_2(Me\text{–}CysO)]$ these ligands are co-ordinated to the palladium *via* the amino- and the methylthio-groups. The carboxyl groups are not involved, but remained protonated.[9,10] The log K_1 values of $[Pd(en)(MetO)]^+$ and $[Pd(en)(Me\text{–}CysO)]^+$ are consistent with this bonding scheme. With the carboxyl group unco-ordinated, there is a loss in electrostatic interaction between the metal ion and the ligands. This can account for the smaller log K_1 of these two complexes relative to complexes of the other amino-acids where charge neutralisations are more effective. The fact that Met forms a less-stable complex than Me-Cys suggests that the six-membered chelate ring in the former complex is energetically less favoured than the five-membered ring in the latter complex.

It is interesting to note that, even though the species crystallising from solutions containing $[PdCl_4]^{2-}$ and Met is $[PdCl_2(HL)]$, from the relative magnitudes of log K_1 and log K_1^H it can be seen that in the present case the predominant species present in solution is $[Pd(en)L]^+$, and $[Pd(en)(HL)]^{2+}$ is only a minor species.

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[9] R. C. Warren, J. F. McConnell, and N. C. Stephenson, *Acta Cryst.*, 1970, **B26**, 1402.

[10] S. E. Livingstone and J. D. Nolan, *Inorg. Chem.*, 1968, **7**, 1447.