Complexes of Doubly Chelating Ligands. Part II. Further Computations on the Polymer System involving Copper(II) Ions and L-β-(3,4-Dihydroxyphenyl)alanine (DOPA)

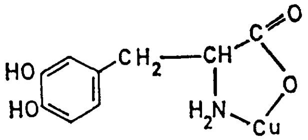
By **J. E. Gorton** and **R. F. Jameson,*** The Chemistry Department, The University, Dundee

A more detailed study of the data on copper(II) complexes of L-β-(3,4-dihydroxyphenyl)alanine DOPA (see Part I) has been carried out by use of computer programs of data-generating type. These have been used to match experimental results with theoretical models by curve-fitting techniques and have led to the conclusion that the open-chain polymers form a set including some of considerable length, whereas the only ring-polymer is the cyclic dimer.

IN the treatment of titration data on complex-forming reactions of doubly chelating ligands it is often quite difficult or even impossible to distinguish between the several general types of reaction which may occur, *e.g.* ligand exchange, various polymerisation schemes, hydroxo-complex formation, *etc.*[1-4] Even if much of this information were available, lack of time would prevent the synthesis of data from mathematical models of all the possible systems (in order to choose the one with the lowest standard deviation compared with the experimental data): not only is the range of possibilities too vast, but if the number of postulated species becomes very large, the fit with the data can be completely coincidental.

As explained by several workers,[2-4] one of the most reasonable ways round the mathematical part of this dilemma is to base the model on the simplest collection of complexes which will give synthesized data commensurate with experimental data. When dealing with polymer formation the best way of achieving this 'simplest set' seems to be to add units successively to the simplest complex, at each stage checking all equilibrium constants and their associated standard deviations, and then to neglect those complexes with standard deviations in their constants which are large compared with experimental error. However, in the present study many such complexes were found materially to improve the fit and so sets of these were treated as polymer series in the mathematical model described below.

The 'Simplest Set'.—In dealing with the copper(II) complexes of DOPA, for which this approach was devised, the simplest complex, and the one first formed in titrating an acid mixture with base, is the 1 : 1 amino-acid type complex ($H_2CuL_1^a$) (see ref. 1):



This complex was considered as the starting point, and three possible reaction schemes were considered: ligand exchange, polymerization, and hydroxo-complex formation. Since the 1 : 1 molar ratio titrations show a final loss of four protons per ligand molecule, polymerization

---

[1] J. E. Gorton and R. F. Jameson, *J. Chem. Soc.* (*A*), 1968, 2615.

[2] F. J. C. Rossotti and H. Rossotti, 'The Determination of Stability Constants,' McGraw-Hill, London, 1961, ch. 5.

[3] C. F. Baes and N. J. Meyer, *Inorg. Chem.*, 1962, **1**, 780.

[4] N. Ingri and L. G. Sillén, *Arkiv Kemi*, 1964, **23**, 97; N. Ingri, W. Kakołowicz, L. G. Sillén, and B. Warnqvist, *Talanta*, 1967, **14**, 1261.

must occur if hydroxo-complexes are excluded, and the latter seemed a reasonable assumption since all the reactions occurred at pH values below 7; it is improbable, but not of course impossible, that copper(II) chelates hydrolyse at lower pH values than the free Cu_{Aq}^{2+} ion. The polymerization may occur with or without simultaneous ligand exchange reactions, but as will be shown below, a ' simplest set ' excluding both ligand exchange and six-co-ordinate species describes the system well within experimental error; indeed all attempts to include such species in describing the copper(II)–DOPA system resulted in gross lack of agreement with experimental data.

Three types of polymer were initially considered based on the 1 : 1 complex as a unit. These were open and closed chain types (in which the copper ions are in a square-planar environment) and those with three ligands attached to the copper ion. It was noted that formation of this six-co-ordinate type of polymer would involve a change of co-ordination stereochemistry.[5]

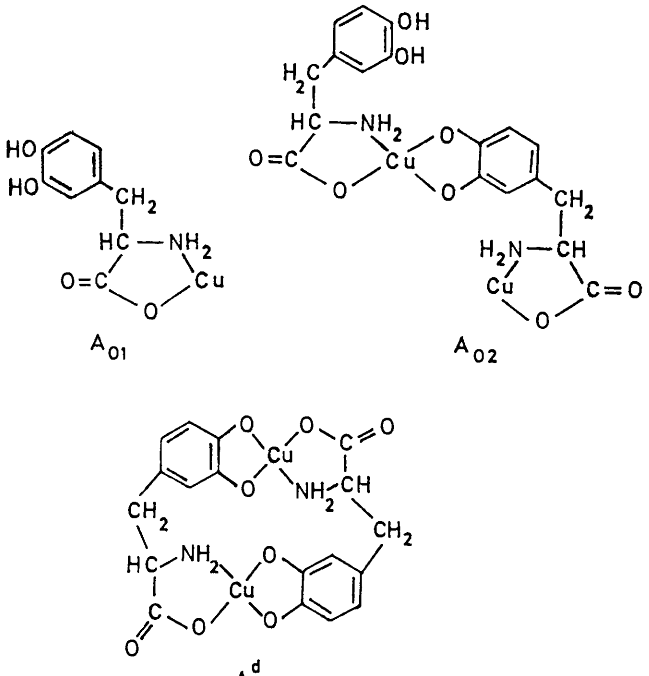


FIGURE 1 Examples of open- and closed-chain DOPA–Cu(II) polymers illustrating nomenclature

In preliminary calculations (using a prototype of the computer GEPOLYC) the program could allow for the presence of the 1 : 1 complex, any specified number of open-chain polymers, and three other species of any chosen stoicheiometry. It was soon realized that successive inclusion of higher open-chain polymers, containing more than ten 1 : 1 units, improved the fit of theoretically generated data with experimental results. This was, therefore, taken to its logical conclusion (in the program GEPOLYC) by treating the possible infinite set of all straight open-chain polymers as a subset of the simplest set with *one* associated chain-forming constant. This assumption is quite reasonable when it is realized that the actual concentrations of such higher polymers are very small indeed and that co-ordination at one chelate site in DOPA is unlikely to affect co-ordination at the other after the formation of the first open-chain polymer, the dimer. Extension of the chain then merely becomes addition of the deprotonated 1 : 1 complex to the chain.

Method.—Let A_{on} represent an open straight-chain polymer of n units of the 1 : 1 complex, A^{d}_{on} represent A_{on} with the two terminal catechol protons removed without complex formation, and A^{d}_{cn} represent the closed chain polymer of order n, this latter polymer is, of course, always deprotonated (see Figure 1 for typical examples of these polymers). For the stoicheiometric equations the concentrations $[A^{d}_{cn}]$ are taken as zero as appreciable ionization of the catechol group protons does not occur in the pH region studied. If the functions $\bar{n}'$, pL', and $[L]_T$ (see Part I) are defined by

$$\bar{n}' = \frac{[H]_T - 2[Cu]_T}{2[Cu]_T}; \quad pL' = -\log_{10}[L'];$$

$$[L'] = \frac{[CuL_1{}^{a}]}{\beta_2{}^{H}[H]^2}; \qquad [L]_T = \text{total ligand concentration}$$

$$i.e. \quad [L]_T = \sum_{n=1}^{\infty} n[A_{on}] + \sum_{n=2}^{\infty} n[A^{d}_{cn}]$$

$$\text{Also } \bar{n}'[L]_T = [A_{o2}] + 2[A_{o3}] + 3[A_{o4}] +, \textit{etc.}$$
$$+ 2[A^{d}_{c2}] + 3[A^{d}_{c3}] + 4[A^{d}_{c4}] +, \textit{etc.}$$
$$= \sum_{n=1}^{\infty} (n-1)[A_{on}] + \sum_{n=2}^{\infty} n[A^{d}_{cn}]$$

Let the formation of a closed chain polymer be represented by an equilibrium constant K, such that

$$K = \frac{[A^{d}_{cn}][H]^2}{[A_{on}]}$$

and, since $[A^{d}_{o1}]$ is stoicheiometrically negligible,

$$\beta_2 = \frac{[A_{o1}]}{[A^{d}_{o1}][H]^2}, \text{ so, substituting for } [H]^2$$

$$\beta_2 K = \frac{[A^{d}_{cn}][A_{o1}]}{[A_{on}][A^{d}_{o1}]}, \text{ or, if } K_u = \beta_2 K \text{ is introduced,}$$

$$[A^{d}_{cn}] = \frac{K_u[A_{on}][A^{d}_{o1}]}{[A_{o1}]}$$

If it is now further assumed that the equilibrium constant for the open-chain species,

$$K_c = \frac{[A_{on}]}{[A_{o(n-1)}][A^{d}_{o1}]}, \text{ is independent of } n$$

$$\text{then } [A_{on}] = (K_c[A^{d}_{o1}])^{(n-1)}[A_{o1}]$$

$$\text{and } [A^{d}_{cn}] = (K_c[A^{d}_{o1}])^{(n-1)}K_u[A^{d}_{o1}]$$

---

[5] P. L. Peczok and J. Bjerrum, *Acta Chem. Scand.*, 1957, **11**, 1419.

Let $Z = (K_c[A^d_{o1}])$

$$\therefore \quad [L]_T = \sum_{n=1}^{\infty} nZ^{(n-1)}[A_{o1}] + \sum_{n=2}^{\infty} nZ^{(n-1)}K_u[A^d_{o1}]$$

$$\therefore \quad [A_{o1}] = \frac{[L]_T - \sum_{n=2}^{\infty} nZ^{(n-1)}K_u[A^d_{o1}]}{\sum_{n=1}^{\infty} nZ^{(n-1)}}$$

and because

$$\bar{n}'[L]_T = \sum_{n=1}^{\infty} (n-1)Z^{(n-1)}[A_{o1}] + \sum_{n=2}^{\infty} nZ^{(n-1)}K_u[A^d_{o1}]$$

$$\bar{n}'[L]_T = \frac{\sum_{n=1}^{\infty} (n-1)Z^{(n-1)}\{[L]_T - \sum_{n=2}^{\infty} nZ^{(n-1)}K_u[A^d_{o1}]\}}{\sum_{n=1}^{\infty} nZ^{(n-1)}} + \sum_{n=2}^{\infty} nZ^{(n-1)}K_u[A^d_{o1}]$$

and $$[L'] = \frac{[L]_T(1-\bar{n}')}{\beta_2[H]^2} = \frac{[L_T](1-\bar{n}')[A^d_{o1}]}{[A_{o1}]}$$

but $[L]_T(1-\bar{n}') = [A_{o1}] + [A_{o2}] + [A_{o3}]$, *etc.*

$$= \sum_{n=1}^{\infty} Z^{(n-1)}[A_{o1}]$$

$$\therefore \quad [L'] = \sum_{n=1}^{\infty} Z^{(n-1)}[A^d_{o1}]$$

Hence pL′ and $\bar{n}'$ can be calculated from assumed values of K_c and K_u using $[A^d_{o1}]$ as parameter. The program GEPOLYC performs this calculation and will allow for two closed-chain polymers, one six-co-ordinate species, and an infinite number of open-chain polymers (since the sum of their concentrations may be written in an explicit form). The program outputs $\bar{n}'$ and pL′ values, and a visual curve-fitting method was then used, since it is found that erroneous conclusions are thereby less likely in the early stages of building up the model system to correspond with experimental data. In the later stages of refinement of constants, it was found that the accuracy of the data was such that a least-squares calculation was not necessary, especially as the relative spread of results at each concentration would have to be determined without knowing the theoretical shape of the titration curve.

The best fit for the DOPA–copper system was $\log K_c = 14{\cdot}605 \pm 0{\cdot}025$, $\log K_2 = 12{\cdot}435 \pm 0{\cdot}025$ (see Figure 2). The dimerization constant, as defined in the previous calculations on this system, is equal to K_cK_2, hence $\log K^F_2 = 27{\cdot}04 \pm 0{\cdot}01$ (the system is more sensitive to this constant than to K_c or K_2). The result is in good agreement with the first calculations.[1] A change in $\log K_c$ or $\log K_2$ of 0·005 could be easily seen, and the best values of the constants gave good fits of theoretical and experimental points for $0{\cdot}2 < \bar{n}' < 0{\cdot}95$ in the cases of the four highest concentrations and $0{\cdot}25 < \bar{n}' < 0{\cdot}75$ for the lowest concentration titrations. Below $\bar{n}' \approx 0{\cdot}2$ the 1 : 1 complex is not completely formed.

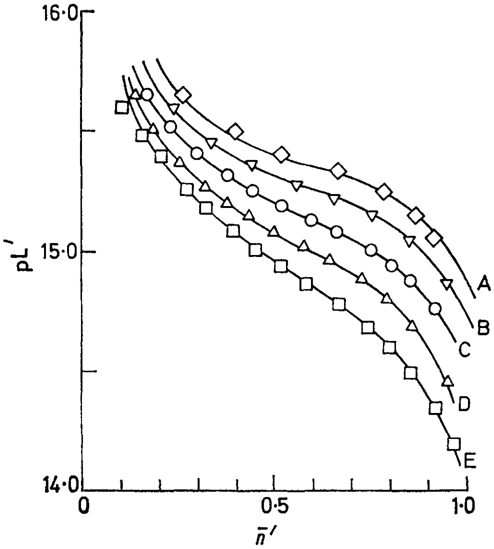


FIGURE 2 Theoretical curves based on calculated formation constants for polymer formation compared with experimental points. [DOPA] or [Cu]: A, 8·810 × 10⁻⁴M, B, 1·321 × 10⁻³M, C, 2·643 × 10⁻³M, D, 5·286 × 10⁻³M, E, 1·056 × 10⁻²M

CONCLUSIONS

The polymer-system resulting from titrations of 1 : 1 molar ratio mixtures of DOPA and copper(II) can be accurately described by the presence of an infinite set of open-chain polymers with only the simplest of the possible closed-chain polymers, the dimer. The magnitude of $\log K_c$ seems high when compared with $\log K^{Mc}_1$ (12·99), but similar effects have been observed[6] with other mixed ligand complexes. The cause of this effect has been partly attributed to charge and entropy factors, but does not appear to be well understood. The great advantage of defining pL′ and $\bar{n}'$ as the 'master variables' is the ease of the resulting calculation and production of the normalized curves, and it overrides the one obvious disadvantage that L′ does not represent a concentration of any particular species just as $\bar{n}'$ does not represent the formation of a single complex.

The calculations were performed on the Elliott 4130 computer at the University.

We thank the S.R.C. for a research grant (to J. E. G.).

[1/1147 *Received, July 5th,* 1971]

---

[6] G. A. L'Heureux and A. E. Martell, *J. Inorg. Nuclear Chem.*, 1966, **28**, 481; T. A. Bohigian and A. E. Martell, *ibid.*, 1967, **29**, 453.