

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF CALIFORNIA, RIVERSIDE, CALIF.]

Properties and Infrared Spectra of Ethylenediaminetetraacetic Acid Complexes. IV. Structure of the Ligand in Solution

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The infrared spectra for ethylenediaminetetraacetic acid and its salts in aqueous solutions have been recorded as a function of solution acidity. On the basis of these data the positions of the acidic protons on the ligand molecule in solution have been established. Two of the protons are on the nitrogen atoms while the other two are on two of the four carboxylate groups. As the solution is neutralized the carboxylate protons are removed first. Structures which are consistent with the infrared data are proposed for the five forms of the ligand and its salts.

The previous papers in this series have been concerned with the metal complexes formed by ethylenediaminetetraacetic acid (EDTA) and their infrared spectra in the solid phase.¹ Recently an investigation of their spectra in aqueous solution has been initiated from which some understanding of the effect of solution and solution acidity upon the chelate structure may be gained. However, before meaningful conclusions can be made concerning the structure of metal-EDTA complexes in solution, the structure of the EDTA molecule and its several protonated salts in aqueous solution must be understood.

The major question is whether two of the four acidic protons of the EDTA molecule are attached to the nitrogen atoms of the ligand or to the carboxylate groups. Schwarzenbach and Ackermann² have argued that the two protons are attached to the nitrogen atoms, using the abnormally low values of the third and fourth dissociation constants for EDTA as the basis for their conclusion. Carini and Martell³ also have concluded that acidification of the EDTA anion brings about protonation of the two nitrogen atoms first. Chapman,⁴ on the other hand, presents arguments based on the infrared spectra of EDTA and its salts in Nujol mulls that the nitrogen atoms are not protonated. Instead the argument is made that for the diprotonated form of EDTA, hydrogen bridges are formed between two carboxylate groups by each proton. However, the conclusions made by Chapman are for the solid phase and may not be valid for the EDTA salts in aqueous solution. Tillotson and Staveley⁵ also have considered the possible structures for EDTA and its protonated forms; they suggest that the most probable structures may be a combination of the structures proposed by Schwarzenbach and Ackermann² and by Chapman.⁴ Thus although Chapman gives arguments against a double "zwitterion" for diprotonated EDTA, this does not preclude a single "zwitterion." Their structures are based on this conclusion. Another structure for the diprotonated salt of EDTA has been proposed by Charles⁶ using viscosity measurements; he suggests that each proton forms a hydrogen bridge between a carboxylate group and a nitrogen atom. More recently Olson and Margerum⁷ have discussed the structures for EDTA and have concluded that the "zwitterion" structures of Schwarzenbach and Ackermann are the correct forms. They also have concluded that the structures proposed by Chapman for the solid phase are incorrect for the EDTA salts in solution.

Because of this continuing uncertainty of the actual positions of the acidic protons on the EDTA anion, an

investigation of the carboxylate-carboxylic acid infrared absorption bands in aqueous solutions has been undertaken. The present discussion is concerned with the results of such a study and the structures that have been established for the protonated forms of EDTA in solution.

Experimental

Equipment.—The infrared spectra were recorded with a Perkin-Elmer Model 421 recording spectrophotometer equipped with a grating. Some preliminary measurements were made with a Perkin-Elmer Model 221G recording instrument. Barium fluoride cells, with 0.025-mm. spacers, were used to contain the aqueous solutions of the EDTA salts. For some preliminary work a pair of 0.025-mm. cells prepared from Irtran-2 (Connecticut Instrument Corp., Wilton, Conn.) were used; however, the high index of refraction caused serious interference patterns. The pH of the solutions was adjusted with a Leeds and Northrup line-operated pH meter equipped with micro-electrodes. Such electrodes permitted the total solution volume to be as small as 0.5 ml. The meter was standardized with N.B.S. buffers.

Reagents.—Because of the interfering absorption bands of the H₂O molecule, all solutions were prepared from deuterium oxide (D₂O) (Bio-Rad Laboratories, Richmond, Calif.); the material used contained 99.9% D₂O. The disodium salt of EDTA (as the dihydrate from the J. T. Baker Co.) was used without further purification and had an assay of 99.9%. The acids and bases used in preparing the solutions were reagent grade in all cases.

The various solutions studied were prepared by adding concentrated NaOH or HCl to aliquot portions of a stock solution of the disodium salt of EDTA (Na₂H₂Y) until the desired pH was obtained. Because the major acidic species present in these solutions was the deuterium ion, the indicated pH values for the pH meter had to be corrected by using the equation given by Mikkelsen and Nielsen⁸

$$pD = \text{"meter reading"} + 0.40$$

By using D₂O as the solvent, interference by solvent absorption was minimized for the region from 2000 to 1550 cm.⁻¹; this permitted investigation of the carboxylic acid and carboxylate bands for the EDTA molecule. The limited resolution of infrared spectroscopy normally causes peak heights not to be proportional to the concentration of a species. However, peak areas obtained by using the baseline technique were found to be more closely related to concentration. Recording infrared instruments record linearly in transmittance, but the area in absorbance units would be expected to be related to concentration. This problem was solved partially by determining the transmittance for the base and for the peak of an absorption band and converting these readings to absorbance. The width at the half-height, in terms of absorbance, was multiplied by the peak height to determine the approximate peak area in absorbance units.

Results

The infrared spectra for the EDTA molecule at various conditions of acidity are shown in Fig. 1. The absorption bands shown are due to the carboxylate-carboxylic acid groups of the ligand, and the important consideration is how these change with acidity. Curve A in Fig. 1 indicates a slight hump in the region of 1700 cm.⁻¹; more acidic solutions often give a larger peak at this frequency. However, the low solubility of the un-ionized form of EDTA precludes quantitative measurements in highly acidic solutions. In the solid phase H₄Y gives a well developed single peak at about 1700 cm.⁻¹.^{1,4} The large absorption peak at 1585 cm.⁻¹ for curve D in Fig. 1 is observed for all basic solutions

(1) (a) D. T. Sawyer and P. J. Paulsen, *J. Am. Chem. Soc.*, **80**, 1957 (1958); (b) **81**, 816 (1959); (c) D. T. Sawyer and J. M. McKinnie, *ibid.*, **82**, 4191 (1960).

(2) G. Schwarzenbach and H. Ackermann, *Helv. Chim. Acta*, **30**, 1798 (1947).

(3) F. F. Carini and A. E. Martell, *J. Am. Chem. Soc.*, **75**, 4810 (1953).

(4) D. Chapman, *J. Chem. Soc.*, 1766 (1955).

(5) M. J. L. Tillotson and L. A. K. Staveley, *ibid.*, 3613 (1958).

(6) R. G. Charles, *J. Am. Chem. Soc.*, **78**, 3946 (1956).

(7) D. C. Olson and D. W. Margerum, *ibid.*, **82**, 5602 (1960).

(8) K. Mikkelsen and S. O. Nielsen, *J. Phys. Chem.*, **64**, 632 (1960).

of EDTA and is the sole carboxylate peak for strongly alkaline solutions. Solid phases of Na_4Y also give this single peak as well as unprotonated forms of ionic metal-EDTA chelates.^{1,4} The intermediate peak at 1620 cm.^{-1} (curves B and C in Fig. 1) is observed only for approximately neutral solutions, where the conditions are such that the EDTA molecule has less than four but at least one proton attached to it.

Under basic conditions where only the 1585 cm.^{-1} peak is observed, the area for the peak is 5.70 absorbance units for a $0.05\text{ }F$ solution of EDTA. This corresponds to 28.5 units per molar COO^- group, remembering that there are four COO^- groups per EDTA molecule. Approximately this same value is obtained for other concentrations of EDTA, and also for the 1620 cm.^{-1} peak at appropriate conditions of acidity.

Table I summarizes the conditions where the area of the 1620 cm.^{-1} peak equals the area of the 1585 cm.^{-1} peak, where it reaches its maximum area, and also where the area of the 1620 cm.^{-1} peak equals three-fourths its maximum area as the solution is acidified. These numbers were obtained by measuring the peak areas at several pD 's and plotting the logarithm of the area of the ratio of the area versus pD . Such plots give a straight line from which the values given in Table I can be obtained. For comparison, the mean value for the negative logarithms of adjacent pairs of the dissociation constants for EDTA are given. These have been estimated using the equations proposed by Li, Tang and Mathur⁹ for carboxylic and amino acids in D_2O ; the calculated pK 's are: pK_1 , 2.3; pK_2 , 3.1; pK_3 , 7.0; pK_4 , 11.7. For the conditions where pD equals these mean values, DY^{\equiv} is the major species at pD equal to about 9.3, $\text{D}_2\text{Y}^{\equiv}$ at pD equal to 5.1, and $\text{D}_3\text{Y}^{\equiv}$ at pD equal to 2.7. Thus curve A in Fig. 1 corresponds approximately to $\text{D}_3\text{Y}^{\equiv}$, curve B corresponds approximately to $\text{D}_2\text{Y}^{\equiv}$, and curve C corresponds approximately to DY^{\equiv} . Curve D of this figure is characteristic of alkaline solutions of EDTA and would be representative of the species Y^{\equiv} .

TABLE I

pD FOR THREE CONDITIONS OF PEAK AREAS, $0.05\text{ }F$ EDTA			
	pD		Major species
1. Area of 1620 cm.^{-1} peak equals that of 1585 cm.^{-1} peak	$\frac{1}{2}(pK_3 + pK_4)$		
	8.4	9.3	DY^{\equiv}
2. Area of 1620 cm.^{-1} peak equals its maximum value	$\frac{1}{2}(pK_2 = pK_3)$		
	5.7	5.1	$\text{D}_2\text{Y}^{\equiv}$
3. Area of 1620 cm.^{-1} peak equals $\frac{3}{4}$ its maximum	$\frac{1}{2}(pK_1 + pK_2)$		
	3.3	2.7	$\text{D}_3\text{Y}^{\equiv}$

Several model compounds have been studied in an effort to make a definite assignment for the 1620 cm.^{-1} band. A substituted glycine, dihydroxyethylglycine, gives a single absorption peak in D_2O at 1620 cm.^{-1} for a pD where it occurs as a "zwitterion." This peak is essentially identical to the one shown by the diprotonated form of EDTA ($\text{H}_2\text{Y}^{\equiv}$); curve B, Fig. 1. The monosodium salts of malonic acid, succinic acid and glutaric acid all give double peaks in D_2O solution; one at 1700 cm.^{-1} corresponding to a carboxylic acid group and one at $1550\text{--}1580\text{ cm.}^{-1}$ corresponding to a carboxylate group.

Discussion and Conclusions

The question to be resolved is whether any of the protons of the protonated EDTA species (H_4Y , H_3Y^+ , $\text{H}_2\text{Y}^{\equiv}$, HY^{\equiv}) are present on the nitrogen atoms. Previous data^{1,4,10} plus the data here indicate that the

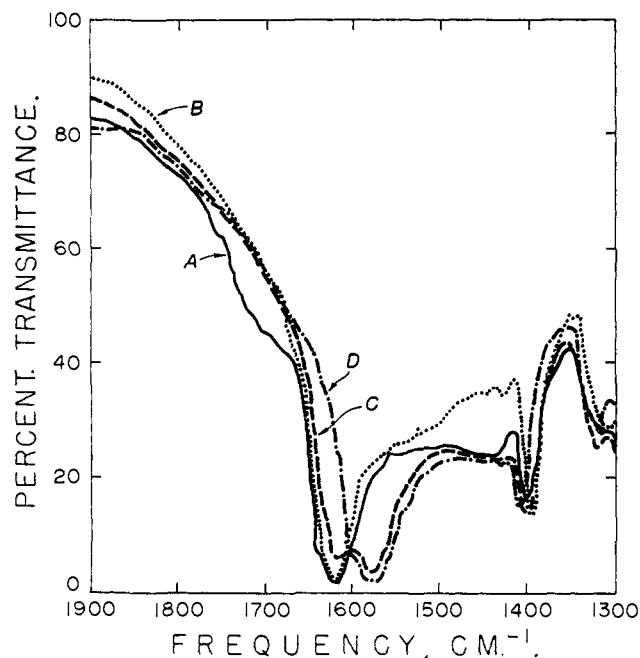


Fig. 1.—Spectra for EDTA in aqueous solution as a function of pH . All solutions contained $0.05\text{ }F$ EDTA in D_2O and their pH was adjusted using HCl or NaOH : curve A, pD 3.1; B, 5.2; C, 9.0; D, 10.9.

1700 cm.^{-1} absorption band is due to the COOH group in the EDTA molecule. Also data from these same sources give essentially conclusive proof that the 1585 cm.^{-1} absorption band is due to the COO^- group of the EDTA molecule.

Curve B in Fig. 1 is for solution conditions where $\text{D}_2\text{Y}^{\equiv}$ would be the major species in solution. The experiments with dihydroxyethyl glycine, and the monosodium salts of malonic acid, succinic acid and glutaric acid have been made to establish an assignment for the 1620 cm.^{-1} absorption band for $\text{D}_2\text{Y}^{\equiv}$. The available evidence^{10,11} indicates that at certain pD 's glycine and its derivatives exist in aqueous D_2O solutions as "zwitterions" with the acidic proton on the nitrogen atom. Thus the similarity between the $\text{D}_2\text{Y}^{\equiv}$ spectrum and the spectrum for the glycine derivative is strong support for the double "zwitterion" structure proposed by Schwarzenbach and Ackermann.² Also, if $\text{D}_2\text{Y}^{\equiv}$ involved bridge hydrogens between the two carboxylate groups as suggested by Chapman,⁴ then similar behavior would be expected for the half-neutralized forms of malonic, succinic and glutaric acids. However, the double peaks which are observed for each of these acids suggests that $\text{D}_2\text{Y}^{\equiv}$ would also give double peaks if the two protons were not on the nitrogen atoms. On the basis of these observations, the absorption band at 1620 cm.^{-1} for the protonated EDTA in D_2O solution is concluded to be due to a COO^- group or groups attached to a protonated nitrogen atom.

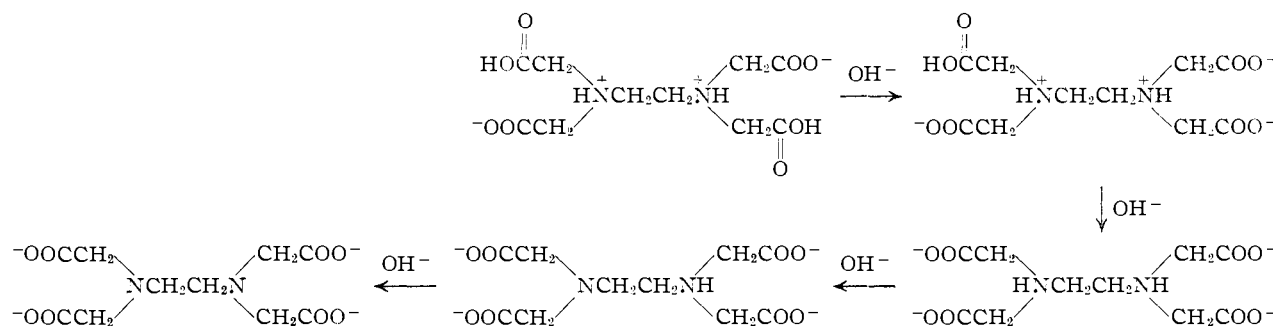
This conclusion is supported by curve C in Fig. 1 where the acidity conditions are such that DY^{\equiv} is the major species in solution. Two peaks are observed with essentially equal areas; one at 1620 cm.^{-1} due to two COO^- groups attached to a protonated nitrogen atom and one at 1585 cm.^{-1} due to two COO^- groups in the absence of a protonated nitrogen atom. Also, at conditions where $\text{D}_3\text{Y}^{\equiv}$ is the major species, a small peak at 1700 cm.^{-1} plus a peak three times as large at

(10) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," 2nd ed., John Wiley and Sons, Inc., New York, N. Y., 1958, pp. 161-177, pp. 234-247.

(11) R. C. Gore, R. B. Barnes and E. Petersen, *Anal. Chem.*, **21**, 382 (1949).

1620 cm^{-1} would be expected if one COOH group plus three COO^- groups attached to the protonated nitrogen atoms is the proper structure. Curve A of Fig. 1 is for such conditions and indicates that such a structure is correct.

A conclusion that the 1620 cm^{-1} band is due to a COO^- group in the presence of a protonated nitrogen atom appears to be totally justified, especially in view of the massive amount of information for amino acids and their infrared spectra.¹⁰ For such systems which are quite similar to EDTA, the acidic proton is definitely on the nitrogen atom; and the frequency for the COO^- group is approximately 1600 cm^{-1} and increases with substitution on the nitrogen atom.^{10,11} Although efforts to observe the presence of a proton on the nitrogen atom by infrared and n.m.r. studies have yielded negative results, these are not the anticipated rapid exchange rate would hinder n.m.r. studies of this type of nitrogen-proton bond. Assuming the double "zwitterion" structure, the dissociation steps and the associated structures for the protonated forms of EDTA in solution can be written as



which are similar to the structures proposed by Schwarzenbach and Ackermann² and Olson and Margerum.⁷ However, the structure for HY^{\equiv} proposed here is different from that proposed by these two groups and indicates that the proton is located on only one nitrogen atom. If it were bridged between the two nitrogen atoms, only a single peak would be observed rather than a double peak (curve C, Fig. 1). The spectra in Fig. 1

are qualitatively and quantitatively compatible with these structures. Thus, if H_3Y were soluble in water, an absorption band at 1700 cm^{-1} and another at 1620 cm^{-1} would be observed. The species $\text{H}_3\text{Y}^{\equiv}$, as expected, gives two peaks at 1700 and 1620 cm^{-1} , while $\text{H}_2\text{Y}^{\equiv}$ gives only a single band at 1620 cm^{-1} because all four COO^- groups are identical. Previous work^{1,4} has noted two peaks for $\text{Na}_2\text{H}_2\text{Y}$ in the solid phase, one at 1675 and one at 1630 cm^{-1} . Apparently there is some difference in the arrangement of the protons when in the solid phase rather than in the solution phase. For HY^{\equiv} two equal area peaks are observed, one at 1620 cm^{-1} due to two COO^- groups which are attached to a protonated nitrogen atom and the other at 1585 cm^{-1} due to two free COO^- groups.

It seems highly unlikely that the 1620 cm^{-1} peak is due to a hydrogen bridge between two carboxylate groups; if it were the structures proposed by Chapman⁴ would be consistent with the data presented here. However, this would be in conflict with the data observed for similar half-neutralized dicarboxylic acids. In any case the data of Fig. 1 are not consistent with

the carboxylate-nitrogen-proton bridge structure proposed by Charles.⁶

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The Structure and Chemistry of Ferrocene. VII. Bridged Ferrocenes¹

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The synthesis of several new bridged ferrocenes is described. Among these are β,β -dimethyl-1,1'-trimethyleneferrocene and transformation products of α -keto-1,1'-trimethyleneferrocene, in which a double bond is included in the bridging elements. Certain aspects of the structure of these substances, in particular ring tilting and conformational mobility within the bridge, are discussed in terms of their n.m.r., infrared and ultraviolet spectra.

Introduction

Ferrocenes having elements bridging the aromatic rings were among the first derivatives of the parent substance to be prepared. Of the several general methods available for the synthesis of such substances, the internal Friedel-Crafts acylation of a suitably chosen ferrocenylalkanecarboxylic acid was initially employed by Woodward and Csendes³ and subsequently by Rinehart,

Curby and Sokol⁴ for the preparation of α -keto-1,1'-trimethyleneferrocene (III) from β -ferrocenylpropionic acid (II). The method appears to be confined to the synthesis of derivatives bridged by a three carbon unit,⁵ since γ -ferrocenylbutyric acid and δ -ferrocenylvaleric acid have been reported to give products of homoannular cyclization.⁴ Schlogl and Seiler⁶ as well as Rinehart, Bublitz and Gustafson⁷ have recently reported

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(2) National Science Foundation Undergraduate Research Participant under Grant G11914.

(3) R. B. Woodward and E. Csendes, private communication, 1953; M. Rosenblum, thesis, Harvard University, 1953.

(4) K. L. Rinehart, R. J. Curby and P. E. Sokol, *J. Am. Chem. Soc.*, **79**, 3420 (1957).

(5) This statement may be true only for unbranched alkyl carboxylic acids.

(6) K. Schlogl and H. Seiler, *Tetrahedron Letters*, **7**, 4 (1960).

(7) K. L. Rinehart, D. E. Bublitz and D. H. Gustafson, Abstracts of Papers of the 141st Meeting of the American Chemical Society, Washington, D. C., March, 1962, p. 19-O.