Studies of the Alkali Metal Ion Complexes of 2,3-Diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic Acid

James D. Carr* and D. G. Swartzfager

Contribution from the Department of Chemistry, University of Nebraska, Lincoln, Nebraska 68508. *Received March 20, 1972*

Abstract: The interactions of the alkali metal ions lithium, sodium, potassium, and cesium with the ligand 2,3-diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic acid are investigated over an extended pH range. The log K_{ML} values of the 1:1 complexes with the dextro isomer are determined to be 5.25, 3.93, and 1.56 for lithium, sodium, and potassium, respectively. For the meso isomer, the log K_{ML} values for lithium and sodium are 2.60 and 0.48, respectively. These values along with those previously determined for the other C-substituted EDTA ligands are shown to be directly related to the proton affinities of these ligands.

Recently several reports have appeared on the formation of weak 1:1 complexes between the alkali metal ions and the aminocarboxylate multidentate ligands: ethylenediaminetetraacetic acid (EDTA),[1] propylenediaminetetraacetic acid (PDTA),[2-4] and *trans*-1,2-diaminocyclohexane-*N*,*N*,*N*′,*N*-tetraacetic acid (CyDTA).[5,6] In the present study we have extended these investigations to include 2,3-diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic acid (abbreviated here as BDTA or B). The optical rotatory properties of *d*-2,3-diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic acid have been employed as a convenient and accurate method of monitoring the formation of these weak complexes. The interactions of the alkali metal ions with the meso form of BDTA were investigated spectrophotometrically. Potentiometric and spectrophotometric techniques were also employed to determine the stability constants of the 1:1 complexes of EDTA with sodium and lithium. Utilizing the stability constants of BDTA[7] determined in this study and those determined previously for the other EDTA-like ligands, we have attempted to correlate the proton affinity of these ligands with their affinity for the alkali metal ions.

Experimental Section

Apparatus. Polarimetric measurements were performed at 365 nm in a 10-cm cell thermostated at 25° in a Perkin-Elmer Model 141M polarimeter. Spectrophotometric measurements were made with a Cary 14 in 1.0-cm cells. All pH measurements and potentiometric titrations were carried out with a Corning Model 12 expanded scale pH meter calibrated at pH's 6.86 and 9.14 and thermostated at 25°.

Reagents. 2,3-Diaminobutane was prepared by reductive amination of dimethylglyoxime with Raney nickel as described by Dickey, *et al.*,[8] and was also obtained from the Wyandotte Chemical Corp. The separation of the meso and racemic isomers and the resolution of *d*-2,3-diaminobutane were accomplished by published procedures.[8] The *d*-2,3-diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic acid and *meso*-2,3-diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic acid were prepared from the respective amines by the procedure described by Dwyer and Garvan[9] for the preparation of *l*-PDTA. All ligand solutions were standardized and all prepared ligands were checked for purity by complexometric titration of primary standard calcium carbonate. A 0.5% aqueous solution of the active acid gave a specific rotation of 49.8° ml/(cm g) at the sodium D line. Stock solutions containing the cations sodium, potassium, cesium (Alfa Inorganics), and tetramethylammonium (Southwestern Analytical) were prepared from their respective hydroxides. Lithium chloride was used as the source of lithium ion. All cation stock solutions were checked for the presence of sodium and potassium by flame photometry. Correction, which was never greater than 5%, was made for these impurities whenever necessary.

Procedure. Working solutions were prepared volumetrically from the stock solutions. The initial concentration of *d*-BDTA was about 2.0×10^{-2} *M* in all runs. After the alkali metal ion was added (in the hydroxide form), the ionic strength was adjusted to 0.5 with tetramethylammonium hydroxide which gave an initial pH of about 13.4. The optical rotation of the solution was determined at approximately 0.2 pH unit intervals as the pH was lowered by the addition of concentrated HCl. The observed molar rotation was then calculated according to eq 1 after the total concentration of the active species was corrected for dilution.

$$[\alpha]_{\mathrm{obsd}} = \alpha_{\mathrm{obsd}}/bc \qquad (1)$$

where α_{obsd} = the observed rotation (deg), b = cell length (cm), and c = concentration (mol/l.).

Similar procedures were followed when spectrophotometric techniques were utilized in the cases of *meso*-BDTA and EDTA. The procedure followed in the potentiometric investigation of EDTA was to titrate the ligand with tetramethylammonium hydroxide from a pH of 3.5 to 12.5 in the presence of each of the ions tetramethylammonium, sodium, and lithium and an ionic strength of 0.5.

Results

***d*-2,3-Diaminobutane-*N*,*N*,*N*′,*N*′-tetraacetic Acid.** The effect of a large excess of each of the cations on the observed molar rotation over the pH range from 1.5 to 13.5 is illustrated in Figure 1. As in previous studies of PDTA and CyDTA it is assumed that the cation tetramethylammonium does not interact with *d*-BDTA. The behavior in the presence of sodium and potassium at high pH (10–13.5) is generally consistent with the known complexation of sodium and potassium by the other aminocarboxylate multidentate ligands. Between pH 5 and 10 there is a dramatic difference in the molar rotation observed in the presence of sodium.

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[1] (a) G. Anderegg, *Helv. Chim. Acta*, 50, 2333 (1967); (b) V. Palaty, *Can. J. Chem.*, 41, 18 (1963); (c) J. Botts, A. Chashin, and H. L. Young, *Biochemistry*, 4, 1788 (1965).

[2] (a) J. L. Sudmeier and A. J. Senzel, *Anal. Chem.*, 40, 1693 (1968); (b) J. L. Sudmeier and A. J. Senzel, *J. Amer. Chem. Soc.*, 90, 6860 (1968).

[3] J. J. R. F. DaSilva, Ph.D. Thesis, Oxford University, 1962 (reference to this unpublished work is made in *J. Inorg. Nucl. Chem.*, 26, 1945 (1964)).

[4] J. D. Carr and D. G. Swartzfager, *Anal. Chem.*, 43, 583 (1971).

[5] (a) J. D. Carr and D. G. Swartzfager, *Anal. Chem.*, 42, 1238 (1970); (b) *ibid.*, 43, 1520 (1971).

[6] R. Sundaresan, S. C. Saraiya, and A. K. Sundaram, *Curr. Sci.*, 36, 225 (1967).

[7] *meso*-BDTA and *dl*-BDTA have the same configurations as *cis*-CyDTA and *trans*-CyDTA, respectively.

[8] F. H. Dickey, W. Fickett, and S. Lucas, *J. Amer. Chem. Soc.*, 74, 944 (1952).

[9] F. P. Dwyer and F. L. Garvan, *J. Amer. Chem. Soc.*, 81, 2955 (1959).

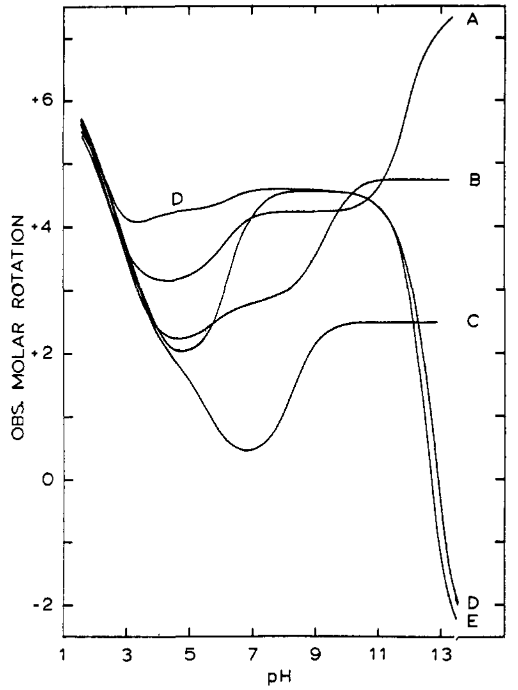

Figure 1. The effect of a large excess of each of the various cations on the observed molar rotation of *d*-BDTA: A, potassium (0.381); B, sodium (0.354); C, lithium (0.201); D, cesium (0.393); E, tetramethylammonium (0.375); λ 365 nm.

This is ascribed to the formation of the protonated complex of this metal ion. Although less obvious it is apparent that potassium also forms a protonated complex of some stability.

The constraints on the system when the concentration of an alkali metal ion is varied are represented by eq 2–7.

$$K_3 = [H^+][HB^{3-}]/[H_2B^{2-}] \tag{2}$$

$$K_4 = [H^+][B^{4-}]/[HB^{3-}] \tag{3}$$

$$K_{MB} = [MB^{3-}]/[M^+][B^{4-}] \tag{4}$$

$$K_{MHB} = [MHB^{2-}]/[M^+][HB^{3-}] \tag{5}$$

$$F_f + F_c = 1 \tag{6}$$

$$[M^+] = [M]_T - [B]_T F_c \tag{7}$$

where F_f and F_c, the fractions of BDTA free and complexed, are identified as follows.

$$F_f = ([B^{4-}] + [HB^{3-}] + [H_2B^{2-}])/[B]_T \tag{8}$$

$$F_c = ([MB^{3-}] + [MHB^{2-}])/[B]_T \tag{9}$$

Utilizing eq 2–7 and eq 10, which relates the observed

$$[\alpha]_{obsd} = [\alpha]_f F_f + [\alpha]_c F_c \tag{10}$$

molar rotation at a given pH to the molar rotations of the free ligand $[\alpha]_f$ (taken as the observed molar rotation in the presence of tetramethylammonium ion), and the complexed ligand $[\alpha]_c$ at the same pH, the following expression was derived.

$$[\alpha]_{obsd} = [\alpha]_c - \frac{Z([\alpha]_{obsd} - [\alpha]_f)}{[M^+]_T - [B]_T F_c} \tag{11}$$

The quantity Z is identified as

$$Z = \frac{[H^+]^2 + K_3[H^+] + K_4K_3}{K_4K_3K_{MB} + K_3K_{MHB}[H^+]} \tag{12}$$

and F_c is expressed in the following terms

$$F_c = \frac{[\alpha]_{obsd} - [\alpha]_f}{[\alpha]_c - [\alpha]_f} \tag{13}$$

$[\alpha]_f$ and $[\alpha]_c$ are conditional values involving two or more terms at each pH. Values of molar rotations of B^{4-}, HB^{3-}, and H_2B^{2-} are resolved from the pH dependence of $[\alpha]_f$. Likewise, values of molar rotations of the complexes are resolved from the pH dependence of $[\alpha]_c$. Values of $[\alpha]_c$ measured in (l. deg)/(cm mol) at 365 nm, 25°, and ionic strength 0.5 are as follows: CsH_2B^- (+4.5), KB^{3-} (+8.2), KHB^{2-} (+3.9), NaB^{3-} (+4.72), $NaHB^{2-}$ (+2.2), LiB^{3-} (+2.15), $LiHB^{2-}$ (−0.2), B^{4-} (−2.3), HB^{3-} (+4.55), H_2B^{2-} (+2.02). Stability constants of the alkali metal complexes and acidity constants of the *d*-BDTA measured at 25° and ionic strength 0.5 are as follows: LiB^{3-} ((1.8 ± 0.4) × 10^5), NaB^{3-} ((8.6 ± 1.8) × 10^3), KB^{3-} (36.0 ± 1.0), $LiHB^{2-}$ (48 ± 5), $NaHB^{2-}$ (6 ± 1), CsH_2B (10 ± 3), pK_4 (12.31 ± 0.03), pK_3 (6.3 ± 0.1). Listed uncertainity is one standard deviation.

In the case of potassium, values of the various protonation and stability constants were determined by a computer assisted regression analysis of the hydrogen ion dependence of Z. In the case of sodium, the value of K_{NaB} was determined *via* a mole ratio plot at pH 13.40 due to the limited pH range over which useful values of Z could be determined. This value was then used in conjunction with eq 12 to resolve the value of K_{NaHB}.

The lack of an isorotatory point near pH 12.5 in a plot of molar rotation *vs.* pH for several lithium ion concentrations clearly indicates the existence of a third distinct species, which appears to be a 2:1 complex between lithium and *d*-BDTA(Li_2BDTA^{2-}). Unfortunately this interaction, though easily distinguishable, proved to be too small to measure quantitatively. This interaction also precluded any attempt to resolve the various protonation and stability constants by means of eq 11 and 12 at any pH where an appreciable fraction of the complexed ligand exists in an unprotonated form. A similar 2:1 complex of lithium with EDTA has been reported previously.[1c] In order to determine the stability of the unprotonated 1:1 complex, values of the conditional stability constant (eq 13a) were determined

$$K_{con} = [LiB]_T/[Li]_T[B]_T = [LiB^{3-}]/[Li^+][B]_T \tag{13a}$$

from mole ratio plots between pH 10 and 11 where no appreciable amount of the protonated complex or the 2:1 complex exists. A plot of the inverse of the conditional stability constant ($1/K_{con}$) *vs.* the hydrogen ion concentration yields an excellent straight line whose slope gives the value of K_{LiB} according to eq 14.

$$\frac{1}{K_{con}} = \frac{1}{K_{LiB}} + \frac{[H^+]}{K_4K_{LiB}} \tag{14}$$

Below pH 7, where the 1:1 unprotonated complex (and therefore the 2:1 complex) is nearly nonexistent, eq 11 and 12 were employed in order to calculate the stability constant of the protonated complex. Upon rearrangement this yields an expression equivalent to eq 14 (the quantities K_{LiB} and K_4 being replaced by K_{LiHB} and and K_3) where the quantity Z is now identified as the inverse of the conditional stability constant of the protonated complex. A plot of Z *vs.* the hydrogen ion concentration in the pH (5.8–7.0) range yields a value of K_{LiHB}.

The effect of the alkali metal ions on the observed molar rotation below pH 6 is illustrated in Figure 1. These are consistent with the reported behavior of *l*-PDTA and *l*-CyDTA under the same conditions. The presence of lithium or sodium ions appears to have little or no effect on the observed molar rotation. In the case of potassium ion the deviation from the rotations observed in the presence of tetramethylammonium ion proved to be too small for meaningful calculations. The effect of varying the cesium ion concentration indicates that the interaction may not be strictly 1:1 but any deviation from 1:1 stoichiometry is too small to warrant any particular significance. It was therefore assumed that the stoichiometry of the cesium–*l*-BDTA complex was 1:1 in which case it can be shown that eq 6, 7, 10, and 12 still apply. The quantity Z is now further complicated by the addition of several terms involving more highly protonated forms of the ligand. However, the observed effects indicate that the interaction is predominantly with the diprotonated form of the ligand. Thus if the quantity Z is evaluated at a pH of 4.8 where the species $\mathrm{H_2B^{2-}}$ is the predominant form of the free ligand, then Z simply reduces to the inverse of the conditional stability constant of the complex ($\mathrm{CsH_2B^-}$).

meso-2,3-Diaminobutane-_N,N,N′,N′_-tetraacetic Acid. The fourth acid dissociation constant and the stability constant of the lithium ion complex of *meso*-BDTA were determined by conventional spectrophotometric techniques. The stability constant of the sodium ion complex was obtained by employing eq 11 (the various molar rotation terms having been replaced by the corresponding molar absorptivities) at a pH of 13.4 where the quantity Z is simply the inverse of the stability constant of the complex. At 270 nm, 25°, and ionic strength 0.5, the molar absorptivities are Li–*ms*-$\mathrm{B^{3-}}$ (2.3), Na–*ms*-$\mathrm{B^{3-}}$ (1.0), *ms*-$\mathrm{B^{4-}}$ (45.2), and H–*ms*-$\mathrm{B^{3-}}$ (7.83). The values of the stability constants at 25° and ionic strength 0.5 are Li–*ms*-$\mathrm{B^{3-}}$ (4×10^2), Na–*ms*-B (3.0), and pK_4 of *meso*-BDTA is 11.08.

Ethylenediaminetetraacetic Acid. The acid dissociation and stability constants of EDTA were determined spectrophotometrically in the same way as those of *meso*-BDTA. Molar absorptivities at 266 nm, 25°, ionic strength 0.5 are $\mathrm{LiY^{3-}}$ (8), $\mathrm{NaY^{3-}}$ (6.6), $\mathrm{Y^{4-}}$ (39.1), and $\mathrm{HY^{3-}}$ (7.20). In addition, potentiometric titrations in the presence of tetramethylammonium, sodium, and lithium were also performed. The *apparent* pK_4 and pK_3 values at 25° and ionic strength 0.5 in these media are 10.22 and 6.12 (0.410 M $\mathrm{TMA^+}$), 9.06 and 6.07 (0.409 M $\mathrm{Na^+}$), and 8.13 and 5.82 (0.417 M $\mathrm{Li^+}$). Although there is good agreement between the two techniques as regards the values of the fourth acid dissociation constant (pK_4 = 10.23 (spectrophotometric) and 10.22 (potentiometric)) and the stability constant of the sodium ion complex (27 (spectrophotometric) and 29 (potentiometric)), the values of the stability constant of the lithium ion complex are vastly different (2.7×10^2 (spectrophotometric) and 5.9×10^2 (potentiometric)). The reason for this discrepancy involves the formation of a 2:1 complex between lithium and EDTA in the potentiometric case, which was carried out in 0.42 M $\mathrm{Li^+}$ (*ca.* 20-fold excess). This species would not be formed substantially in the spectrophotometric experiments carried out in a 1:1 Li:EDTA solution. For this reason, the spectrophotometric method and resultant stability constant are preferred.

Discussion

The large difference between the pK_4 values of *dl*-BDTA (12.31) and *meso*-BDTA (11.08) and between those of *trans*-CyDTA (13.09)[5b] and *cis*-CyDTA (10.70)[10] is indicative of the fact that the structure of these ligands rather than inductive effects is the primary factor influencing the proton affinity of these ligands. These results differ from those of Irving and Parkins who found little difference in pK_4 of the *dl*- and *meso*-BDTA isomers,[11] probably because the basicity of *dl*-BDTA was masked by complexation with KCl used to control ionic strength. Our observation is not surprising in light of recent evidence indicating that the mono-protonated forms of PDTA[2] and *trans*-CyDTA[12] exist predominantly as chelated structures (chelated in the sense that both ends of the molecule are simultaneously involved in binding the proton). Such a chelated structure would be unfavorable in the case of either *meso*-BDTA or *cis*-CyDTA due to the steric interactions of the substituent which is axial to the chelate ring. The greater stability of the *dl* isomer of BDTA compared to the meso isomer is in agreement with Dwyer's work with PDTA[13] which shows the preference for the equatorial conformation of the PDTA methyl group with transition metals. Both methyls can assume an equatorial position with *dl*-BDTA but one of the methyl groups must be axial with *meso*-BDTA. Such an axial methyl group would result in steric interactions with the hydrogens of the out-of-plane acetate groups.

Comparing the pK_4, log K_{LiL}, and log K_{NaL} values for the structurally similar ligands EDTA, PDTA, *dl*-BDTA, and *trans*-CyDTA, it is apparent that a simple correlation exists between the proton affinity of these ligands and their affinity for the alkali metal ions lithium and sodium. Figure 2 shows a plot of the log K_{LiL} and log K_{NaL} values *vs.* the log of the proton affinity (pK_4) for these ligands, which yields two straight lines whose slopes are equal to 1. This indicates that, in the case of lithium and sodium ions, the free energy change accompanying the reaction illustrated by eq 15

$$\mathrm{HL^{3-} + M^+ \longrightarrow ML^{3-} + H^+} \qquad (15)$$

is independent of the identity of the ligand. This strongly indicates that both the mono-protonated forms of these ligands and their sodium and lithium ion complexes have very similar structures. It should be noted that the correlation is not particularly good for EDTA. This may be due to a structural equilibrium between a chelated and nonchelated form of the mono-protonated ligand. Such an equilibrium is reasonable in view of the pK_4 values of trimethylenediamine-*N,N,N′,N′*-tetraacetic acid (10.27) and tetramethylenediamine-*N,N,N′,N′*-tetraacetic acid (10.45)[10] (which are nearly

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[10] L. G. Sillen and A. E. Martell, *Chem. Soc., Spec. Publ.*, No. 17 (1964).

[11] H. M. N. H. Irving and R. Parkins, *J. Inorg. Nucl. Chem.*, 28, 1629 (1966).

[12] Y. Fujiwara and C. N. Reilley, *Anal. Chem.*, 40, 890 (1968).

[13] F. P. Dwyer and F. L. Garvan, *J. Amer. Chem. Soc.*, 83, 2610 (1961).

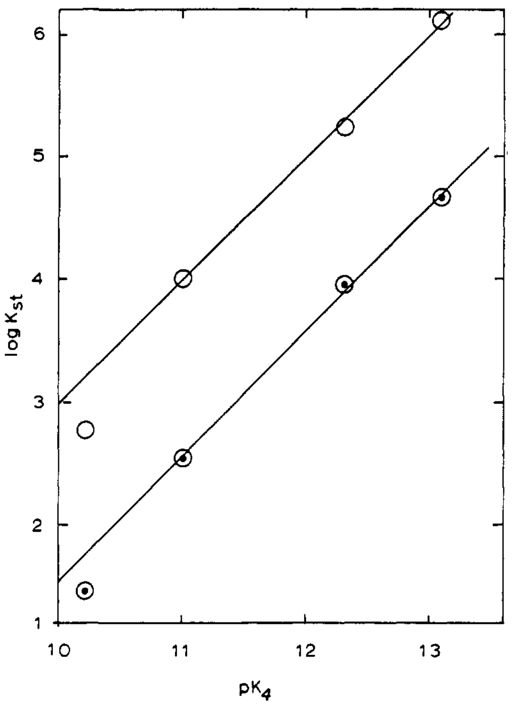

Figure 2. A plot of the log of the stability constants *vs.* the log of proton affinity constants of the ligands EDTA, PDTA, *d*-BDTA, and CyDTA: ○, lithium; ⊙, sodium.

the same as the pK_4 value of EDTA), in which proton chelation is highly improbable due to the increased ring size required for such structures. A graph of log K_{KL} *vs.* pK_4 is linear but has a slope much less than unity. The increase of basicity of these ligands with respect to hydrogen ion is not reflected in their basicity with respect to potassium ion. Possibly potassium ion is too large or too soft to fit well into a chelate structure of any of these ligands.

Utilizing the information acquired in this work along with that reported for the ligands PDTA[2b] and *trans*-CyDTA,[12] an energy relationship among these ligands and their proton, sodium ion, and lithium ion chelates is apparent. A reference point for such a relationship is the energy of the protonated, chelated species which is presumed constant for all four ligands. The relative position of the energy level for nonchelated HPDTA^{3-} and its population is based on Sudmeier's estimate[2b] of the minimum relative stability of the proton chelate (K_t = 5.7). The position and the population of the energy level for the nonchelated form of HEDTA^{3-} is an estimate based on the equation

$$\frac{1}{K_{4\mathrm{obsd}}} = \frac{1}{K_{4\mathrm{c}}} + \frac{1}{K_{4\mathrm{nc}}} \qquad (16)$$

where pK_{4c} (9.9) is the value necessary to bring EDTA into conformance with the linear correlation between the pK_4 values and the log K_{NaL} and log K_{LiL} values of these ligands, and pK_{4nc} (9.9) represents the pK_4 value which would be observed if the mono-protonated ligand existed only in a nonchelated structure. The equality of these two values leads to the conclusion that equal fractions of protonated EDTA exist in the chelated and nonchelated forms. The populations of the energy levels for the nonchelated forms of *trans*-CyDTA and *dl*-BDTA were estimated by assuming a pK_{4nc} value of 10.0 for these ligands. Such calculations show that the fraction of nonchelated, proton–ligand species decreases from 50, 15, 2 to <1% through the series EDTA, PDTA, BDTA, and CyDTA.

The existence of a 2:1, Li:BDTA^{4-}, complex and the relatively large value for the stability of the 1:1, Li:HBDTA^{3-}, complex seems to indicate that lithium ion can be complexed by one end of this molecule. Attempts to verify this by measuring the stability constant for a lithium iminodiacetate complex were moderately successful yielding a K_{LiL} value of approximately 2.[14]

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(14) Figures depicting the effects on the pH dependance of the observed molar rotations by varying the concentrations of the alkali metal ions will appear following these pages in the microfilm edition of this volume of the journal. Single copies may be obtained from the Business Operations Office, Books and Journals Division, American Chemical Society, 1155 Sixteenth St., N.W., Washington, D. C. 20036, by referring to code number JACS-73-3569. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche.