Table IV. Electrochemical Mn(III)/Mn(II) Data for Manganese Complexes Containing Hexadentate Ligands

complex	V, mV/s	E_{pc}, V	E_{pa}, V	ΔE, mV	i_{pc}, μA	i_{pc}/i_{pa}
Mn(SAL-1,4,7,10)NCS	2	−0.140	−0.066	74	2.6	1.06
	5	−0.148	−0.065	83	4.0	1.07
	10	−0.153	−0.060	93	5.6	1.11
	20	−0.160	−0.055	105	7.6	1.13
Mn(SAL-1,5,8,12)NCS	2	−0.275	−0.192	83	3.2	1.01
	5	−0.279	−0.188	91	4.9	1.07
	10	−0.285	−0.181	104	6.7	1.08
	20	−0.296	−0.170	126	9.0	1.08
Mn(SAL-1,5,9,13)NCS·$^1/_2H_2O$	2	−0.228	−0.099	129	2.6	1.03
	5	−0.245	−0.090	155	3.8	1.02
	10	−0.253	−0.090	163	5.3	0.99
	20	−0.268	−0.087	181	7.2	0.98

Mn(SAL-1,4,7,10)NCS and Mn(SAL-1,5,8,12)NCS exhibit a quasi-reversible oxidation similar to that of Mn(SALEPT)NCS discussed above. The oxidation and subsequent reduction is well defined in Mn(SAL-1,4,7,10)NCS (Figure 4) in contrast to the other complexes. The origin of this oxidation remains a mystery but is clearly related to those ligands with one or more bridging C_2H_4 groups. Crystal structures of Fe(SAL-1,4,7,10)X (X = Cl·2H_2O and NO_3·H_2O)[20] show unequivocally that this ligand can accommodate the short C_2H_4 bridging groups and coordinate as a hexadentate ligand with little steric strain. If the Mn(III) complex also contains a hexadentate ligand (as is believed to be the case[4]), then oxidation of a noncoordinated amine is not the source of this oxidation.

In conclusion, the stabilization of manganese(III) has been demonstrated to be determined only in part by the ligand donor atom set. With the same donor set dramatic changes in redox potential and reversibility can be created by different aromatic ring substituents, different chelate ring sizes and different α-carbon substituents. An oxidation of unknown origin occurs in the Mn(III) complexes containing ligands with a C_2H_4 bridging group. The influence of analogous ligand modifications on the stability of manganese(II) will be dealt with in a forthcoming manuscript.

Acknowledgment. This research was supported by NIH Research Grant 21844-04. R.K.B. wishes to express appreciation to the Research Corp. for funds to purchase the polarographic equipment.

Registry No. Mn(5-NO_2SALEPT)NCS, 76430-54-1; Mn(3-NO_2SALEPT)NCS, 76430-55-2; Mn(SALEPT)NCS, 76430-56-3; Mn(5-NO_2SALBPT)NCS, 76430-57-4; Mn(3-NO_2SALBPT)NCS, 76430-58-5; Mn(SALBPT)NCS, 76430-59-6; Mn(5-CH_3OSALBPT)NCS, 76430-60-9; Mn(3-NO_2SALDAPE)NCS, 76430-61-0; Mn(SALDAPE)NCS, 70754-27-7; Mn(SALHTDA)NCS, 76430-62-1; Mn(SALEN)Cl, 53177-12-1; Mn(SAL-1,4,7,10)NCS, 76430-63-2; Mn(SAL-1,5,8,12)NCS, 76430-64-3; Mn(SAL-1,5,9,13)NCS, 76430-65-4; SAL, 90-02-8; 5-NO_2SAL, 97-51-8; 3-NO_2SAL, 5274-70-4; BPT, 124-20-9; DAPE, 2157-24-6; EPT, 13531-52-7.

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Kinetics and Mechanism of the Regiospecific Alkylation of Cobaloxime–Tetrazole Complexes

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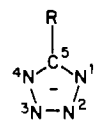
A series of complexes of the type (n-Bu_3P)Co$(DH)_2$(5-R-tetrazolate) (DH is the monoanion of dimethylglyoxime; R = CF_3, CH_3, C_6H_5, $C_6H_5CH_2$, $(CH_3)_2N$, 4-FC_5H_4, and 3-FC_6H_4) have been treated with a variety of alkylating agents. NMR spectral comparison with known compounds revealed that in each case regiospecific alkylation of the coordinated tetrazolate produced exclusively 1,5-disubstituted tetrazoles. None of the isomeric 2,5-disubstituted tetrazoles were formed, in marked contrast to all previous alkylations of tetrazoles where mixtures of the two isomers are always formed. The results of ^1H NMR monitored kinetic experiments under pseudo-first-order conditions indicated that the alkylations proceed by two consecutive steps. Long-lived intermediates were spectroscopically observed in the alkylations of the 5-methyl- and 5-benzyltetrazolate complexes. The rate constants and activation parameters are consistent with an overall second-order nucleophilic attack of the alkyl halide on the coordinated tetrazolate to form an intimately associated charged intermediate. Formation of the intermediate is followed by a dissociative interchange of halide and 1,5-disubstituted tetrazole producing (n-Bu_3P)Co$(DH)_2$X and liberating free 1,5-disubstituted tetrazole. Alkylation of the 5-(N,N-dimethylamino)tetrazolate complex involves initial attack at the exocyclic amino nitrogen followed by an unusual inner-sphere migration of the alkyl group to an N-1 ring site of the coordinated tetrazolate The relationship of these studies to other investigations of the alkylations of tetrazoles is discussed.

Introduction

Recently[1] we described the preparation and characterization (spectroscopic and crystallographic) of a series of complexes of the type Co$(DH)_2$(5-R-tetrazolate). One purpose in preparing these complexes was to determine whether the steric environment imposed on the tetrazolate ligand by the equitorial oxime ligands was sufficient to induce regiospecific coordination of the ambidentate, anionic 5-R-tetrazolate rings (I)



I

tetrazolate ring numbering scheme

via the less hindered N_2 nitrogen. NMR and X-ray crystallographic data showed that this objective was fully realized. Each of the complexes contained exclusively N_2 coordinated tetrazolate regardless of the electronic properties of the 5-

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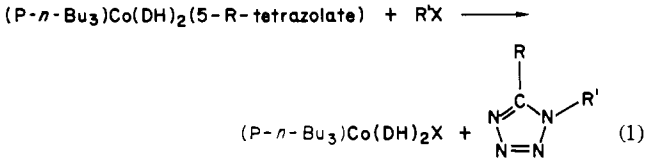
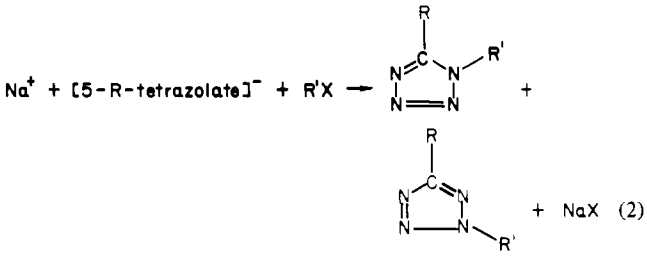
0020-1669/81/1320-1258$01.25/0

substituent on the tetrazolate ring. A second objective was to utilize these complexes as intermediates in the synthesis of 1,5-disubstituted tetrazoles, a highly useful series of compounds,[2] according to reaction 1. If a reaction such as (1)



is to be of significant synthetic utility, its rate should be comparable to the rate of the alternative but not regiospecific alkylations[3] (eq 2). Consequently the kinetics and mechanisms



of reaction 1 have been investigated and are reported herein.

Experimental Section

The preparation and characterization of $(n\text{-}Bu_3P)Co(DH)_2$(5-R-tetrazolates) and 1,5- and 2,5-disubstituted tetrazoles have been previously described.[1] All solvents were purified and dried by standard techniques.

Kinetic Experiments. Qualitative alkylations of the tretrazole complexes were carried out in 5-mm NMR tubes containing a saturated solution of a given complex and 2–3 drops of an alkylating agent. The tubes were kept at room temperature, and ^1H NMR spectra were obtained periodically on a Perkin-Elmer R24B NMR spectrometer. These experiments were utilized in order to gain a rough estimate of the rates of the reactions and to determine the nature of the products. Quantitative alkylations were carried out as follows. Pseudo-first-order conditions were used to measure the rates of alkylation by ^1H NMR at 99.54 MHz on a JEOL FX-100 Fourier transform spectrometer. The temperatue readings of the JES-VT-3 variable-temperature controller were corrected to readings obtained by inserting a thermocouple lead or a thermometer directly into the probe. Temperatures are believed to be constant and accurate to within 1 °C. Each kinetic experiment commenced by dissolving 0.1 mmol of the desired complex in 0.5 mL of a solution which was 2.0 M in alkylating agent. The time of mixing was noted, and the solution was transferred to a 5-mm NMR tube. The tube cap was sealed with Teflon tape, and the tube was inserted into the temperature-regulated probe for periodic recording of spectra. The appropriate region of the proton spectrum was expanded, and the instrument was adjusted to give *N*-alkyl signals at the end of the experiment which were of sufficient size to reach the maximum peak height allowed by the vertical scale of the instrument's recorder. This allowed the concentration of the new species to be measured as a function of peak areas or peak heights. Peak areas were measured by cutting and weighing. Least-squares analyses of plots of ln peak area vs. time were accomplished with the computer program[4] LSQR.

Some of the alkylations were also followed by measuring the change in conductivity of these same solutions, as a function of time at constant temperature. Conductance measurements were made with use of a Yellow Springs Instruments conductivity cell, Model 3403 (cell constant 1.01), and were measured with an Industrial Instruments conductivity bridge, Model RC16B2, which was adapted inhouse for use with a Teletronix Type 310 oscilloscope. Temperature regulation was achieved with a Brinkman Lauda K-2/R temperature controller. It was found that all of the $(P\text{-}n\text{-}Bu_3)Co(DH)_2$(5-R-tetrazolate) complexes were nonelectrolytes in both $CHCl_3$ and $C_6H_5NO_2$ solutions. Upon addition of an alkyl halide to solutions of the tetrazolate complexes the conductance slowly increased very slightly from essentially zero to a maximum of ca. 1 Ω^{-1} and then slowly returned to essentially zero, indicating that only very small amounts of transient ionic species were formed during the course of these reactions.

Isolation of 1,5-Disubstituted Tetrazoles. For further verification of the regiospecific alkylation and for assessment of the synthetic utility of these reactions, three of the disubstituted tetrazoles formed by the alkylation of $(P\text{-}n\text{-}Bu_3)Co(DH)_2$(5-R-tetrazolate) complexes were isolated. These reactions were run on a scale calculated to yield about 1 g of the tetrazole product. Instead, only trace amounts were isolated in each case. The low isolated yields are due to difficulties encountered in separating the disubstituted tetrazole from the complex owing to their very similar solubility properties. All the spectroscopic data[1] demonstrated that the reactions proceeded essentially to completion. Isolation was accomplished as follows. $(P\text{-}n\text{-}Bu_3)Co(DH_2$(5-R-tetrazolate) (R = C_6H_5, 4-FC_6H_4, and $(CH_3)_2N$) complexes (0.005 mol) were dissolved in 50 mL of $CHCl_3$ and treated with 0.1 mol of CH_3I (or $C_6H_5CH_2Br$ in the case of R = $(CH_3)_2N$). The reaction solutions were stoppered tightly and placed in an oil bath maintained to 40 °C. The progress of the reactions was checked periodically by ^1H NMR. After the signals due to starting complex dissappeared, the solutions were evaporated to a syrupy residue by rotary evaporation at room temperature. Further solvent was evaporated from the residue containing the alkylated 5-(4-fluorophenyl)tetrazole by passing a stream of air over it for several days. The residue was then sublimed at a pressure of 0.1 torr and a temperature of 78 °C for 3 days. Attempts to increase the rate of sublimation resulted in decomposition of $(B\text{-}n\text{-}Bu_3P)Co(DH)_2I$ and contamination of the sublimate by dimethylglyoxime. The ^1H NMR spectrum, melting point, and elemental analysis of the colorless sublimate identified it as pure 1-methyl-5-(4-fluorophenyl)tetrazole. 1-Methyl-5-phenyltetrazole and 1-benzyl-5-(*N,N*-dimethylamino)tetrazole were isolated by hot-water extraction of their residual reaction solutions. Reduction of the water volumes produced colorless crystals identified by their melting points, elemental analyses, and ^1H NMR spectra to be pure 1,5-isomers.

Results and Discussion

It has previously been established[1] that the entire series of $(P\text{-}n\text{-}Bu_3)Co(DH)_2$(5-R-tetrazolate) complexes exhibits exclusive N-2 coordination of the tetrazolate ring to the cobalt center. This is equivalent, in effect, to a series of 2,5-disubstituted tetrazoles where the 2-substituent is the $[(P\text{-}n\text{-}Bu_3)Co(DH)_2]^+$ moiety. Because the tetrazole ring contains an odd number of atoms, substitution at any two sites creates an anisotropic charge distribution among the remaining unsubstituted sites. Consequently these sites can be distinguished in their relative ability to attract incoming electrophiles such as alkyl halides. To gain a feeling for the charge distribution, we performed MINDO/3 calculations on some representative 2,5-disubstituted tetrazoles. The results of the calculated charge densities are as follows [compound (atomic charge)]: 2,5-H_2-tetrazole, N-1 (−0.177), N-3 (−0.049), N-4 (−0.122); 2,5-$(CH_3)_2$-tetrazole, N-1 (−0.211), N-3 (−0.065), N-4 (−0.137); 2-H-5-$(CH_3)_2$N-tetrazole, N-1 (−0.221), N-3 (−0.042), N-4 (−0.166), exocyclic N (−0.77). Similar calculations on a variety of tetrazoles[5] also indicate that the N-1 nitrogen has the greatest electron density and that the N-4 nitrogen is nearly as electron rich. Thus, on a purely electronic

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(4) Howells, P. N.; Nelson, J. H. *J. Chem. Educ.* **1978**, *55*, 311.

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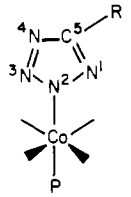
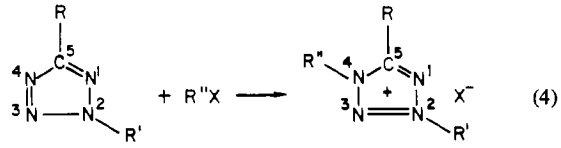
basis electrophilic attack would be expected to occur at N-1. However, the steric environment imposed on the tetrazolate ring by the $[(P\text{-}n\text{-}Bu_3)Co(DH)_2]^+$ moiety limits the accessibility of the unsubstituted nitrogens, rendering N-4 the more likely point of attack. Of course the ultimate product is the same whether attack occurs at N-1 or N-4.



Qualitative Alkylation Experiments. In order to demonstrate that alkylation of the tetrazole complexes occurred regiospecifically, we treated $CDCl_3$ solutions of each complex with an excess of alkyl halide in an NMR tube. The alkylations were monitored by observing the appearance and growth of new signals in the ^1H NMR spectra of these reaction solutions. The products of the alkylations were identified by spectral comparison with free disubstituted tetrazoles.[1] No trace of a 2,5-isomer[6] was found in any of the alkylation reactions. This is strong, albeit indirect, evidence that (1) all of the tetrazoles were N-2 coordinated, (2) rapid interconversion of N-1- and N-2-coordinated tetrazoles did not occur in solution, and (3) alkylation of the coordinated tetrazole preceded its dissociation from the complex. The general scheme for the alkylation reactions is given in eq 3. According to this scheme, attack

$$PBu_3Co(DH)_2\text{-}5\text{-}Rtet + R'X \rightarrow [PBu_3Co(DH)_2\text{-}1\text{-}R'\text{-}5\text{-}Rtet]^+X^- \rightarrow PBu_3Co(DH)_2X + 1\text{-}R'\text{-}5\text{-}R\text{-tetrazole} \quad (3)$$

by the alkyl halide occurred at the N-4 site of the N-2-coordinated 5-R-tetrazolate rings. Because the alkylations gave rise to only one of two possible structural isomers, they are termed "regiospecific". This parallels the steric control of regiospecific tetrazolate coordination established earlier.[1] By contrast, alkylation of 2-Sn-n-Bu_3-5-R-tetrazoles with CH_3I was not regiospecific because this small alkyl halide was not sterically bulky enough to prevent attack at the N-3 position.[3d] In support of eq 3 it has been reported that, when free 2,5-disubstituted tetrazoles are alkylated, only attack at the N-4 site results in an isolable, trisubstituted species,[7] as illustrated in reaction 4.



(4)

For verification that the tetrazoles were cleaved from the cobaloxime complex following alkylation, disubstituted tetrazole products were isolated from three alkylation solutions as described in the Experimental Section. They included 1-CH_3-5-C_6H_5-tetrazole, 1-CH_3-5-(4-FC_6H_4)-tetrazole, and and 1-$CH_2C_6H_5$-5-$N(CH_3)_2$-tetrazole which were identified to be pure 1,5-isomers by their melting points, elemental analysis, and ^1H NMR spectra.

Probably the most convincing support for the proposed scheme is the existence of spectroscopically detectable intermediates when the 5-substituents were the relatively electron-releasing methyl or benzyl groups. Figure 1 follows the

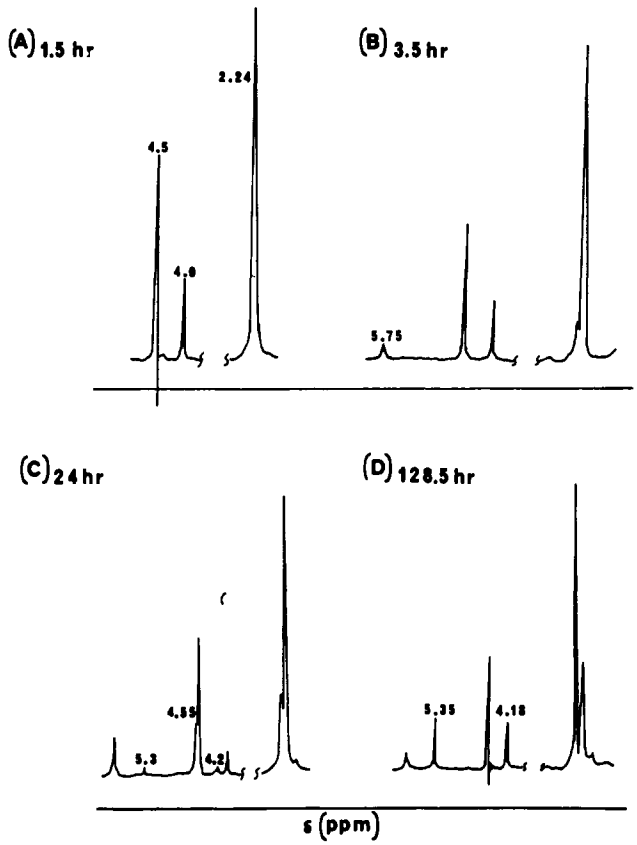


Figure 1. Chronological 60-MHz ^1H NMR spectra following the alkylation of (P-n-Bu_3)$Co(DH)_2$(5-benzyltetrazolate) by benzyl bromide in $CDCl_3$ at 36 °C.

progress of the alkylation of (P-n-Bu_3)$Co(DH)_2$(5-benzyltetrazolate) with benzyl bromide in $CDCl_3$ by ^1H NMR. In the following discussion, the term "benzyl signal" refers to the ^1H resonance of this group's CH_2 protons. In Figure 1 a the alkylation has not yet begun. The signals, from left to right, represent benzyl bromide (δ 4.50), the tetrazole *C*-benzyl of the reactant complex (δ 4.00), and the oxime methyl groups of the same δ 2.24. In Figure 1B the small signal at δ 5.75 is due to the *N*-benzyl group of the intermediate. The latter's *C*-benzyl signal coincides with the large benzyl bromide resonance. In Figure 1C the *C*-benzyl signal of the intermediate is now visible at δ 4.55. The intermediate has begun to decay, and the first traces of the cleaved, alkylated tetrazole's *C*- and *N*-benzyl groups appear at ca. δ 4.2 and 5.3, respectively. The separation between the latter two signals is the same as the separation between the corresponding signals in the intermediate. This result and the relative shielding seen in the pair of product signals show that alkylated tetrazole product is simply the result of breaking the bond between cobalt and the tetrazole ring, thus freeing the latter from the deshielded environment of the cationic cobalt complex. In Figure 1D the oxime methyl region indicates that about 90% of the intermediate has decayed. The *N*-benzyl (δ 5.35) and *C*-benzyl (δ 4.18) chemical shifts of the free, alkylated tetrazole identify it as the 1,5-isomer.

The presence of a charged intermediated was difficult to substantiate by conductance measurements. For a mixture of equimolar solutions of benzyl bromide and (P-n-Bu_3)$Co(DH)_2$(5-benzyltetrazolate) a slow, irregular increase in conductance followed by a similar decline was observed. Though the conductance increased relative to a solution containing the complex alone, it was still a very small value in absolute terms ($\simeq 1\ \Omega^{-1}$). This result is consistent with a partially associated ion-pair intermediate.

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Table I. Kinetic Results for $[PBu_3Co(DH)_2(5\text{-Rtet})] + R'X \xrightarrow{k_1} [PBu_3Co(DH)_2(1\text{-R}'\text{-5-Rtet})]^+X^-$ and $\xrightarrow{k_2}$ 1-R′-5-R-tetrazole + $[PBu_3Co(DH)_2X]$

expt. no.	R	R′	X	solvent	temp, °C	k_1, s^{-1}	k_2, s^{-1}
IA	CH_3	$CH_2C_6H_5$	Br	$CDCl_3$	36	7.5×10^{-4}	3.6×10^{-5}
IB	$CH_2C_6H_5$	$CH_2C_6H_5$	Br	$CDCl_3$	36	4.8×10^{-4}	5.3×10^{-5}
IC	C_6H_5	$CH_2C_6H_5$	Br	$CDCl_3$	36	4×10^{-5} [a]	4×10^{-5} [a]
ID	4-FC_6H_4	$CH_2C_6H_5$	Br	$CDCl_3$	36	3×10^{-5} [a]	[b]
IE	3-FC_6H_4	$CH_2C_6H_5$	Br	$CDCl_3$	36	1×10^{-5} [a]	[b]
IF	CF_3	$CH_2C_6H_5$	Br	$CDCl_3$	36	8×10^{-6} [a]	[b]
IIA	$CH_2C_6H_5$	$CH_2C_6H_5$	Cl	$CDCl_3$	36	7×10^{-6} [a]	[b]
IIB	C_6H_5	$CH_2C_6H_5$	Cl	$CDCl_3$	36	7×10^{-6} [a]	[b]
IIIA	$CH_2C_6H_5$	$CH_2C_6H_5$	Br	$NO_2C_6H_5$	36	2.1×10^{-3}	5.6×10^{-5}
IIIB	C_6H_5	$CH_2C_6H_5$	Br	$NO_2C_6H_5$	36	1×10^{-4} [a]	[b]
IVA	CH_3	CH_3	I	$CDCl_3$	36	5.4×10^{-4}	4.9×10^{-5}
IVB	$CH_2C_6H_5$	CH_3	I	$CDCl_3$	36	4.7×10^{-4}	8.8×10^{-5}
IVC	C_6H_5	CH_3	I	$CDCl_3$	36	1×10^{-4} [a]	1×10^{-4} [a]
VA	$CH_2C_6H_5$	$CH_2C_6H_5$	Br	$CDCl_3$	51	1.3×10^{-3}	2.4×10^{-4}
VB	$CH_2C_6H_5$	$CH_2C_6H_5$	Br	$CDCl_3$	57	2.1×10^{-3}	4.8×10^{-4}

[a] Estimated by procedure described in text; k's are believed to be accurate to 0.5×10^n, where n is the exponent of the k in question. [b] No intermediate observed.

Kinetics and Mechanism of Alkylation. The alkylation of the tetrazole complexes can be described by modifying the general description of consecutive reactions such that the first step is an associative process[8] as schematically shown in reaction 5. The complex situation described by eq 5 can be

$$A + B \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} C \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} D + E \qquad (5)$$

reduced[8] to consecutive irreversible first-order reactions by employing an excess of B, the alkylating agent (reaction 6).

$$A \xrightarrow{k_1} C \xrightarrow{k_2} D + E \qquad (6)$$

The large excess of B allows its concentration to be neglected in the rate equations describing reaction 5, forces the first equilibrium to the right and allows k_{-1} to be neglected. The irreversibility of the second equilibrium, allowing k_{-2} to be neglected, can be argued a priori on both steric and electronic grounds. Morever, the reactant in both individual steps is more than 95% consumed, a percentage that has been used as a criterion for irreversibility.[8] Three possible relationships exist between the independent pseudo-first-order rate constants in eq 6: $k_1 \gg k_2$, $k_1 \approx k_2$, and $k_2 \gg k_1$.

Several kinetic experiments were performed with three objectives in mind: (1) to verify that the rate behavior described by eq 6 applies to the alkylation of the $PBu_3Co(DH)_2$(5-R-tetrazolate) complexes; (2) to deduce the relative magnitudes of k_1 and k_2 for each complex; (3) to acquire enough data to describe the mechanism of the alkylation. The results of these experiments are given in Table I. Experiments IA–F accomplished the first two objectives. These results show that the electronegativity of R in $PBu_3Co(DH)_2$(5-R-tetrazolate) determines the magnitude of k_1. In general, the more electron releasing the R group the faster the reaction, with the reaction rates spanning 2 orders of magnitude.

A Hammett σ–ρ plot of log k vs. σ for the three complexes where R is CH_3, C_6H_5, and CF_3 (experiments IA, IC, and IF) was linear with the slope $\rho = -2.79$. A very similar ρ (−2.96) has previously been observed[9] for the reaction of *N,N*-dimethylaniline with CH_3I. This result suggests[10] that the alkylations of the tetrazolate complexes all proceed via the same mechanism and that the first step is, as expected mechanistically the same as alkylation of a tertiary amine. Only experiments IA, IB, IIA, IVA, IVB, VA, and VB fall into the $k_1 \gg k_2$ category. This condition allows both steps in eq 6 to be analyzed separately. The rate equations are

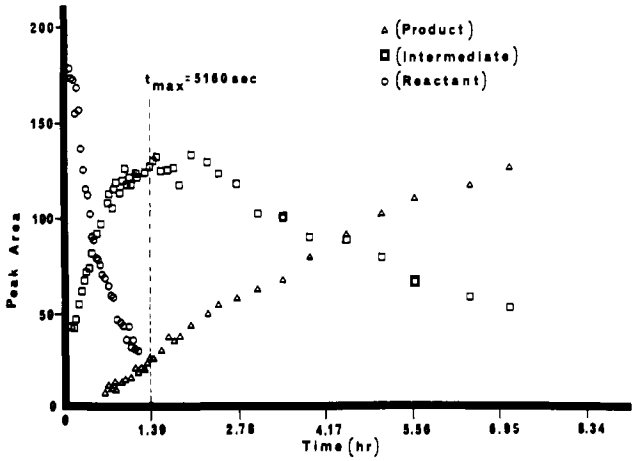

Figure 2. Superimposed plots of concentration vs. time for the alkylation of (P-*n*-Bu_3)$Co(DH)_2$(5-benzyltetrazolate) in $CDCl_3$ at 57 °C.

$$-d[A]/dt = k_1[A] \qquad (7)$$

$$d[C]/dt = k_1[A] - k_2[C] \qquad (8)$$

$$d[D]/dt = k_2[B] \qquad (9)$$

The other extreme $k_2 \gg k_1$ was not encountered in this study. In this case, only the first step would be observed. When $k_2 \gg k_1$, the only method for determining k_2 is through isolation and separate examination of the intermediate. When $k_1 \approx k_2$ the situation is the most complex and the intermediate must be isolable for quantitative results. The complexes analyzed in experiments IC–F fall into this broad category. In experiment IC, $k_1 = k_2$ within experimental error while in experiments ID–F, k_2 is believed to be greater than k_1 but not so great that $k_2 \gg k_1$.

The above conclusions were based on the results of pseudo-first-order kinetic plots. Of all the complexes, (P-*n*-Bu_3)$Co(CH)_2$(5-benzyltetrazolate) was best suited for detailed analysis because the values of k_1 and k_2 could each be determined from either of two kinetic plots. Thus, k_1 could be calculated by following either the disappearance of the reactant's *C*-benzyl or the formation of the intermediates *N*-benzyl signal. Following the decay of the latter signal or the formation of product's *N*-benzyl signal led to k_2. Figure 2 contains superimposed plots of reactant, intermediate, and product

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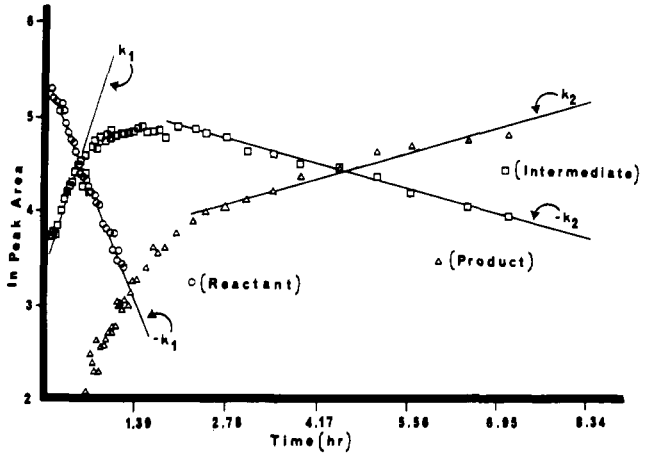

Figure 3. Typical kinetic plots used to determine k_1 and k_2 for the alkylation of (P-*n*-Bu_3Co$(DH)_2$(5-benzyltetrazolate) by benzyl bromide in $CDCl_3$ at 57 °C. These data represent one of the very few reported cases for which it is possible to follow both the formation and disappearance of an intermediate.

concentrations (as NMR peak areas) vs. time for the alkylation of (P-*n*-Bu_3)Co$(DH)_2$(5-benzyltetrazolate) by benzyl bromide in $CDCl_3$. The parameter t_{max} as defined in eq 10 has been

$$t_{max} = [\ln (k_1/k_2)]/(k_1 - k_2) \qquad (10)$$

used to confirm consecutive first-order reaction kinetics.[11] This calculation defines the time at which the concentration of the intermediate reaches its maximum value. Figure 2 shows that the calculated value is very close to the experimental value (i.e., the peak of the intermediate plot). Figure 3 contains typical semilog plots of NMR peak area vs. time which yielded the rate constants used for the calculation of t_{max}. The plots in this figure, should yield identical absolute values for k_1 and k_2, respectively. The difference between the two values of k_1 suggests a realistic error bar of 0.5×10^n, where n is the exponent of the k in question. The values of k_1 and k_2 reported in Table I were derived from plots of the reactant's decay and the product's formation, respectively. The former process is the simplest of the four (Figure 3) and the only one in which all of the data points represent a single rate process. The plot of the time rate of change of the intermediate concentration required separation into two regions. The early stages of the alkylation involved only the k_1 process because it is larger than k_2. Eventually all of the original reactant becomes converted into intermediate, and in the late stages only first-order decay of the intermediate takes place. During the period in between, both k_1 and k_2 contribute, the intermediate is maintained at a steady-rate concentration, and data analysis is complex. Another way to verify that k_1 and k_2 are for first-order processes is to compare the calculated and experimental values of the half-life of each species. For example, the latter value for the reactant complex is simply the time at which its concentration is half of its original value. The calculated value was obtained from $t_{1/2} = 0.693/k$. The observed and calculated half-lives for the processes represented in Figure 3 are

	$t_{1/2}$(calcd), s	$t_{1/2}$(obsd), s
formation of intermediate	1.4×10^3	1.4×10^3
decay of reactant	1.3×10^3	1.5×10^3
formation of product	1.4×10^4	1.4×10^4
decay of intermediate	1.3×10^4	1.3×10^4

In experiments IC–F k_1 and k_2 were too close together to allow separate interpretation by pseudo-first-order kinetic plots. The boundaries of the category $k_1 \approx k_2$ varies with each system. In a similar kinetic study isolation of the intermediate was required to determine the rate of the hydrolysis of Cr(III) complexes where the consecutive rate constants were within a factor of 2–4 of each other.[12] In experiments IC–F no intermediate was observed because its decay was in each case as fast as its formation.

The value estimated for k_2 in experiment IC suggests that this rate constant, in general, is affected by more than simply the electronegativity of the 5-substituent. This consideration together with the results of experiments II–V supported the mechanism described by reaction 3. The first step involves a nucelophilic attack at the methylene carbon of benzyl bromide. This conclusion is supported by a large body of recent work which indicates that solvolysis of benzyl bromide proceeds by a simple S_N2 mechanism.[13] The first transition state, being nearer in free energy to the charge-separated intermediate, should also contain a certain amount of charge separation. This type of transition state is termed "Loose" because it is characterized by longer N–C and C–X bond lengths than one which is purely S_N2.[13] Exchange reactions of the axial base in cobaloximes typically involve loose transition states[14-16] —a result anticipated for soft metal centers. The intermediate consists of the cationic, alkylated tetrazole complex and the anionic halide ion, the latter probably residing between the second and third coordination spheres. The second step consists of a dissociative interchange between the alkylated, coordinated tetrazole and a halide ion in the second coordination sphere. Because the intermediate has a finite lifetime, the cobalt–tetrazole bond gradually weakens and eventually the second transition state, also believed to be loose, is reached.

The rate constants of both steps are affected by a combination of electronic and steric effects but respond in different ways. As the electron density in the tetrazole ring increases, the first transition state is reached more quickly, and k_1 increases while the second transition state is reached more slowly, causing k_2 to decrease. As the steric interactions between the 1- and 5-substituents increases, k_1 decreases and k_2 increases. The contrasting effects described above are not inconsistent if one remembers that k_1 represents a process with an associative transition state but k_2 represents as interchange process.

In experiment II, the effect of the leaving group X^- of the alkyl halide is seen. Chloride is inferior to bromide as a leaving group[17] and causes a significant reduction of k_1 (compare experiments IIA and IIB with IB and IC). In fact, no intermediate was seen in the alkylations using benzyl chloride. Chloride should also be a poorer entering group in the interchange step because it is harder than bromide.

The results of experiment III indicate an increase in k_1 upon switching from chloroform to the more polar, better dielectric nitrobenzene. This is evidence supporting the formation of a charge-separated intermediate from neutral reactants.[18] The value of k_2 is practically the same as the corresponding value in $CDCl_3$. If the halide ion were completely free of the complex, k_2 would also have increased in nitrobenzene because this solvent facilitates the mobility of charged species and, consequently, should increase the rate at which transition state 2 is reached.

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Use of CH_3I as the alkylating agent instead of $C_6H_5CH_2Br$ increased k_2 for all three complexes in experiment IV. for (P-*n*-Bu_3)Co(DH)$_2$(5-phenyltetrazolate), k_1 also increased. Nonlinear data for the latter complex again preempted determination of k_2, but a short-lived intermediate was observed in the ^{1}H NMR spectrum. The increase of k_1 in experiment IVC relative to that in IC is a steric effect.[19] The increase in k_2 values reflects the superiority of the soft iodide ion as an entering group.

Experiments VA, VB, and IB yielded the activation parameters

	k_1	k_2
$\Delta H^{\ddagger}$, kcal/mol	13.5	20.3
$\Delta S^{\ddagger}$, eu	−30.4	−12.0

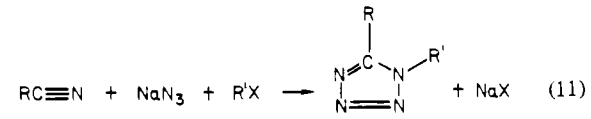
which suggested the nature of transition states 1 and 2. The activation parameters based on k_1 reflect the associative nature of this process. The values for k_2 are interesting because $\Delta H^{\ddagger}$ is typical of a dissociative process, but $\Delta S^{\ddagger}$ is not the zero or slightly positive value expected for a purely dissociative process.[20] Dissociative interchange involving an iodide ion which has migrated a short distance from the third to the second coordination sphere is consistent with these values. These activation parameters should be compared to those obtained[21] for the reaction of dimethyl sulfate with potassium 5-phenyltetrazolate: $\Delta H^{\ddagger}$ = 12.1 kcal/mol; $\Delta S^{\ddagger}$ = −18.0 eu.

Alkylation of PBu$_3$Co(DH)$_2$[5-N(CH$_3$)$_2$-tetrazolate]. This complex was not suitable for alkylation kinetic studies because of overlapping signals in the ^{1}H NMR spectrum. But the sequence of changes that occurred in the spectrum during benzylation could be explained by an additional and new process involving alkylation of the exocyclic nitrogen[3e] (producing a coordinated "ylide") at a rate sufficiently greater than alkylation of the usual N-4 endocyclic site to allow detection of the intermediate PBu$_3$Co(DH)$_2$(5-N(CH$_3$)$_2$-1-Bzltet)$^+$Br$^-$. Apparently the benzyl group then migrates to the N-4 site of the tetrazole ring and forms the usual N-3-coordinated 1,5-disubstituted tetrazole intermediate. The rate of the migration was also sufficiently fast compared to the subsequent interchange step to detect the latter intermediate. Finally, the disubstituted tetrazole was cleaved from the complex as the pure 1,5-isomer without any remaining trace of exocyclic alkylation. The overall process appears to involve three consecutive pseudo-first-order reactions such that $k_1 \gg k_2 \gg k_3$. Over 3 months were required for these three steps in $CDCl_3$ compared to about 2 months in nitrobenzene, even though the concentration of the complex in the latter solvent was much smaller. The rate increase in nitrobenzene agrees with the proposed mechanism described above. despite the faster overall rate, evidence of the second intermediate was not seen in nitrobenzene. This result requires the interchange to have a greater rate constant than the migration. Because this type of migration occurs completely within the first coordination sphere, it is impaired by any dipole–dipole interactions between solvent molecules and the tetrazole ring.[14,15,22] The interchange, on the other hand, should increase in rate as the solvent increases in polarity.[23]

Alkylation of (P-*n*-Bu_3)Co(DH)$_2$[5-N(CH$_3$)$_2$-tetrazolate] with CH_3I was more difficult to follow in detail because of the many different methyl signals observed in the ^{1}H NMR spectrum as the reaction progressed. The overall rates were much faster, in both $CDCl_3$ and nitrobenzene, than those observed when benzyl bromide was used, probably due to a favorable steric effect in both of the first two steps.

Conclusions

The ultimate goal of this research is to find a catalytic system for reaction 11, regiospecific synthesis of 1,5-disubstituted tetrazoles. The data reported herein suggest that this goal is potentially attainable. It has previously been widely shown that nitriles undergo 1,3-dipolar cycloadditions with both the azide ion and transition-metal azides to form tetrazoles. Tetrazole anions are good ligands for a variety of transition metals, but neutral disubstituted tetrazoles are much poorer ligands. Sterically induced regiospecific coordination of tetrazolate anions does lead to regiospecific alkylation of the coordination tetrazolate. This work demonstrates that the mechanisms and rates of alkylation of free tetrazolate anions and coordinated tetrazoles are similar. Thus we are now much closer to realizing our goals. What remains to be done, is to find a transition-metal center which sufficiently activates the azide ion toward 1,3-dipolar cycloadditions to increase the rate of this reaction while being sterically encumbered enough to promote specific coordination of the tetrazole at the N-2 nitrogen. There is an additional requirement that this transition-metal center must meet. Its physical properties must differ sufficiently from those of 1,5-disubstituted tetrazoles to allow for their facile separation. We are currently investigating other systems in search of some which meet these requirements.



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Registry No. PBu$_3$Co(DH)$_2$(5-CH$_3$tet), 74305-27-4; PBu$_3$Co(DH)$_2$(5-CH$_2$C$_6$H$_5$tet), 74305-29-6; PBu$_3$Co(DH)$_2$(5-C$_6$H$_5$tet), 74305-28-5; PBu$_3$Co(DH)$_2$(5-(4-FC$_6$H$_4$)tet), 74305-31-0; PBu$_3$Co(DH)$_2$(5-(3-FC$_6$H$_4$)tet), 74305-32-1; PBu$_3$Co(DH)$_2$(5-CF$_3$tet), 74305-26-3; PBu$_3$Co(DH)$_2$(5-N(CH$_3$)$_2$tet), 74305-30-9; C$_6$H$_5$CH$_2$Br, 100-39-0; C$_6$H$_5$CH$_2$Cl, 100-44-7; CH$_3$I, 74-88-4; 1-CH$_3$-5-(4-FC$_6$H$_4$)-tetrazole, 74308-40-0; 1-CH$_3$-5-C$_6$H$_5$-tetrazole, 20743-50-4; 1-CH$_2$C$_6$H$_5$-5-N(CH$_3$)$_2$-tetrazole, 24301-98-2; 2,5-H$_2$-tetrazole, 288-94-8; 2,5-(CH$_3$)$_2$-tetrazole, 4135-93-7; 2-H-5-(CH$_3$)$_2$N-tetrazole, 5422-45-7.

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