Inversion at Carbon in the Cleavage of Cobalt–Carbon Bonds by Mercuric Ion[1]

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Abstract: Deuterium-decoupled proton nmr measurements were used to establish the stereochemical course of (a) the conversion of *threo*-$(CH_3)_3CCHDCHDOH$ to *erythro*-$(CH_3)_3CCHDCHDCo(dmgH)_2py$ by reaction of the *threo*-*p*-bromobenzenesulfonate derivative with $Co^I(dmgH)_2^-$ and (b) the conversion of the alkylcobaloxime to *threo*-$(CH_3)_3CCHDCHDHgCl$ ($k = 1.9 \times 10^{-3}\ M^{-1}\ sec^{-1}$). Both reactions proceed with inversion of configuration at the α-carbon atom.

Several kinetic studies of the dealkylation of alkylcobalamins and alkylcobaloximes[2] by reaction with Hg(II) salts under different conditions were reported nearly simultaneously (eq 1).[3-7] The different authors

$$RCo(dmgH)_2H_2O + Hg(II) \longrightarrow RHg^+ + (H_2O)_2Co(dmgH)_2^+ \quad (1)$$

offered consistent mechanistic descriptions of this as a bimolecular electrophilic substitution process (SE2 mechanism).

The question of the accompanying stereochemistry—whether cleavage occurs with retention or inversion of configuration at the α-carbon atom—was approached with diverse results by the groups involved in the rate measurements[4,5] and by others[8-10] who later commented upon the kinetic data. Stereochemical inferences drawn from kinetic data concerning relatively unknown reaction systems in which the structures differ markedly from the comparison reactions may stand roughly a 50–50 chance of being correct; these matters will be considered in the Discussion.

As complete a description as possible of the mechanism of reaction 1 is clearly of interest, including the direct determination of its stereochemical course. This is so particularly because this reaction has been implicated in the methylation of mercury in natural waters.[11] As far as is known, all secondary alkyl centers show essentially zero reactivity toward Hg(II), prohibiting the use of asymmetric cobaloximes such as the 2-octyl or *sec*-butyl. Consequently, we have determined the stereochemistry of the reaction between *erythro*-3,3-dimethylbutyl-*1,2-d*$_2$-pyridinatobis(dimethylglyoximato)cobalt(III) (**2**) and mercuric ion in aqueous perchloric acid. The use of this particular primary alkyl substituent in stereochemical determinations was pioneered by Whitesides and coworkers.[12] The procedure relies upon the distinctly different ranges of coupling constants[12a] between vicinal hydrogen atoms in the threo and erythro diastereomers of the molecules $(CH_3)_3CCHDCHDX$, permitting a direct and unambiguous assignment of stereochemistry.

Methods and Results

The rate law for reaction 1 in aqueous perchloric acid solution is given by[4,7]

$$d[HgR^+]/dt = k[RCo(dmgH)_2H_2O][Hg^{2+}] \quad (2)$$

The reaction of the 3,3-dimethylbutyl derivative follows the same equation with $k = 1.9 \times 10^{-3}\ M^{-1}\ sec^{-1}$ at 25°. The alkylmercuric ion product was isolated in nearly quantitative yield from a 1:1 reaction solution by addition of chloride at the end of the reaction. The nmr spectra of the product and of authentic $(CH_3)_3CCH_2CH_2HgCl$ were identical.

Compounds having the general formula $(CH_3)_3CCHDCHDX$ exist as threo and erythro diastereomers, the former shown with R = H (**1a**) and the latter with X = $Co(dmgH)_2H_2O$ (**2**). The coupling constant J_{AB} between vicinal hydrogen atoms can be evaluated from the deuterium-decoupled pnmr spectra.[11] The bulk of the *tert*-butyl and X groups favors the trans conformation over the gauche, leading to different ranges of J_{AB} = 5–7 Hz for the threo form and 11–14 Hz for the erythro.[12]

The preparation[12a,d] of *threo*-**1a** was accomplished in nearly pure form,[13] asymmetry being introduced by

(1) Work performed in the Ames Laboratory with support from the National Science Foundation through Grant No. GP-33258.

(2) Cobaloxime is the trivial name given to bis(dimethylglyoximato)-cobalt compounds.

(3) (a) H. A. O. Hill, J. M. Pratt, S. Risdale, F. R. Williams, and R. J. P. Williams, *Chem. Commun.*, 341 (1970); (b) G. Agnes, S. Bendle, H. A. O. Hill, F. R. Williams, and R. J. P. Williams, *ibid.*, 850 (1971); (c) R. E. DiSimone, M. W. Penley, L. Charbonneau, S. G. Smith, J. M. Wood, H. A. O. Hill, J. M. Pratt, S. Risdale, and R. J. P. Williams, *Biochim. Biophys. Acta*, **304**, 851 (1973).

(4) A. Adin and J. H. Espenson, *Chem. Commun.*, 653 (1971).

(5) G. N. Schrauzer, J. H. Weber, T. M. Beckham, and R. K. Y. Ho, *Tetrahedron Lett.*, 275 (1971).

(6) (a) J.-Y. Kim, J. Imura, T. Ukita, and T. Kwan, *Bull. Chem. Soc. Jap.*, **44**, 300 (1971); (b) N. Imura, E. Sukegawa, S.-K. Pan, K. Nagao, J.-Y. Kim, T. Kwan, and T. Ukita, *Science*, **172**, 1248 (1971).

(7) P. Abley, E. R. Dockal, and J. Halpern, *J. Amer. Chem. Soc.*, **95**, 3166 (1973).

(8) F. R. Jensen, V. Madan, and D. H. Buchanan, *J. Amer. Chem. Soc.*, **93**, 5283 (1971).

(9) J. Lewis, R. H. Prince, and D. A. Stotter, *J. Inorg. Nucl. Chem.*, **35**, 341 (1973).

(10) M. H. Abraham and P. L. Grellier, *J. Chem. Soc. Perkin Trans. 2*, 1132 (1973).

(11) (a) J. M. Wood, F. S. Kennedy, and C. G. Rosen, *Nature (London)*, **220**, 173 (1968); (b) S. Jensen and A. Jernelov, *ibid.*, **223**, 753 (1969); (c) A. Kivimae, A. Swensson, U. Ulfvarson, and G. Westoo, *J. Agr. Food Chem.*, **17**, 1014 (1969).

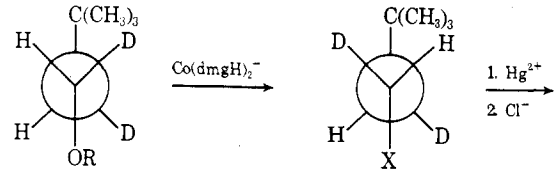
(12) (a) G. M. Whitesides, J. P. Sevenair, and R. W. Goetz, *J. Amer. Chem. Soc.*, **89**, 1135 (1967); (b) G. M. Whitesides and D. J. Boschetto, *ibid.*, **91**, 4313 (1969); (c) *ibid.*, **93**, 1529 (1971); (d) P. L. Bock and G. M. Whitesides, *J. Amer. Chem. Soc.*, submitted for publication.

(13) The compounds are free of the other diastereomer to within an estimated detection limit of *ca.* 10%; they do contain mono- and trideuterated isotopic impurities (identified by mass spectroscopy), presumably from isotopic scrambling on the palladium catalyst used in the deuteration step. These compounds do not exist as diastereomers, however, and their weaker nmr signals, which do not change in pattern upon reaction, offer no interference to the assignment of chemical shifts and coupling constants to the *1,2-d*$_2$ compounds.

cis-addition reaction of *trans*-$(CH_3)_3CH{=}CHOAc$ with D_2 over a palladium on charcoal catalyst. The product contains, in addition to the desired **1a**, certain non-diastereomeric products which do not interfere.

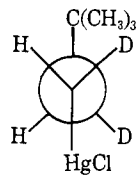
The deuterium-decoupled pnmr spectrum[14] of alcohol **1a** shows the expected two doublets with J_{AB} = 5.8 Hz, in agreement with the reported value.[13,15] Alcohol **1a** is converted to the *p*-bromobenzenesulfonate **1b** without cleavage of any bond to carbon; the latter upon reaction with $Co^I(dmgH)_2^-$ yields $(CH_3)_3CCHDCHDCo(dmgH)_2py$ (**2**) (see Scheme I). Since the primary

Scheme I



threo
1a, R = H
b, R = *p*-$SO_2C_6H_4Br$

erythro
(**2**)
X = $Co(dmgH)_2py$



threo
(**3**)

concern was chiral purity, yield was not of major importance; **2** was isolated in 20% yield based on Co(I). The downfield doublet has a coupling constant between vicinal protons of 13.2 Hz, but the upfield doublet is unfortunately obscured by the coincidental resonance of the *tert*-butyl group. The value of 13.2 Hz strongly suggests **2** is the erythro structure, considering the values for virtually every other X group.[12a] Moreover, as discussed below, independent evidence that the reaction in question (**1b** to **2**) proceeds with inversion of configuration has been obtained.

The reaction of the erythro cobaloxime **2** afforded the mercurichloride (**3**)—isolated in this instance in 30% yield—whose coupling constant was determined to be 5.3 Hz (>90% threo[13]) which agrees exactly with that reported earlier for the threo diastereomer by Whitesides and coworkers.[12a,b]

Discussion

The diastereomeric cobaloxime **2** was synthesized under conditions minimizing possible racemization, adding the Co(I) slowly to an excess of the asymmetric brosylate (**1b**). This reduces the opportunity for the following alkyl exchange[8,16–18]

$$R(Co^{III})H_2O + (*Co^I)^- \rightleftharpoons (Co^I)^- + R(*Co^{III})H_2O \quad (3)$$

which is an SN2 process accompanied by inversion and claimed to be responsible for the slow decrease in optical activity of *sec*-butylcobaloxime in the presence of $(Co^I)^-$.

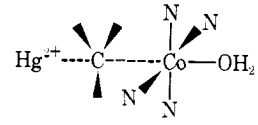
As prepared from **1b**, the cobaloxime **2** was >90% of the erythro diastereomer,[13] affirming the earlier assignment of an SN2 inversion mechanism to reaction 4 for

$$RX + Co^I(dmgH)_2^- \longrightarrow RCo(dmgH)_2 + X^- \quad (4)$$

X = *p*-bromobenzenesulfonate. Three lines of evidence had previously been advanced: (a) kinetic data[19] for reaction 4, mostly for X = halide, especially the order of reactivity of different R groups, (b) the conversion of *cis*-1,4-dibromocyclohexane to *trans*-(4-bromocyclohexyl)cobaloxime (and *vice versa*),[20] and (c) the formation of (+)-2-octylcobaloxime from (−)-2-octyl bromide and (Co^I).[17] The two stereochemical studies strongly suggest inversion, and little reason exists to doubt the assignment, but it is not completely unique in that (b) might be attributed to some special but unspecified feature of the cyclohexyl system leading to preferential inversion atypical of other alkyls and (c) relies upon the assumption of an unambiguous relation between the sign of $[\alpha]D$ and absolute configuration.

The present work is, we believe, based only upon the assumption that, in the class of compounds *threo*- and *erythro*-$(CH_3)_3CCHDCHDX$, the previously unknown member, X = $Co(dmgH)_2py$, has coupling constants lying within the ranges noted for virtually every other X group.[12] Furthermore, the stereochemistry determined by use of a primary alkyl is more reasonably taken to be applicable to the simpler alkyls.

The major stereochemical result to which we wish to call attention concerns reaction 1. The starting alcohol (**1a**), the brosylate (**1b**) prepared therefrom without breaking any bond at carbon, and the final mercurichloride (**3**) are shown quite unambiguously to be the threo diastereomers (Scheme I). The immediate conclusion is that the two sequential reactions either both occur with retention of configuration at carbon or both occur with inversion. As discussed in the preceding paragraphs the assignment of the erythro structure to cobaloxime **2** seems so certain as to be hardly a point of contention. Consequently the assignment of reaction 1 as proceeding with inversion seems a virtually certain one. We propose a transition state such as



which is termed an "open" arrangement describing the SE2 inversion process.[21–23]

As far as we are aware, this is the first example of an electrophilic metal–alkyl cleavage reaction of Hg(II) proceeding with inversion; numerous examples of

(14) The deuterium decoupled nmr spectra could not be determined using equipment available at Iowa State University. We are grateful to the Department of Chemistry of the University of Nebraska for access to their instrumentation and to Dr. D. Thoennes for his assistance.

(15) The isotopic impurities give rise to peaks of lower intensity, including an easily recognized three-line pattern between the peaks of the low field doublet. This remains the same for all compounds (**1a**, **2**, **3**), and in any event the high-field doublet is essentially unaffected by these isotopic compounds.

(16) D. Dodd and M. D. Johnson, *Chem. Commun.*, 571, 1371 (1971).

(17) While reaction 3 is reasonably rapid for R = CH_3 and C_2H_5, it is quite slow ($t_{1/2}$ > 10 hr) for *sec*-butyl and 2-octyl,[18] and presumably much slower still for the more sterically hindered neohexyl.

(18) D. Dodd and M. D. Johnson, *Chem. Commun.*, 1371 (1971).

(19) G. N. Schrauzer and E. A. Deutsch, *J. Amer. Chem. Soc.*, **91**, 3741 (1969).

(20) F. R. Jensen, V. Madan, and D. H. Buchanan, *J. Amer. Chem. Soc.*, **92**, 1414 (1970).

(21) M. Gielen, *Accounts Chem. Res.*, **6**, 198 (1973).

(22) F. R. Jensen and B. Rickborn, "Electrophilic Substitution of Organomercurials," McGraw Hill, New York, N. Y., 1968.

(23) D. S. Matteson, *Organometal. Chem. Rev., Sect. A*, **4**, 263 (1969).

Table I. Relative Rates of Dealkylation of Cobaloximes by Hg(II) and of Comparison Reactions of Known Stereochemistry

R	Hg^{2+} + R(Co)H_2O[a] (inversion)[b]	$Hg(OAc)_2$ + R(Co)B[c]	$RSn(CH_2C(CH_3)_3)_3$ + Br_2[d] (inversion)[d]	HCl + HgR_2[e] (retention)[f]
$-CH_3$	1.0	1.0	1.0	1.0
$-C_2H_5$	1.9×10^{-3}	1.2×10^{-2}	1.4×10^{-1}	5.95
$-n-C_3H_7$	1.4×10^{-3}	1.1×10^{-2}	4.1×10^{-3}	3.2
$-i-C_3H_7$	$<10^{-8}$	$<10^{-5}$	7.5×10^{-3}	3.5
$-CH_2CH(CH_3)_2$	5.5×10^{-3}	3.1×10^{-3}		
$-CH_2C(CH_3)_3$	1.4×10^{-4} [g]	2.1×10^{-3}	5.8×10^{-4} [h]	*i*
$-CH_2CH_2CH(CH_3)_2$		8.9×10^{-3}		
$-CH_2CH_2C(CH_3)_3$	2.9×10^{-5} [b]			

[a] From ref 4, except as noted; values at 25.0° in $HClO_4$–$LiClO_4$ solutions of μ = 1.0 *M*, relative to k_{Me} = 65 M^{-1} sec^{-1}. [b] This work. [c] From ref 5; values at 26° in 0.1 *M* NaOAc–HOAc buffer with [$Hg(OAc)_2$] = 1.0 *M*, relative to $k_{Me} = 6.6 \times 10^{-2}$ M^{-1} sec^{-1}. The cobaloxime is added with pyridine as the axial base, which is likely replaced by H_2O or OAc^- shortly after dissolution in water. [d] From ref 26; values at 45.0° in CH_3OH containing 0.366 *M* NaBr, relative to k_{Me} = 16.6 M^{-1} sec^{-1}. [e] From R. E. Dessy and J. Y. Kim, *J. Amer. Chem. Soc.*, **83**, 1167 (1961); in DMSO at 25°. [f] From L. H. Gale, J. Landgrebe, and F. R. Jensen, *Chem. Ind. (London)*, 118 (1960), stereochemistry in dioxane. [g] We thank Dr. J. S. Shveima for this result. The determination was carried out with 0.07 *M* H^+ (at μ = 1.0 *M*, 25°); the second-order rate constant was 7.3×10^{-3} M^{-1} sec^{-1}, which was corrected[4] using an estimated K_B = 4 M^{-1}. [h] Corrected for a statistical factor of 4. [i] The value was not determined for neopentyl but in other SE2 retention processes neopentyl cleaves at a rate comparable to other alkyl groups (ref 26 and E. D. Hughes and H. C. Vogler, *J. Chem. Soc.*, 2359 (1961)).

Hg(II)–alkyl cleavage reactions proceeding with retention can be cited, including, for example, its reactions with HgR_2,[22,23] HgRX,[22,23] and $RFe(C_5H_5)(CO)_2$.[12c] The factors contributing to this unprecedented departure may be the sterically hindered macrocyclic ligand of the cobaloxime preventing a sufficiently close approach of Hg^{2+} to the alkyl and the inability of the Hg^{2+} to coordinate with the organometallic group, which favors the electrophilic inversion pathway.[8] The previous examples of SE2 retention reactions all related to substrates which appear much less sterically hindered.

Since completion of this work, Tada and Ogawa[24] have also demonstrated inversion of configuration for the same cleavage by conversion of *trans*-4-*tert*-butylcyclohexylcobaloxime to *cis*-4-*tert*-butylcyclohexylmercuric chloride.[25]

Finally we raise a question with which we started. How reliably may stereochemistry be inferred from rate comparisons? Table I summarizes the rate constants for reaction 1 under two different conditions. In addition, following Jensen and Davis,[26] values are cited for two SE2 comparison reactions having reliably established stereochemistry. The pattern shown by reaction 1 agrees well with neither standard.

Schrauzer, *et al.*,[5] originally asserted from the kinetic determinations in acetate medium that reaction 1 occurred with inversion, whereas we had suggested[4] a retention process noting the relatively large rate effect of α substitution and a negligible effect of β substitution. Jensen, *et al.*,[8,27] criticized Schrauzer's assertion. Lewis, Prince, and Stotter,[9] on the other hand, asserted that Jensen's reference for this criticism does not clearly show that Schrauzer's data are inconsistent with an inversion process. Abraham and Grellier[10] have also used kinetic comparisons with reactions of known stereochemistry to conclude from the published rate data[4,5] that the cleavage of alkylcobaloximes by $Hg(OAc)_2$[4] and Hg^{2+} [5] proceeds by retention of configuration. This again is now shown to be erroneous.

The most telling features of reaction 1 appear to be (a) the failure of secondary alkyls to undergo electrophilic cleavage with Hg(II) in spite of their ready homolytic cleavage in photochemical processes[28] and in spite of the reactivity of other isopropyl–metal bonds to undergo SE2 cleavage, both retention and inversion (see Table I), and (b) the inversion of stereochemistry at carbon. Both aspects may arise from the steric bulk of the macrocyclic ligand, but further work is needed to establish this point.

Whether the same inversion process is also applicable to the reaction of alkylcobalamins with Hg(II) cannot be stated with certainty. Considering the similarities[29] between cobalamins and cobaloximes, however, inversion is a natural inference.

Experimental Section

Absorption spectra were determined using a Cary 14 recording spectrophotometer, which was also used for the rate determinations which were made at the 453-nm peak of the cobaloxime. Nuclear magnetic resonance spectra at 60 MHz were determined using a Perkin-Elmer R-20B spectrometer in deuteriochloroform with chemical shifts relative to TMS. The deuterium-decoupled spectra were measured in $CDCl_3$ using a Varian XL-100 spectrometer at the University of Nebraska, Lincoln.[14] The deuterium nuclei were decoupled from the protons using a 300-Hz broad band decoupling technique.

(24) M. Tada and H. Ogawa, *Tetrahedron Lett.*, 2639 (1973).

(25) Tada and Ogawa[24] also used a second reaction, that of *cis*-2-hydroxylcyclohexylcobaloxime with mercuric acetate. G. N. Schrauzer (private communication) pointed out that the latter may not constitute a reliable demonstration, however, since the 2-hydroxylalkyl compound is unstable with respect to cyclohexene formation under the reaction conditions: G. N. Schrauzer and R. J. Windgassen, *J. Amer. Chem. Soc.*, **89**, 143 (1967).

(26) F. R. Jensen and D. D. Davis, *J. Amer. Chem. Soc.*, **93**, 4048 (1971).

(27) They noted that not only did the rate data in ref 5 not follow the expected pattern for an SE2 inversion process but that "all cleavages of carbon–metal bonds by mercuric ion whose stereochemistry is known proceed by retention of configuration."[8]

(28) G. N. Schrauzer, L. P. Lee, and J. W. Sibert, *J. Amer. Chem. Soc.*, **92**, 2997 (1970).

(29) Two important differences in the reaction of Hg(II) toward RCo(dmgH)$_2$ and RCo(corrin) should be noted, however. (1) Secondary alkylcobaloximes are completely unreactive toward Hg(II), whereas the *sec*-alkylcobalamins do undergo slow cleavage. The experiments necessary to verify that the reaction of (say) isopropylcobalamin with Hg(II) follows a second-order kinetic expression (which are necessary to rule out that the rate step is the spontaneous dissociation of R–Co) do not appear to have been done. (2) The reactivity of $MeHg^+$ toward methylcobalamin[3] but its failure to react with methylcobaloxime is noted.[4,7] D. Dodd and M. D. Johnson, *Organometal. Chem. Rev.*, **52**, 77 (1973), have suggested that the formation of $Hg(CH_3)_2$ may be the symmetrization reaction of $HgCH_3^+$ rather than its electrophilic reaction with methylcobalamin.

3,3-Dimethylbutan-1-ol[30] was prepared by hydroboration of 3,3-dimethylbut-1-ene, product bp 138–140° (lit.[31] bp 141–143°).

3,3-Dimethylbutyl *p*-bromobenzenesulfonate (4)[12a] was prepared from 3,3-dimethylbutan-1-ol and *p*-bromobenzenesulfonyl chloride. The nmr spectrum is consistent with that expected for this compound.

3,3-Dimethylbutyl(pyridine)bis(dimethylglyoximato)cobalt(III) was prepared by reaction of **4** with $Co(dmgH)_2^-$ under a nitrogen atmosphere.[32] The product was washed with ether to remove unreacted **4** and recrystallized from methanol by addition of an equal volume of a 1% solution of pyridine in water: pnmr spectrum δ 0.75 (s, 9, $C(CH_3)_3$), 0.78 (m, 2, CH_2-2),[33] 1.63 (m, 2, CH_2-1),[20] 2.14 (s, 12, CH_3-dmgH), 7.20, 7.70, 8.58 (m, 5, pyridine); uv-visible spectrum in $HClO_4$ (aq), 453 nm (ϵ 1.47×10^3 M^{-1} cm^{-1}), 387 (1.66×10^3).

Anal. Calcd for $C_{19}H_{33}N_5O_5Co$: Co, 13.0. Found: Co, 12.8.

3,3-Dimethylbutyl chloride[34] was prepared from *tert*-butyl chloride and ethylene using $AlCl_3$ catalyst, product bp 115–118° (lit.[34] bp 115–122°).

3,3-Dimethylbutylmercuric chloride was prepared by the reaction of mercuric chloride and 3,3-dimethylbutylmagnesium chloride in ether, product mp 133° (lit.[35] mp 133–133.5°).

threo-**3,3-Dimethylbutan-1-ol-*1,2-d*$_2$ (1a)** was prepared by the methods of Whitesides, *et al.*,[12] product bp 138–140° (lit.[31] 141–143°); deuterium-decoupled pnmr spectrum (in $CDCl_3$)[15] δ 0.92 (s, 9, $C(CH_3)_3$), 1.48 (d, J = 5.8 Hz, 1, CHD-2),[36] 3.66 (d, J = 5.8 Hz, 1, CHD-1),[36] 1.67 (s, 1, OH). This compound was converted to the *threo*-*p*-bromobenzenesulfonate (**1b**) on a 20 mmol scale analogous to the preparation of the undeuterated compound.

erythro-**3,3-Dimethylbutyl-*1,2-d*$_2$-(pyridine)bis(dimethylglyoximato)cobalt(III) (2)** was prepared by adding 20 mmol of $Co(dmgH)_2^-$ [32] in methanol to a methanol solution of 20 mmol of **1b** over a period of 30 min. Excess $NaBH_4$ in the $Co(dmgH)_2^-$ solution was destroyed with acetone to avoid reduction of **3** which might lead to racemization *via* eq 3; the isolated yield was 20%: deuterium-decoupled pnmr spectrum (in $CDCl_3$)[15] δ 0.75 (s, 9, $C(CH_3)_3$), 0.78 (d, 2, CHD-2, partially obscured by large singlet at 0.75), 1.63 (d, J = 13.2 Hz, 1, CHD-1).[37]

threo-**3,3-Dimethylbutyl-*1,2-d*$_2$-mercuric chloride (4)** was prepared by the reaction of **2** (0.56 mmol) in 250 ml of 0.20 *F* aqueous $HClO_4$ with $Hg(ClO_4)_2$ (0.56 ml of 1.0 *M* aqueous solution) at 75° with the exclusion of light. The reaction progress was monitored spectrophotometrically, and after 17 hr (80% completion) the solution was cooled to room temperature. Sodium chloride (1.12 mmol) was added to precipitate **3**, which was filtered and recrystallized from hot 95% ethanol, yield 30 mg of **3** (30%): Deuterium-decoupled pnmr spectrum (in $CDCl_3$)[15] δ 0.92 (s, 9, $C(CH_3)_3$), 1.58 (d, J = 5.3 Hz, 1, CHD-1),[38] 1.91 (d, J = 5.3 Hz, 1, CHD-2).[3]

Acknowledgment. We are grateful to Professor G. M. Whitesides for the synthetic procedures and to the University of Nebraska and Dr. D. Thoennes for the deuterium-decoupled nmr spectral measurements.

(30) G. Zweifel and H. C. Brown, *Org. React.*, **13**, 1 (1963). We are grateful to Dr. R. C. Larock for suggesting this synthesis and for advice in carrying it out.

(31) R. C. Houston and A. H. Agett, *J. Org. Chem.*, **6**, 123 (1941).

(32) G. N. Schrauzer, *Inorg. Syn.*, **11**, 65 (1968).

(33) The multiplets at δ 0.78 and 1.70 ppm are the upfield and downfield parts of an A_2B_2 pattern; the pertinent nmr parameters are discussed in the body of the paper.

(34) A. Brandstrom, *Acta Chem. Scand.*, **13**, 611 (1959).

(35) F. C. Whitmore and H. Bernstein, *J. Amer. Chem. Soc.*, **60**, 2626 (1938).

(36) The resonance at δ 3.67 also contains four smaller extraneous peaks throught to arise from the alcohol with partial deuterium scrambling; see Discussion Section. The doublet at δ 1.49 shows several smaller peaks also due to improperly deuterated molecules.

(37) The resonance at δ 1.63 also contains four smaller extraneous peaks from partial deuterium scrambling.[15]

(38) The resonance at δ 1.58 also contains four smaller extraneous peaks thought to arise from partial deuterium scrambling; see Discussion Section.

Thermochemistry of Azoalkanes

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Abstract: The following enthalpies of formation (ΔH_f, kcal mol^{-1}) of five gaseous azoalkanes at 25° are calculated from the measured heats of combustion and vaporization: azoisopropane (**1**), 8.6; azo-*n*-propane (**2**), 12.4; azo-*tert*-butane (**3**), −10.4; 2,3-diazabicyclo[2.2.1]heptene-2 (**4**), 46.8; 1,4-dimethyl-2,3-diazabicyclo[2.2.2]octene-2 (**5**), 21.6. If the carbons α to the azo nitrogens are treated as aliphatic carbons, the revised thermochemical trans azo group contribution is 52.3 kcal mol^{-1}. Consideration of the difference between trans and cis azoalkanes allows calculation of upper limits on the ring strain energy of **4** and **5** of 11.3 and 6.4 kcal mol^{-1}, respectively. The values of ΔH_f are related to the activation energy of azoalkane thermolysis and are used to calculate that this process is less exothermic than previously estimated.

In recent years, there has been a great renewal[2] of interest in azoalkanes as sources of free radicals,[4] for synthesis of strained ring systems,[5] for study of orbital symmetry[6] and spin correlation effects,[7] and for testing unimolecular reaction theory.[8] Moreover, the study of thermal[9] and photochemical decomposition[10] of azo compounds has become an active area of research.

Understanding the reactivity of azoalkanes would be greatly facilitated by a knowledge of their thermochem-

(1) On leave from David Lipscomb College, Nashville, Tenn.

(2) Early work on the gas-phase thermolysis of azoalkanes is cited in ref 3.

(3) R. Rebbert and P. Ausloos, *J. Amer. Chem. Soc.*, **87**, 1847 (1965).

(4) W. A. Pryor, "Free Radicals," McGraw-Hill, New York, N. Y., 1966, p 129.

(5) (a) H. Tanida, S. Teratake, Y. Hata, and M. Watanabe, *Tetrahedron Lett.*, 5341 (1969); (b) R. Criegee, *Ber.*, **90**, 414 (1957); (c) G. L. Closs, L. Kaplan, and V. I. Bendall, *J. Amer. Chem. Soc.*, **89**, 3376 (1967).

(6) W. Roth, *Justus Liebigs Ann. Chem.*, **702**, 1 (1967); J. A. Berson and S. S. Olin, *J. Amer. Chem. Soc.*, **91**, 777 (1969); N. Rieber, J. Alberts, J. A. Lipsky, and D. M. Lemal, *ibid.*, **91**, 5668 (1969).

(7) P. S. Engel and P. D. Bartlett, *J. Amer. Chem. Soc.*, **92**, 5883 (1970).

(8) S. S. Collier, D. H. Slater, and J. G. Calvert, *Photochem. Photobiol.*, **7**, 737 (1967); T. F. Thomas, C. I. Sutin, and C. Steel, *J. Amer. Chem. Soc.*, **89**, 5107 (1967).

(9) R. J. Crawford and K. Takagi, *J. Amer. Chem. Soc.*, **94**, 7406 (1972); J. Hinz, A. Oberlinner, and C. Rüchardt, *Tetrahedron Lett.*, 1975 (1973).

(10) For a recent review, see P. S. Engel and C. Steel, *Accounts Chem. Res.*, **8**, 275 (1973).