is in accord with our previous studies of the influence of polar substituents on the stereoselectivity of oxazine formation.\textsuperscript{7} Selected destilation provided the corresponding alcohols, 5\textsuperscript{x} and 5\textsuperscript{n}, which were readily separable by chromatography on silica gel (31 and 1% yields, respectively, from 3). Further derivatization of the alcohols, without disruption of the oxazine, proved to be relatively simple. Thus, the major epimeric (exo) alcohol, 5\textsuperscript{x} was converted to the crystalline p-nitrobenzoate; X-ray diffraction fully confirmed the assigned structure and stereochemistry.\textsuperscript{8}

To initiate rearrangement, a better leaving group was required.\textsuperscript{10} Thus, 5\textsuperscript{n} was converted to the sensitive trifluoromethanesulfonate ester (2x) under standard conditions.\textsuperscript{11} Much to our delight, this triflate rearranged spontaneously during chromatography on silica gel. The product, eluted from the column along with un consumed 2x, was the enol ether 6, resulting from ring expansion of the oxazine. The reaction could be run more conveniently by simply stirring the triflate 2x in a slurry of dichloromethane and silica gel, resulting in a 65% yield of 6. Unfortunately, this procedure was not totally satisfactory: the efficiency of the reaction proved to be particularly sensitive to the source of silica gel, even to the point where some brands of silica failed to promote the rearrangement at all. A search for better reaction conditions was well rewarded by the finding that 2x was smoothly converted to 6 simply by stirring at room temperature in CH\textsubscript{2}CN buffered with NaHCO\textsubscript{3}. In this way, the rearranged peroxide was obtained in up to 90% yield. The structure of 6 follows from spectroscopic data\textsuperscript{14} and is supported by its conversion with ozone to the lactone endoperoxide 7, a compound previously reported by Adam.\textsuperscript{13} The enol ether 6 is, not surprisingly, sensitive to acids and bases, but is not especially difficult to handle. Purification can be accomplished by chromatography and bulb-to-bulb distillation (40 °C/12 mm). Samples of 6 can be kept for months at −10 °C.

The ease of ionization/rearrangement of 2x is striking and suggests that triflate loss is assisted by neighboring-group participation of the antiperiplanar peroxide group. Consistent with this interpretation, the epimeric endo-triflate 2n, prepared from the minor alcohol oxide 5n, does not rearrange under these conditions. Indeed, when the diastereomeric mixture of alcohols is processed through the sulfonylation/rearrangement sequence, the unchanged endo-triflate 2n can be recovered efficiently after essentially complete conversion of the isomer to 6.

These results establish the catanionic ring expansion of oxazines as a viable route to 1,2,4-trioxanes. Further work, to explore the scope and limitations of this process, is in progress and will be reported in due course.

Acknowledgment. We are grateful to the National Science Foundation (CHE-8806198) for support of this work. T.A.I. thanks the Department of Chemistry, University of Missouri—Columbia, for Nightingale and Bent Summer Fellowships.

Supplementary Material Available. \textsuperscript{1}H and \textsuperscript{13}C NMR and IR spectral data for 2-5 and X-ray data including coordinates, bond distances, bond angles, and torsion angles for the p-nitrobenzoate of 5x (7 pages); observed and calculated structure factors for the p-nitrobenzoate of 5x (7 pages); ordering information is given on any current masthead page.

Isomerism in the Mo\textsubscript{2}(\mu-\textsubscript{2}-CCF\textsubscript{3})\textsubscript{4}/bpy Reaction System: Thermal and Photochemical Conversion of the Ion-Pair Complex [Mo\textsubscript{2}(\mu-\textsubscript{2}-CCF\textsubscript{3})\textsubscript{2}(bpy)]\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{2} to the Unbridged Neutral Isomer Mo\textsubscript{2}(\nu-\textsubscript{2}-OC\textsubscript{2}F\textsubscript{3})(bpy)\textsubscript{2}

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Received May 28, 1991

The development of carboxylic chemistry is a central theme in transition-metal chemistry.\textsuperscript{3} Research in this area ranges from biological modeling applications\textsuperscript{4} to catalysis\textsuperscript{5} and materials chemistry.\textsuperscript{6,7} Our interest is centered on the Mo\textsubscript{2}(\nu-\textsubscript{2}-OC\textsubscript{2}F\textsubscript{3}) chemistry stems from a desire to understand the factors that influence the binding of neutral N-donor chelates to systems with four relatively rigid bridging groups. Novel perturbations of the tetrabridged structures were found for products of bipyridine reactions with Cu\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{4} and Rh\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{4}.\textsuperscript{1,10} In the latter case, the 1:1 adduct, Rh\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{4}(bpy), was found to exhibit an unsymmetrical structure containing a chelating acetate ligand.\textsuperscript{10} This paper describes the synthesis of two isomers obtained from reactions of a quadruply bonded dimolybdenum tetracarboxylate compound with bpy, along with the remarkable photochemical and thermal conversion of the bridged form to an unsupported structure.

Reaction of Mo\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{4} (0.20 g, 0.31 mmol) with 2,2'-bipyridine (0.097 g, 0.62 mmol) in CH\textsubscript{2}CN (10 mL) at room temperature led to the rapid formation of red microcrystals. After reduction in volume, the solution yielded additional product, which was collected by filtration, washed with diethyl ether (3 × 5 mL), and dried in vacuo. The total yield of [Mo\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{2}(bpy)][OC\textsubscript{2}F\textsubscript{3}]\textsubscript{2} (1) was 0.252 g (85%).\textsuperscript{11} Large X-ray quality crystals were grown by slow diffusion of a diethyl ether solution of bpy into a solution of Mo\textsubscript{2}(OC\textsubscript{2}F\textsubscript{3})\textsubscript{4} in CH\textsubscript{2}CN through a hexane interface layer.\textsuperscript{11} An IR spectrum of the crystals revealed

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(11) Anal. Caled for C\textsubscript{29}H\textsubscript{2}N\textsubscript{2}F\textsubscript{5}O\textsubscript{4}Mo: C, 35.10; H, 0.67. Found: C, 34.89; H, 1.99.

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absorptions arising from coordinated CF<sub>3</sub>COO<sup>-</sup> and bppy as well as
ionic CF<sub>3</sub>COO<sup>-</sup>.13

An ORTEP plot of the compound is shown in Figure 1. Salient
features are the presence of two equatorially bound bppy chelates
on the same side of the molecule and two CF<sub>3</sub>COO<sup>-</sup> anions which
occupy axial positions of the Mo<sub>5</sub> cation unit through weak ion-pair
interactions (average Mo-O(axial) = 2.472 (8) Å).14 The effect of
removing two bridging carboxylates and replacing them with
topogen donor chelates is to weaken the bonding between the Mo
atoms (Mo-Mo = 2.181 (2) Å), as was found for the cations in
[Mo<sub>5</sub>(O<sub>2</sub>CH<sub>2</sub>)<sub>3</sub>(NCCCH<sub>3</sub>)<sub>3</sub>(BF<sub>4</sub>)<sub>2</sub> (2.136 (1) Å).15
Axial interactions are also expected to affect the M-M bond
lengthening in these cases,16 For example, the Mo-Mo bond
distance in Mo<sub>5</sub>(O<sub>2</sub>CF<sub>3</sub>)<sub>2</sub> is 2.090 (4) Å,17 whereas the
corresponding distance in Mo<sub>5</sub>(O<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>(py) is 2.129 (1) Å.

Variable-temperature 1H NMR spectroscopic studies of I in
chloroform and CD<sub>3</sub>CN indicate solvent- and temperature-
dependent behavior. At +50°C in chloroform, the spectrum displays
four sets of resonances due to magnetically equivalent environ-
ments for each CH<sub>3</sub>H<sub>2</sub>N rings on the two bppy ligands (δ, ppm: d,
8.70; d, 8.51; t, 7.98; t, 7.47). At 25°C and below, the signals broaden
and reappear as separate sets of resonances due to at least three
different compounds. This behavior is consistent with the presence of several isomers in equilibrium.18 A 19F NMR spectrum of I at 25°C
exhibits a broad resonance at δ = -74 ppm, +74 ppm for sharper signal at -77.4 ppm. The signal becomes more complicated at low temperatures, with a series of resonances appearing between -72 and -78 ppm. Electrochemical studies performed in CD<sub>3</sub>CN revealed an irreversible reduction at E<sub>poe</sub>
= -1.1 V vs Ag/AgCl.

The solvent dependence of the reaction was verified by the
isolation of a second isomer from a less polar solvent. Crystals of
Mo<sub>5</sub>(μ<sup>1</sup>-O<sub>2</sub>CF<sub>3</sub>)<sub>4</sub>(bppy)<sub>2</sub>(CH<sub>3</sub>)CO (2) were grown at -78°C
by layering a solution of Mo<sub>5</sub>(O<sub>2</sub>CF<sub>3</sub>)<sub>4</sub>(0.20 g, 0.31 mmol)
dissolved in 3 mL of acetone with 2 equiv of bppy (0.095 g, 0.61
mmol) in 5 mL of hexane; yield: 0.250 g, 87%.19 The infrared spectrum of 2 indicated the presence of coordinated bppy and
trifluoroacetate but no bands attributable to ionic CF<sub>3</sub>COO<sup>-</sup>.20

The X-ray structure of 2 revealed bppy ligands in an anti
arrangement and, surprisingly, four monodentate trifluoroacetate
groups (Figure 2). This result is unprecedented in quadruply
bonded carboxylate chemistry, to our knowledge. Of importance
to note in this unbridged molecule is the short Mo-Mo bond (2.077
(1) Å) as compared to the corresponding distance in isomer I or
most other Mo<sub>6</sub> complexes containing bridging groups.16 In fact,
molecule 2 possesses the shortest unsupported Mo-Mo quadruple
bond reported to date.

Mo<sub>5</sub>(μ<sup>1</sup>-O<sub>2</sub>CF<sub>3</sub>)<sub>4</sub>(bppy)<sub>2</sub> was also synthesized by irradiating an
CH<sub>3</sub>CN solution of I at λ &gt; 499 nm for 1 h, during which
time the color noticeably changed from dark red to red-purple.

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(15) The lability of trifluoroacetate groups is well-documented, including in
the chemistry of Mo<sub>5</sub>(O<sub>2</sub>CF<sub>3</sub>)<sub>4</sub> with neutral donor ligands: (a) Garrett,
G. S.; Mainz, V. V.; Andersson, R. A. Inorg. Chem. 1980, 19, 805. (d) Cotton,
Inorg. Chem. 1982, 21, 1318. (f) Santure, D. J.; McLaughlin, K. W.; Huffman,
J. C.; Sattelberger, A. P. Inorg. Chem. 1983, 22, 1877. (g) Santure, D. J.; Huffman,

(16) The infrared absorptions for a Nujol mull of 2 between CsI plates
(cmm<sup>-1</sup>): CF<sub>3</sub>COO<sup>-</sup>, 1700 cm<sup>-1</sup> and bppy, 1605 cm<sup>-1</sup>, 1430 s, 1420
s, C-F, 1190 s, 1140 s; CF<sub>3</sub>COO<sup>-</sup> and bppy, 845 m, 840 m, 785 s, 770 s, 725
s.
Large crystals of 2 slowly appeared over the period of several days after irradiation. The product was harvested in 50% yield and characterized by infrared spectroscopy as well as by a single-crystal X-ray study. This observation is consistent with excitation of the $\delta \to \delta^*$ transition for an unbridged solution isomer of 1 with subsequent rotation about the Mo-Mo bond to give 2. For samples of 1 in CH$_3$CN, the $\delta \to \delta^*$ transition occurs as a broad feature at $\lambda = 520$ nm. Presumably the concentration of unbridged isomers of 1 can be increased by photochemical or thermal dissociation of Mo-O bridge bonds, and indeed, solutions of 1 in acetone or CH$_3$CN that have been subjected to light from an intense white light source or heated to reflux also yield large quantities of isomer 2. Acetonitrile solutions of 1 stored in the dark give only trace quantities of 2 upon workup. These findings point to a subtle difference in energies between two isomeric forms of Mo$_2$(O$_2$CCF$_3$)$_4$(bpy)$_2$ with preference for the neutral complex occurring in less polar solvents and under conditions that increase the likelihood of forming unbridged isomers. The high-temperature isomerization of 1 to 2 suggests that the unsupported structure is actually more thermodynamically stable than the cis-trifluoroacetate-bridged structure. Although this conclusion may appear to be counterintuitive, it is not unreasonable if one compares the bonding interactions in the two structures. Molecule 2 possesses a much shorter Mo-Mo bond and stronger Mo-O interactions than 1. Additional work on this intriguing system is in progress.

Acknowledgment. We are grateful to the National Science Foundation for instrumentation grants (X-ray CHE-8908088 and NMR CHE-8800770) and grants to K.R.D. (CHE-8914915) and G.C. (CHE-8808019). We also thank Professor D. G. Nocera and Carolyn Hsu for use of the photochemical equipment and Steven C. Haefner for helpful discussions.

Supplementary Material Available: Tables and summaries of X-ray data, positional parameters, bond distances, bond angles, and thermal parameters for 1 and 2 (18 pages); tables of observed and calculated structure factors for 1 and 2 (45 pages). Ordering information is given on any current masthead page.

New Mechanistic and Stereoinformatic Insights on the Biosynthesis of Sterols from 2,3-Oxidosqualene

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Received May 20, 1991

The enzymic cyclization of 2,3-oxidosqualene to lanosterol is of great interest from both chemical and biochemical perspectives. The recent demonstration that the 20-oxa analogue of 2,3-oxidosqualene is converted by the cyclase from yeast to the 17β-acetyl sterol 1 has provided new information on the stereochemical course of the cyclization and has suggested a more detailed analysis of the previously reported bioconversion of (20E)-20,21-dehydro-2,3-oxidosqualene (2) to a protosterol of gross structure 3 (Chart 1). We report herein on the complete structure of 3 and its bearing on the detailed mechanism of action of the cyclase.

Tritiated (±)-2 was synthesized from epoxy aldehyde 4 by Wittig coupling 5 (7:3 mixture of 18E and 18Z isomers, separable by HPLC). Biosynthetic experiments were carried out using sterol-free microsomal enzyme of Saccharomyces cerevisiae (yeast) which had been purified by successive chromatography on DEAE and hydroxylapatite columns. 3 The structures of 2 (more polar isomer) and the less polar 18Z isomer were clear from H NMR NOEDIFF measurements at 500 MHz. Whereas the 18Z isomer of 2 was not transformed into sterol by the cyclase, 2 was converted in ca. 30% yield (HPLC analysis) to a protosterol, which was demonstrated to be 8 by 500-MHz H NMR analysis and comparison with synthetic compounds as described below. 4 Incubation of 2 with a cyclase-containing homogenate of porcine liver at 23

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Footnotes:
(4) Preparative-scale enzymic experiments were performed using sterol-free enzyme from yeast at 23 °C for 24 h. After chromatographic purification, pure 5 was isolated in 17% yield.

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