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[20] This diastereomer can be described as a kind of *meso*-form. However, this description is not quite correct as the complex remains chiral because of the axial chirality of the BINOL. In fact, this complex is less symmetric (C_2) than the other two D_2-symmetric, helical diastereomers.

[21] ESI – MS spectra of dichloromethane/acetonitrile solutions (5×10^{-4} mM concentration of **1a**, **1b**, or **1c**) were recorded on a Thermo Finnigan LCQ.

[22] See Supporting Information for further details.

[23] Crystal structure of ($\mathit{\Delta},\mathit{\Delta}$)-[$Zn_2\{(S_a)$-**1a**$\}_3$]$(BF_4)_4 \cdot 2.5\,THF \cdot 5\,CH_3CN$: STOE-IPDS-diffractometer ($Mo_{K\alpha}$ radiation), $T = 193$ K. Crystal dimensions $= 0.25 \times 0.24 \times 0.17$ mm^3, $C_{164}H_{137}B_4F_{16}N_{17}O_{14.5}Zn_2$; $M_r = 3055.89$, orthorhombic, space group $P2_12_12_1$, $a = 28.3103(10)$, $b = 33.0824(15)$, $c = 35.7949(14)$ Å, $V = 33\,525(2)$ Å^3, $Z = 8$, $\rho_{calcd} = 1.211$ mg m^{-3}, $F(000) = 12\,640$, $\theta_{max} = 22.47°$, $-30 < h < 30$; $-35 < k < 35$; $-38 < l < 38$, 180 110 measured reflections, 43 248 independent reflections ($R_{int} = 0.2759$). All non-hydrogen atoms were anisotropically refined and the H atoms were inserted in the calculated positions. 11 548 reflections $I > 2\sigma(I)$ and 1776 refined parameters, GOF(F^2) $= 0.786$, final R indices: $R_1 = 0.1067$, $wR_2 = 0.2483$, Flack parameter $x = 0.01(2)$, max./min. residual electron density 0.980/-0.539 e Å^{-3}. The structures were solved by the direct method (SHELXS-97)[24] and refined on F^2. CCDC-178150 ((Δ,Δ)-[$Zn_2\{(S_a)$-**1a**$\}_3$]$(BF_4)_4 \cdot 2.5\,THF \cdot 5\,CH_3CN$) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB21EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).

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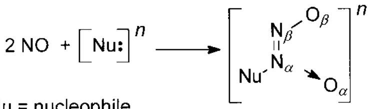
Traube's "Oxazomalonic Acid" is a 3-Hydroxysydnone Carboxylate with an *E*-ONNO Geometry**

Navamoney Arulsamy and D. Scott Bohle*

In his seminal early investigations of the base-mediated condensation of nitric oxide with organic acids,[1–4] Wilhelm Traube prepared an adduct of diethylmalonate, which he formulated as "$ON_2C(CO_2H)_2$" and termed an "oxazomalonic acid".[3] As written, this derivative is formally a conjugated diazotate,[5, 6] and in contrast with the low thermal stability of diazotates, Traube's disodium salt is stable to 343 °C. These observations and much of the organic chemistry of nitric oxide have received scant attention since then, but the discovery of the numerous roles of nitric oxide in biology has renewed interest in this once obscure chemistry.[7] We and others have recently extended many of Traube's original discoveries,[8–12] and one of the universal observations is that the condensation of nitric oxide with nucleophiles returns diazeniumdiolate products **1**, often in high yields and with a *Z* orientation of the two oxygen atoms that flank the newly formed N=N bond (Equation (1)).[9] We have recently reexamined Traube's reaction and his "oxazomalonic" acid product. Herein we report: 1) the product is, in fact, an unusual heterocycle with a five-membered ring and corresponds to the 3-hydroxy-2-carboxysydnone dianion; 2) the synthesis, structure, and spectroscopic analysis of its methyl ester; and 3) theoretical results, which suggest a low-lying transition state for *Z* to *E* isomerization of an initial NO condensation product. Taken together, these results allow the unambiguous characterization of a new diazeniumdiolate with an *E*-ONNO framework.[13]



(1)

Nu = nucleophile
n = 0 or -1

1

The condensation products of nitric oxide and dimethyl malonate depend on the temperature and on the substrate/base stoichiometry (Scheme 1). There are three predominant reactions that account for the observed products: 1) condensation of two nitric oxide molecules, followed by ring closure to give the planar heterocycle 2-carboxy-3-hydroxysydnone (**2**), which was isolated as either a monomethyl ester **2a** or as a dianionic salt **2b,c**; 2) condensation of four nitric oxide molecules and decarboxylation to give the bisdiazeniumdiolate **3**, which was isolated as a tripotassium salt; and 3) one-

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[**] This research was supported by the Airforce Office of Scientific Research and the National Institutes of Health.

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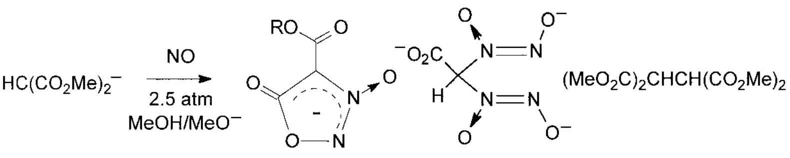


2a: M = K, R = Me
b: M = K, R = K
c: M = Na, R = Na

		3	**4**
RT	17% (as **2b**) :	15% :	trace
0 °C	31% (as **2a**) :	0% :	18%

Scheme 1. Reaction products for the nitrosylation of dimethyl malonate.

electron oxidation of the dimethyl malonate anion by nitric oxide to give the dimer $(MeO_2C)_2CHCH(CO_2Me)_2$ (**4**). The monopotassium salt **2a** was characterized by single-crystal X-ray diffraction (Figure 1) and has a coplanar array of all the heavy atoms of the anion. Based on its planarity and on the short C–C bond length, the methylcarboxylato group is conjugated with the $C_2O_3N_2$ ring. Hydrolysis of **2a** in KOH (1M) returns Traube's salt ($K_2C_3O_5N_2$, **2b**) in good yield.

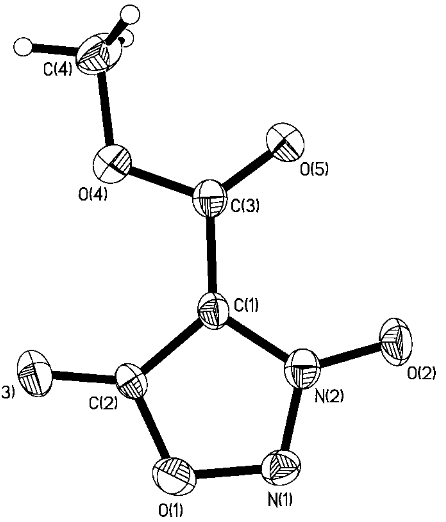
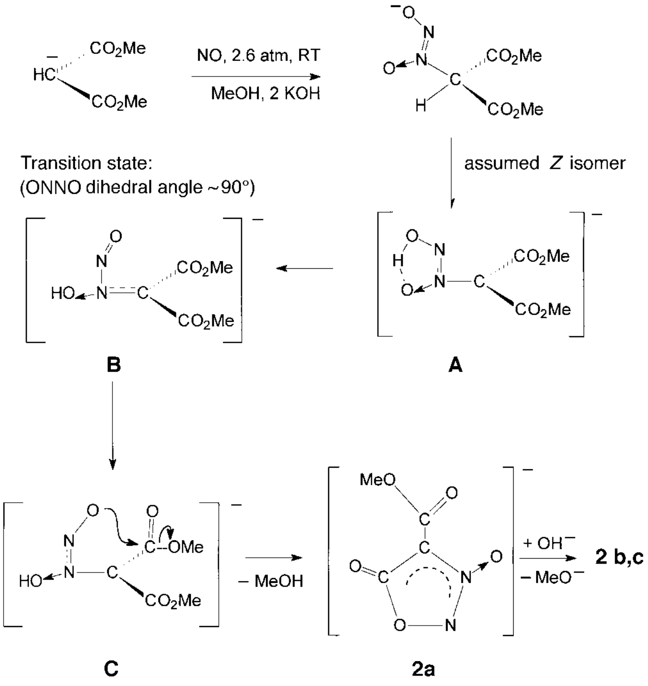


Figure 1. ORTEP view of the 1,2,3-oxadiazole-3-oxido-4-methylcarboxylate-5-hydroxylate anion in the crystals of **2a**. Important metric parameters: C(1)-N(2) 1.380(3) Å, N(2)-N(1) 1.324(3), N(2)-O(2) 1.262(3), N(1)-O(1) 1.386(3), O(1)-C(2) 1.367(3), C(2)-O(3) 1.229(3), C(2)-C(1) 1.405(3), C(1)-C(3) 1.448(3), C(3)-O(4) 1.333(3), C(3)-O(5) 1.212(3), O(4)-C(4) 1.447(3); C(1)-N(2)-O(2) 130.2(2), O(2)-N(2)-N(1) 118.3(2), N(2)-N(1)-O(1) 106.6(2), N(1)-O(1)-C(2) 109.5(2), O(1)-(2)-O(3) 119.1(2), O(1)-C(2)-C(1) 106.7(2), O(3)-C(2)-C(1) 134.1(2), C(2)-C(1)-N(2) 105.7(2), N(2)-C(1)-C(3) 125.1(2), C(2)-C(1)-C(3) 129.1(2).

The structure shown in Figure 1 is the first report of a structurally characterized diazeniumdiolate with an *E* geometry. The mechanistic origin of this geometry is in surprising contrast with the general stereospecificity observed in the products of Equation (1). We suggest that the mechanistic origins of this product are a result of a cyclizing condensation of one of the malonate esters with an *E*-ONNO group, (Scheme 2, **C**), which traps the *Z* conformer. Further, we propose that the initial diazeniumdiolate from the condensation reaction has a *Z* geometry, (Scheme 2, **A**) and that this undergoes *Z* to *E* isomerization before cyclization. The diazenium diolate moiety is recognized as a strong electron-withdrawing substituent[18] and either the *α*-proton will be lost or the diazeniumdiolate tautomerizes to the $N_2O_2^-$ moiety. Although our experience is that the calculated *E*/*Z* isomerization barriers are relatively high (>40 kcal mol^{-1}) for anionic diazeniumdiolates, it is possible to draw resonance structures for the first intermediate, which has a formal N–N single-bonded nitroso group in a $[(HO_2C)_2C{=}N(OH){-}N{=}O]^-$ fragment. To test more thoroughly this valence-bond prediction that low *Z*/*E* isomerization barriers are present when the *α*-nitrogen atom can form multiple bonds to its R substituent, we have examined the gas-phase isomerization potential energy surface with density functional ab initio theoretical methods (B3LYP/6-311++G**) and a quadratic synchronous transit algorithm.[14, 15] Both **A** and **C** optimize to ground-state geometries, with the *Z* conformer in **A** being 1.33 kcal mol^{-1} more stable than the *E* conformer. The lowest energy saddle point found on this surface corresponds to a species with a monoprotonated *α*-oxygen atom, the monoanion $[(HO_2C)_2C{=}N(OH){-}NO]^-$ (**B**), which lies 19.66 kcal mol^{-1} above the ground-state *E* and *Z* geometries. The reaction coordinate that leads from the optimized ground state of the proposed intermediate **A** to that of **C** primarily correlates with a twisting of the ONNO dihedral angle (Figure 2), and confirms that this saddle point connects the two ground states by a low-energy isomerization pathway.



Scheme 2. Proposed mechanism for the synthesis of new sydnones.

As sydnones **2b** and **2c** are unique in that they are remarkably stable towards hydrolysis in base yet easily hydrolyze in acid, both trends are opposite to the stabilities of

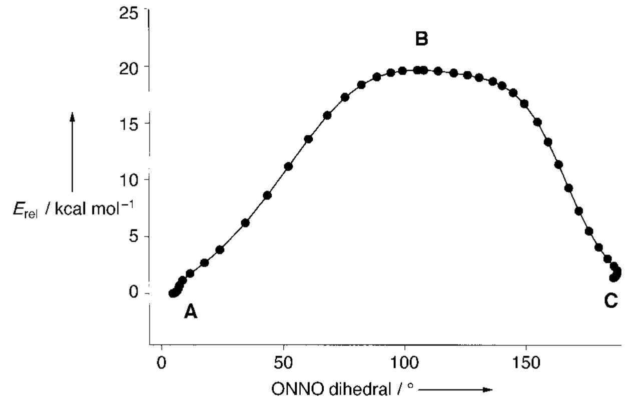


Figure 2. Ab initio calculated (B3LYP/6-311++G**) energy profile for the Z to E isomerization $(HO_2C)_2C\{N(OH)O\}^-$. The dihedral angle for the ONNO group, which dominates the internal reaction coordinate, correlates **A**, **B**, and **C** (see Scheme 2) for the proposed low-energy pathway for Z to E isomerization.

other sydnones. At neutral pH values, **2a** slowly hydrolyzes to release two equivalents of NO, and thus these new sydnones may be useful as potential NO prodrugs. A similar reactivity pattern has however been observed for methanetris(diazeniumdiolates),[12] and the products of acid hydrolysis include nitric oxide, nitrous oxide, and carbon dioxide. A closely related spectroscopically characterized heterocycle has been proposed to result from the reaction of nitrosyl chloride and 1,1,4,4-tetramethyl-1,3-butadienes.[16] This new type of compact ring structure forms dense crystals, and thus **2a,b,c** are potential energetic materials which decompose exothermally at high temperatures.

Experimental Section

2a: A solution of potassium methoxide (prepared from potassium metal (3.90 g, 0.1 mol) and absolute methanol (100 mL)), was filtered at room temperature and mixed with dimethyl malonate (13.21 g, 0.1 mol) in a glass medium-pressure reaction vessel. The vessel was cooled in an ice bath to 0 °C with rigorous exclusion of oxygen before the introduction of nitric oxide (24 kPa). Although the absorption of nitric oxide significantly subsided within 4 h, the reaction mixture was allowed to warm to room temperature and kept under an atmosphere of nitric oxide overnight. The reaction mixture was treated with water (50 mL) and filtered. Recrystallization of the resulting white solids from a chloroform/methanol solvent mixture gave bis(dimethyl malonate) (**4**) (2.4 g, 18 %).[17] The filtrate was reduced in volume (to ca. 50 mL) and the yellow solution was allowed to evaporate slowly. The colorless crystals which formed were filtered, washed with methanol, and dried to afford **2a** (6.2 g, 31 %). IR: $\tilde{\nu}$ = 2964 w, 1812 w, 1738 s, 1698 s, 1654 s, 1629 s, 1512 m, 1490 s, 1469 s, 1429 m, 1386 s, 1324 m, 1310 s, 1208 s, 1140 s, 1047 m, 1039 s, 956 s, 938 m, 806 w, 773 s, 767 s, 683 w, 678 w, 659 w, 500 cm^{-1} m; ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 3.85 ppm (s); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 171.0, 163.3, 98.5, 54.4 ppm; MS (ESI): m/z: calcd for $C_4H_3N_2O_5$ [M^-] 159.078; found 159.1 [M^-], 357.1 [$M^-K^+M^-$], 119 [$M^- - NO$], 99 [$M^- - N_2O_2$]; UV/Vis (water): λ_{max} = 230 (11540), 276 nm (8830); elemental analysis calcd for $C_4H_3N_2O_5K$ (%): C 24.24, H 1.52, N 14.14; found: C 24.16, H 1.51, N 14.08; DSC: T_{onset} = 330 °C (explodes).

2b and **3**·H_2O: Potassium methoxide (prepared from potassium (3.9 g) in methanol (100 mL)) under nitrogen was treated with dimethyl malonate (6.61 g, 0.05 mol), and the mixture was rigorously degassed before being pressurized with nitric oxide (24 kPa) at 20 °C with vigorous stirring. As the reaction progressed, rapid absorption of nitric oxide was observed in the first 6 h. After 2 d the reaction mixture was flushed with N_2 gas and the white precipitate (7.1 g) was filtered and dried at room temperature. The powder was dissolved in aqueous KOH (1 N, 50 mL) and boiled for 30 min. The solution was filtered to remove a small amount of insoluble solids and treated with methanol (10 mL). The cloudy solution was allowed to stand at 5 °C overnight. The large colorless crystals formed were separated by filtration and dried at 120 °C for 6 h (yield: 1.9 g, 17 %). IR: $\tilde{\nu}$ = 1769 m, 1734 s, 1690 s, 1619 s, 1454 s, 1385 s, 1343 s, 1245 m, 1228 s, 1150 m, 1039 m, 1011 m, 956 m, 921 m, 823 s, 796 s, 776 m, 758 w, 728 w, 681 m, 658 m, 478 cm^{-1} w; ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 172.2, 168.0, 101.7 ppm; UV/Vis (water): λ_{max} = 224 (11130), 280 nm (8810); elemental analysis calcd for $C_3N_2O_5K_2$ (%): C 16.21, N 12.60; found C 16.24, N 12.53. The filtrate was again treated with methanol (50 mL), and the cloudy solution was allowed to stand at 5 °C for several days. Crystals of hydrated **3** formed, and were filtered and dried at room temperature under reduced pressure (yield: 2.3 g, 15 %). IR: $\tilde{\nu}$ = 3650–3260 b, 2970 m, 1670–1660 s, 1377 s, 1353 m, 1290 m, 1255 m, 1228 s, 1211 s, 1146 m, 962 s, 933 m, 862 s, 805 s, 758 s, 654 m, 585 w, 565 cm^{-1} w; ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 6.40 ppm (s); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 169.70, 91.50 ppm (J = 154.1 Hz); UV/Vis (water): λ_{max} = 258 nm (15620); elemental analysis calcd for $C_2H_3N_4O_7K_3$ (%): C 7.69, H 0.97, N 17.93; found: C 7.78, H 0.89, N 17.95; DSC: $\Delta H = -93.6$ kcal mol^{-1}, T_{onset} = 322 °C. The sodium derivative **2c** was prepared analogously.

Crystal data for **2a**: $C_4H_3KN_2O_5$, M_r = 198.18, 298 K, monoclinic space group $P2_1/c$; a = 10.736(1), b = 4.5730(8), c = 14.874(2) Å, β = 106.23(1)°, V = 701.2(2) Å^3, Z = 4, ρ_{calcd} = 1.877 Mg m^{-3}, $F(000)$ = 400, 121 parameters; R_1 (wR_2) [$I > 2\sigma(I)$] = 0.053 (0.14), $s(GOF)$ = 1.034. Crystals of **2a** were mounted on glass fibers with epoxy, and diffraction data was collected on a Siemens P4 four-circle diffractometer equipped with a sealed molybdenum tube, which was monochromated to give λ = 0.71073 Å. The structure was solved by using direct methods and refined by using full-matrix least-squares on F^2 with SHELXTL. All non-hydrogen atoms were refined anisotropically with element assignments as described in the text. CCDC-174994 (**2a**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB21EZ, UK; fax: (+44)1223-336-033; or deposit@ccdc.cam.ac.uk).

Theoretical calculations: Ground and transition state optimizations were performed with Gaussian98. The energies of **A**, **B**, and **C** are −677.1544, −677.1231, and −677.1522 Hartrees, respectively. Ground-state geometries and important metric parameters are collected in the Supporting Information.

Received: December 5, 2001
Revised: February 26, 2002 [Z18330]

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