oxidation (PCC, dichloromethane) and reduction (LAH, ether) giving a mixture rich in **22**. Completion of the synthesis required the selection of an appropriate protecting group that would also be useful for the subsequent steps in our synthesis of boromycin. The *O*-(trichloroethoxy)carbonyl group proved to be useful in this regard. Thus the readily formed trichloroethyl carbonate derivative of **22** was treated with acid and oxidized to the lactone **23**, $[\alpha]_D$ +28.8°. Removal of the protecting groups gave the desired lactone **2**, $[\alpha]_D$ +33°, in high overall yield. Similar treatment of the other isomer gave the C-9′ epimeric lactone, $[\alpha]_D$ +3.4°.[16] Oxidation of des-valine-des-boron-boromycin with periodic acid followed by mild base treatment and chromatographic separation gave a product which was identical with **2** in all respects [$[\alpha_D]$, mass spectrum, ^{1}H NMR (400 mHZ) spectrum, TLC, IR spectrum].

In addition to establishing the correct structure and stereochemical identity of the $C_{18}H_{32}O_5$ degradation product from boromycin by its total synthesis, we have found efficient and virtually regio- and stereospecific routes to the component chiral tetrahydrofuran and tetrahydropyran subunits as well as a practical method for joining them.[17,18]

Acknowledgment. We thank the National Science and Engineering Council of Canada for financial support and the CNRS (France) for fellowships. We would like to particularly thank Professor V. Prelog and Ciba-Geigy, Basel, for a sample of boromycin.

Supplementary Material Available: Infrared and proton magnetic resonance spectra, optical rotations, and other physical constants of the new compounds (9 pages). Ordering information is given on any current masthead page.

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(16) The somewhat large change in the value of optical rotation compared to **2** can be ascribed to a change in conformation of the acyclic portion, which is borne out by the difference in chemical shift of the *gem*-dimethyl group in both isomers.

(17) Attachment of the glycolic acid chain in **23** was done by the Meinwald procedure. See: Duggan, A. J.; Adams, M. A.; Brynes, P. J.; Meinwald, J. *Tetrahedron Lett.* **1978**, 4323-4326.

(18) Another approach for the stereoselective synthesis of segments of boromycin has been recently described. See: White, J. D. "Abstracts of Papers"; 179th National Meeting of the American Chemical Society, TX, Houston, March 24-28, 1980; American Chemical Society: Washington, DC, 1981; ORG 48.

Synthesis and Structure of a New Type of Mo-Fe-S Double-Cubane Cluster and Evidence for Formation of Magnetically Uncoupled $S = {}^3/_2$ $MoFe_3S_4$ Subclusters

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In the course of our synthetic approach to the catalytic site(s) of the nitrogenase FeMo proteins we have been encouraged as to the viability of the double-cubane clusters $[Mo_2Fe_6S_9(SR)_8]^{3-}$ (**1**), $[Mo_2Fe_6S_8(SR)_9]^{3-}$ (**2**), $[Mo_2Fe_7S_8(SR)_{12}]^{3-}$ (**3**), and $[Mo_2Fe_7S_8(SR)_{12}]^{4-}$ (**4**)[1-5] as preliminary models by several observations: elements of apparent similarity in Mo coordination site environments from comparative EXAFS[1] of clusters and native proteins and their common cofactor[6-8] (FeMo-co) and occurrence of at least one type of substrate reduction (H_2 evolution from protic sources) using reduced forms of **2**.[9] However, clusters **1-4** are likely to prove ineffectual in activation of other nitrogenase substrates if binding at a Mo site is requisite, owing to coordinative saturation completed by strong bridge-sulfur atom ligation as in, e.g., **3**.[2,3] Clusters lacking this structural feature should prove more manipulable chemically. In addition, single clusters or double cubanes having magnetically insulated subclusters would facilitate examination of the electronic properties of individual $MoFe_3S_4$ units for comparison with the spin-quartet cluster present in FeMo-co[8,10] and native enzymes.[11] Such species have not been detected among direct synthesis products[1,3] nor are they accessible from **1-3** by reactions with electrophiles, which afford terminal ligand substitution only.[4] Cleavage of the Fe(III) bridge in **3** with catechol yields **5**,[12] a single cluster but with an appended, paramagnetic $Fe(cat)_3{}^{3-}$ subunit. The structure of **5** indicates steric destabilization from Et/3-substituent interactions when the latter is methyl or larger, suggesting a different product upon reaction of **3** with an appropriate 3,6-disubstituted catechol.

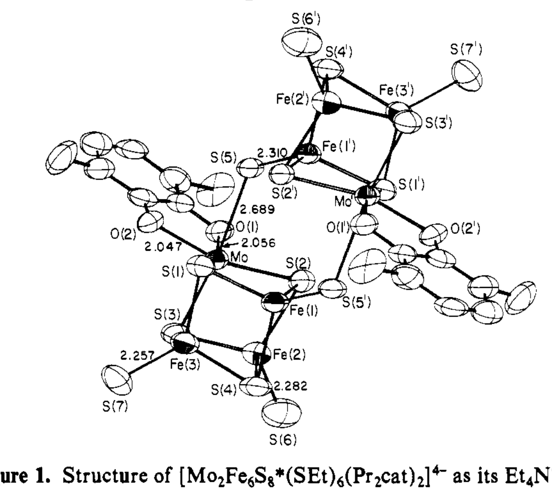

Figure 1. Structure of $[Mo_2Fe_6S_8^*(SEt)_6(Pr_2cat)_2]^{4-}$ as its Et_4N^+ salt; shown are 50% probability ellipsoids and bridging and terminal ligand-metal bond distances (Å). Primed and unprimed atoms are related by an inversion center. Mean distances within a cluster: Mo-S*, 2.371 (10); Mo-Fe, 2.737 (32); Fe-Fe, 2.714 (9), Fe-S*, 2.278 (19) Å. Distances between clusters: Mo···Mo′, 6.042 (4); Mo···Fe(1′), 4.380 (4); Fe(1)···Fe(1′), 4.055 (5) Å. Ethyl groups are omitted for clarity.

Reaction of $(Et_4N)_3[Mo_2Fe_7S_8(SEt)_{12}]^3$ (**3**, 3.6 mmol) and 3,6-$(n\text{-}Pr)_2C_6H_2(OH)_2$[13] (22 mmol) in the presence of Et_3N (44 mmol) and Et_4NBr (21 mmol) in acetonitrile (100 mL) for 48 h (N_2 atmosphere) produced a solid which after recrystallization from acetonitrile gave black crystals of composition $(Et_4N)_4$-$[Mo_2Fe_6S_8(SEt)_6(Pr_2cat)_2]$ (**6**-Mo, 32%, λ_{max} 395 nm (ϵ_M 35 000), Me_2SO). The tungsten cluster, **6**-W, was prepared analogously. One form of **6**-Mo[14] crystallizes in monoclinic space group $C2/c$ with a = 31.474 (7) Å, b = 19.544 (5) Å, c = 25.182 (6) Å, β

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(1) Wolff, T. E.; Berg, J. M.; Hodgson, K. O.; Frankel, R. B.; Holm, R. H. *J. Am. Chem. Soc.* **1979**, *101*, 4140.

(2) Wolff, T. E.; Berg, J. M.; Power, P. P.; Hodgson, K. O.; Holm, R. H. *Inorg. Chem.* **1980**, *19*, 430.

(3) Wolff, T. E.; Power, P. P.; Frankel, R. B.; Holm, R. H. *J. Am. Chem. Soc.* **1980**, *102*, 4694.

(4) Palermo, R. E.; Power, P. P.; Holm, R. H. *Inorg. Chem.*, in press.

(5) Type **2** clusters have been independently investigated by others: (a) Christou, G.; Garner, C. D. *J. Chem. Soc., Dalton, Trans.* **1980**, 2354. (b) Christou, G.; Garner, C. D.; Miller, R. M.; Johnson, C. E.; Rush, J. D. *Ibid.* **1980**, 2364.

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(11) Huynh, B. E.; Henzl, M. T.; Christner, J. A.; Zimmermann, R.; Orme-Johnson, W. H.; Münck, E. *Biochim. Biophys. Acta* **1980**, *623*, 124.

(12) Wolff, T. E. Berg, J. M.; Holm, R. H. *Inorg. Chem.* **1981**, *20*, 174.

(13) Müller, E.; Günter, F.; Rieker, A. *Z. Naturforsch.* **1963**, *18b*, 1002.

(14) Data were collected on a Nicolet R3m diffractometer with graphite monochromatized Mo Kα radiation. The Mo atom position was determined from a Patterson map; subsequent maps revealed remaining nonhydrogen atoms, all of which in the anion were refined anisotropically. The structure of a second crystalline form (triclinic, space group $P\bar{1}$) has been solved to R = 8.3%; its anion structure is unimportantly different from that reported here.

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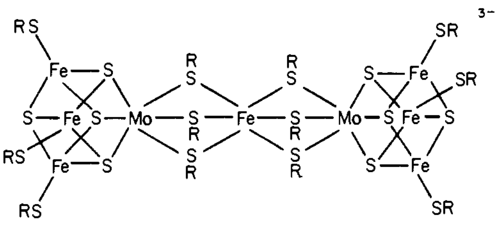

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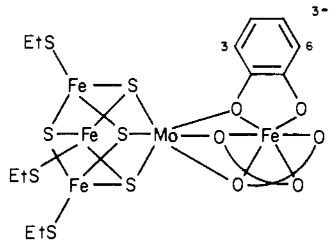

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= 141.77 (1)°, $V = 9586$ (3) Å^3, and $Z = 4$. From 3994 unique data [$F_o > 3\sigma(F_o)$] at $2\theta \leq 42°$ the structure has been refined to $R = 6.5\%$ by standard procedures.[14] The anion structure (Figure 1), with imposed centrosymmetry, consists of two $MoFe_3S_4(SEt)_2$ subclusters of mean dimensions conforming closely to those of **1**–**5**,[1,3,12] two $Mo(Pr_2cat)$ chelate units, and two unprecedented $Mo(\mu_2\text{-}SEt)Fe$ bridges. The latter possess Fe–S bonds [2.310 (5) Å] 0.04 Å longer than the mean terminal Fe–SEt distance (2.270 Å) and Mo–S bonds [2.689 (4) Å] ~0.11 Å longer than bridge Mo–SR distances in **2**–**4**.[1,3] The possible substitutional lability of bridge ligands implied by these results has been investigated.

The ^1H NMR spectra[15] of solutions of **6**-Mo and **6**-W, respectively, in $Me_2SO\text{-}d_6$ contain these signals (relative integrated intensities): (a) $FeSCH_2$, −48.9 (2.8), −46.8 (2.8) ppm; (b) ring-H, −10.0 (1), −9.00 (1) (confirmed by deuteration) ppm; (c) $FeSCH_2CH_3$, ~−3.7 (sh), −4.07 (4.7) ppm. Reaction of **6**-Mo and **6**-W with 6 equiv of $p\text{-}MeC_6H_4SH$ in $Me_2SO\text{-}d_6$ under reduced pressure results in elimination of signals a and c, retention of Pr_2cat signals, and appearance of these resonances of the generated clusters **7**-Mo and **7**-W, respectively: (d) *m*-H, −12.9 (2.9), −12.7 (3.0) ppm; (e) *p*-Me, −12.1 (4.7), −11.6 (4.7) ppm; (f) ring-H, −10.6 (1), −9.35 (1) ppm; (g) *o*-H, +3.1, +1.5 ppm (br). Corresponding results were obtained with PhSH. Shift patterns similar to the terminal ligands of **2** (R = Et, Ph, $p\text{-}C_6H_4Me$)[3,4,5a] substantiate the assignments as do relative intensities, which afford the conclusion that all thiolates are present as terminal (Fe–SR) ligands. Shift comparisons are justified to the extent that, from preliminary Mössbauer spectra of **6**-Mo,[16] this compound and **2**[1,17] contain isoelectronic $[MoFe_3S_4]^{3+}$ subclusters. Additionally, relative intensities of thiolate and $(CH_3CH_2)_4N^+$ (h) signals indicate that most or all of the former have been located, consistent with lack of detection of other isotopically shifted features at ±400 ppm vs. Me_4Si. For example, the following ratios are found (theoretical) for **7**-Mo and **7**-W, respectively: h/e = 1.9, 2.1 (1.78); h/f = 9.0, 8.8 (8). The NMR results are consistent with the presence at ambient temperature of, largely, clusters lacking the M–S(R)–Fe bridge unit. Possible formulations include solvated (L) individual or bridged clusters $[MFe_3S_4(SR)_3(Pr_2cat)L]^{2-}$ (**8**) or $[M_2Fe_6S_8(\mu_2\text{-}L)(SR)_6(Pr_2cat)_2]^{4-}$ (**9**).[18]

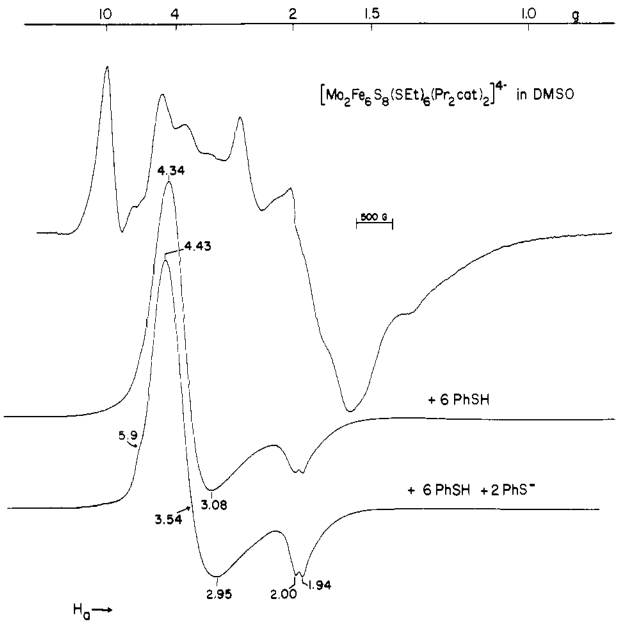

Figure 2. X-band EPR spectra at ~7 K of Me_2SO solutions of **6**-Mo (upper), **6**-Mo + 6 equiv of PhSH (middle), and 6 equiv of PhSH + 2 equiv of $(Et_4N)(SPh)$ (bottom). Spectra of ca. 7 mM solutions were recorded at 5-mW microwave power and 20-G modulation amplitude; apparent *g* values are indicated.

EPR spectra at ~7 K of Me_2SO solutions prepared from **6**-Mo are complex (Figure 2) and resemble that of the polycrystalline compound, suggesting the presence at this temperature and concentration of intact **6**-Mo or another bridged species. However, solutions of **7**-Mo and those to which 1 equiv of PhS^-/Mo have been added give markedly simpler but somewhat broad spectra indicative of an $S = {}^3/_2$ spin system with $0 < |E/D| < 0.33$. The small differences between the latter two spectra may arise from terminal Mo–SPh binding. From theory[19] we assign $g_y \simeq 4.4$, $g_x > 3.0$, and $g_z \simeq 1.94$ to the $|\pm{}^1/_2\rangle$ Kramers' doublet. If $g_x \simeq 3.5$ (base line crossing point) the spectra are reconcilable with $|E/D| \sim 0.08$. The magnetic moment $\mu = 3.9\ \mu_B$ for clusters in solutions of **6**-Mo and **7**-Mo in Me_2SO (298 K). These results are compatible with **8** or any bridged species with magnetically uncoupled subclusters. The magnetic susceptibility of polycrystalline $(Et_3NCH_2Ph)_3[Mo_2Fe_6S_8(SEt)_9]$ (**2**) exhibits a near-Curie temperature dependence at 4.3–150 K with moments per subcluster of, e.g., 3.97 (4.3), 3.91 (150), and 4.05 μ_B (299 K),[17] also indicative of a spin-quartet ground state. However, low-temperature solution EPR spectra are complex and do not resemble that of **7**-Mo, presumably because of intercluster spin interactions.

Native FeMo proteins and FeMo-co exhibit a biologically unique spin system whose spectroscopic properties are consistent with a $S = {}^3/_2$ Fe–Mo–S cluster unit.[8,10,11] Typically, *g* values are 4.3, 3.7, and 1.98, $|E/D| \sim 0.06$, and $D \sim +6$ cm^{-1}. The EPR spectra of **7**-Mo are clearly similar to those of biological clusters but the *g* anisotropy is less well resolved, presumably because of the line width (430 G) of the $g \sim 4.4$ feature.[20] The resonance at $g \sim 5.9$ finds an apparent (but fully resolved) counterpart in FeMo-co spectra at 13 K[8] which in these cases has been assigned to the g_z component of the $|\pm{}^3/_2\rangle$ Kramers' doublet. Clusters **6**-Mo and **7**-Mo do not possess the FeMo-co composition (6–8 Fe/Mo[6–8,10]) and at least one other Fe–Mo–S complex of known structure,[21] $[Fe(MoS_4)_2]^{3-}$, displays a $S = {}^3/_2$-type EPR spectrum.[22] Nonetheless, the collective EXAFS and EPR results

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(15) All spectra were recorded at 300 MHz and 296–299 K. Shifts designated as − and + are downfield and upfield, respectively, of Me_4Si reference. Catecholate *n*-Pr group resonances occur from −0.7 to −1.6 ppm.

(16) Preliminary data at 4.2 K based on a two-site fit: $\Delta E_{Q_1} = 1.16$, $\Delta E_{Q_2} = 1.54$ mm/s; $\delta_1 = 0.31$, $\delta_2 = 0.34$ mm/s (vs. Fe metal at 4.2 K).

(17) Christou, G.; Mascharak, P. K.; Armstrong, W. H.; Papaefthymiou, G. C.; Frankel, R. B.; Holm, R. H. *J. Am. Chem. Soc.*, submitted for publication.

(18) This proposal is offered with due note that inequivalencies of RS groups in **8** and **9**, required if the $M(Pr_2cat)L$ portion is stereochemically rigid, are not resolved in NMR spectra. If not all ethanethiol liberated in the formation of **7** is removed by evacuation, then, possibly, L = EtS^- in **8** and **9**. However, no ^1H NMR signals ascribable to such a ligand were observed.

(19) Münck, E.; Rhodes, H.; Orme-Johnson, W. H.; Davis, L. C.; Brill, W. J.; Shah, V. K. *Biochim. Biophys. Acta* **1975**, *400*, 32.

(20) Spectra of **7**-Mo also resemble that of $Mo(acac)_3$ ($S = {}^3/_2$) for which the $g = 5.8$ signal, but not the g_x, g_y signals, is resolved and *D* is negative: Averill, B. A.; Orme-Johnson, W. H. *Inorg. Chem.* **1980**, *19*, 1702. The sign of *D* for **7**-Mo has not yet been established.

(21) Coucouvanis, D.; Simhon, E. D.; Baenziger, N. C. *J. Am. Chem. Soc.* **1980**, *102*, 6644.

enhance the appositeness of $MoFe_3S_4$ clusters as synthetic representations of the nitrogenase Mo site at this early stage of development in the modeling problem.

Acknowledgment. This research was supported by NSF Grants CHE 80-06601 and 81-06017. We thank Drs. R. B. Frankel and G. C. Papaefthymiou for Mössbauer data. X-ray and NMR equipment used in this research were obtained by NSF Grants CHE 80-00670 and CHE 80-08891.

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(22) McDonald, J. W.; Friesen, G. D.; Newton, W. E. *Inorg. Chim. Acta* **1980**, *46*, L79.

Isotope Scrambling with ^{15}N-Labeled Azide Ion and *p*-Toluenesulfonyl Azide[1a]

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p-Toluenesulfonyl azide (**1**) reacts with azide ion in dimethyl sulfoxide solution to form *p*-toluenesulfinate anion and dinitrogen (eq 1, Ts = $4\text{-}CH_3C_6H_4SO_2^-$).[2] For a determination of whether

$$\underset{\mathbf{1}}{TsN_3} + N_3^- \rightarrow Ts^- + 3N_2 \qquad (1)$$

or not there are solvent effects on this reaction, it has been studied in other solvents by ^{15}N NMR spectroscopy using potassium azide-*1,3-*$^{15}N_1$ (99%) as a tracer. In dichloromethane using potassium azide solubilized with 18-crown-6,[3] azide-ion exchange (eq 2) leading to **1**-*1,3-*$^{15}N_1$ takes place, just as it does in dimethyl

$$TsN_3 + {}^{15}N{=}N{=}N^- \rightarrow Ts{-}{}^{15}N{=}N{=}N + Ts{-}N{=}N{=}{}^{15}N + N_3^- \qquad (2)$$

sulfoxide. However, in this solvent, reaction 1 does not occur. Instead, ^{15}N NMR spectra[4a] (Figure 1), show a slow and unexpected formation of **1**-*2-*^{15}N (eq 3). The metathesis products of

$$TsN_3 + {}^{15}N{=}N{=}N^- \rightarrow Ts{-}N{=}{}^{15}N{=}N + N_3^- \qquad (3)$$

1 with azide-*1,3-*$^{15}N_1$, **1**-*1-*$^{15}N_1$ (236.5 ppm), and **1**-*3-*^{15}N (133.3 ppm) form quickly in accord with eq 2 (Figure 1a). The resonance of the terminal nitrogen of azide ion is strong at 275.8 ppm. The signals at 154.0 and 295.6 ppm result from an as yet unidentified product of a separately observable reaction of azide ion with dichloromethane. After 5 days (Figure 1b), no azide ion remained, and there is clear formation on the order of 10% of **1**-*2-*^{15}N (142.5 ppm).[4b]

The formation of *p*-toluenesulfonyl azide-*2-*^{15}N is consistent with addition of labeled azide ion to **1** to give a *p*-toluenesulfonylhexazene (**2**) (eq 4) which could give ^{15}N scrambling of

$$Ts{-}N{=}N{=}N + {}^{15}N{=}N{=}N^- \rightarrow Ts{-}N^-{-}N{=}\underset{\mathbf{2}}{N}{-}{}^{15}N{=}N{=}N \qquad (4)$$

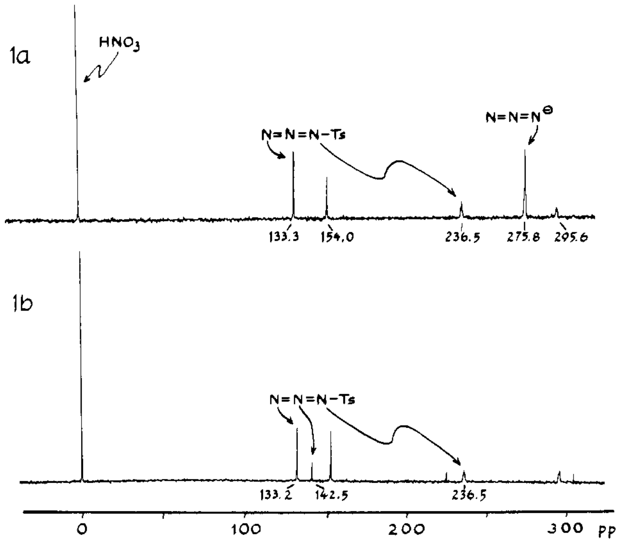
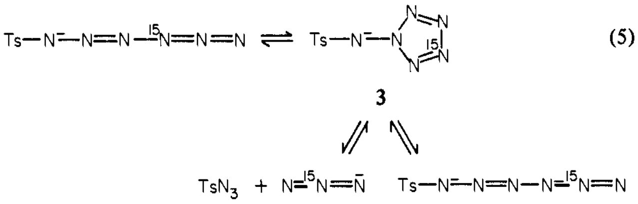


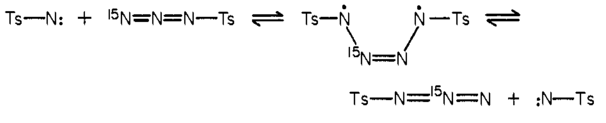
Figure 1. ^{15}N spectra of a solution containing 5.9 × 10^{-3} mol of potassium azide-*1,3-*$^{15}N_1$, 6.1 × 10^{-3} mol of **1**, and 6.7 × 10^{-3} mol of 18-crown-6 in 30 mL of dichloromethane, taken with a 20-μs pulse and 10-s repetition rate in a Bruker WH-180 spectrometer[4a] at 25 °C. (a) Spectrum started immediately after preparation, 3748 transients; (b) five days after preparation, 5213 transients. The signals at 225 ppm and 304 ppm are artifacts of the instrument.

the *azide ion* if it were to be involved in *reversible* formation of the *N*-pentazole derivative **3** (eq 5).[5,6] Once azide-*2-*^{15}N is formed,



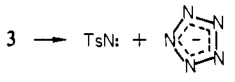
(5)

then metathesis between **1** and this ion would lead to **1**-*2-*^{15}N. The only reasonable alternative we have so far devised to formation of **3** for the observed ^{15}N scrambling is a chain addition–dissociation of singlet[7] *p*-toluenesulfonylnitrene and **1**-*3-*^{15}N (eq 6).[8]



(6)

$$\mathbf{2} \longrightarrow TsN{:} + N_2 + N_3^- \qquad (7)$$



(8)

Possible *p*-toluenesulfonylnitrene precursors include **2** and **3**. Loss of dinitrogen and azide ion from **2**[9] (eq 7) or elimination of pentazole anion from **3**[10] (eq 8) would be expected to give the

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(1) (a) Supported by the National Science Foundation. (b) IBM Graduate Fellow, 1979–1980. (c) DAAD Postdoctoral Fellow, 1980–1981.

(2) Casewit, C.; Roberts, J. D. *J. Am. Chem. Soc.* **1980**, *102*, 2364–2368.

(3) Gokel, G. W.; Durst, H. D. *Aldrichim. Acta* **1976**, *9*, 3–12.

(4) (a) The ^{15}N spectra were measured at 18.25 MHz with a Bruker WH-180 spectrometer using 25-mm sample tubes. Lock and reference signals were provided by a concentric 5-mm tube containing 1 M 95% $H^{15}NO_3$ in D_2O solution. Spectra were proton coupled and obtained at ambient probe temperature. (b) A mixture of 1-, 2-, and 3-^{15}N-labeled **1**[2] in dichloromethane shows ^{15}N resonances at 133.2 (N3), 142.4 (N2), and 236.5 (N1) ppm. Shift assignments are based on ^{15}N labeling experiments reported by: Duthaler, R. O.; Förster, H. G.; Roberts, J. D. *J. Am. Chem. Soc.* **1978**, *100*, 4974–4979. The N1 resonance for potassium azide-*1-*^{15}N in dichloromethane, solubilized by 18-crown-6, comes at 275.8 ppm.

(5) The reaction of heterocyclic azidinium salts with azide ion is also thought to involve substituted hexazene intermediates. Balli, H. *Helv. Chim. Acta* **1974**, *57*, 1912–1919.

(6) A similar ring-chain equilibrium has been postulated for the reaction of aryldiazonium salts with azide ion. Smith, P. J.; Westaway, K. C. In "The Chemistry of Diazonium and Diazo Groups"; Patai, S., Ed.; Interscience: New York, 1978; pp 716–717.

(7) Nitrene singlet-to-triplet intersystem crossing is inhibited by dichloromethane. Casagrande, P.; Pellacani, L.; Tardella, P. A. *J. Org. Chem.* **1978**, *43*, 2725–2726.

(8) It should be noted that attack of electrophilic *p*-toluenesulfonylnitrene on the terminal nitrogen of **1** would be not an expected reaction because the terminal nitrogen of **1** normally reacts with nucleophiles. Breslow, D. S. In "Nitrenes"; Lwowski, Ed.; Interscience: New York, 1970; Chapter 8.

(9) See ref 2 for a similar decomposition in the coupling of azide ion with heterocyclic azidinium salts.

(10) Some related compounds have been investigated as possible sources of *p*-toluenesulfonylnitrene by: Abramovitch, R. A.; Takaya, T. *J. Org. Chem.* **1973**, *38*, 3311–3316. Abramovitch, R. A.; Bailey, T. D.; Takaya, T.; Uma, V. *J. Org. Chem.* **1974**, *39*, 340–345.

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