the dinitrobenzenes, however, electron transfer can only be observed photochemically. Based on our observation of photochemical oxidation of $Mo(NCS)_6^{3-}$ by 1,3-dinitrobenzene, the redox-active $Mo(NCS)_6^{3-}$ excited state may have an energy as high as 1.3 eV. Since the $Mo(NCS)_6^{3-}$ absorption spectrum indicates that the lowest energy excited state lies no higher than 1.0 eV, our photochemical experiments suggest that upper excited states of $Mo(NCS)_6^{3-}$ may be participating in these electron-transfer reactions.

The properties of photogenerated $Mo(NCS)_6^{2-}$ can be explored further by using CCl_4 as an irreversible electron acceptor. One-electron reduction of CCl_4 is followed by rapid fragmentation;[12] thus, back electron-transfer reactions such as (2) should be inhibited. Flash irradiation of $Mo(NCS)_6^{3-}$ in CH_3CN–CCl_4 (90:10 w/w) results in immediate permanent formation of red-brown $Mo(NCS)_6^{2-}$, which is stable under these conditions.

Photooxidation of $Mo(NCS)_6^{3-}$ (ca. 8×10^{-3} M; 0.2 M KNCS) is also observed in CCl_4–H_2O–CH_3CN (7:31:62 w/w; chosen to keep H_2O and CCl_4 stable in the same phase), but the $Mo(NCS)_6^{2-}$ that is produced slowly disappears. After several flashes, each of which leads to formation and slow disappearance of $Mo(NCS)_6^{2-}$, a new, permanent absorbance at 456 nm is observed. We attribute this new feature to the molybdenum(V) product formed by disproportionation of $Mo(NCS)_6^{2-}$. Of the three possible Mo(V) products suggested by Sykes and co-workers,[8] both $MoO(NCS)_5^{2-}$[13] and $Mo_2O_4(NCS)_6^{4-}$[10] exhibit intense absorption near 456 nm. However, the mononuclear complex is stable only in strongly acidic solutions.[13b,14] Thus, $Mo_2O_4(NCS)_6^{4-}$ is the most likely product under our conditions, and the overall sequence of reactions is as follows:

$$Mo(NCS)_6^{3-} + CCl_4 \xrightarrow{h\nu} Mo(NCS)_6^{2-} + [CCl_4^-] \quad (3)$$

$$[CCl_4^-] \xrightarrow{\text{fast}} \text{decomposition products} \quad (4)$$

$$4Mo(NCS)_6^{2-} + 4H_2O \xrightarrow{\text{slow}} 2Mo(NCS)_6^{3-} + (SCN)_3MoO(\mu\text{-}O)_2MoO(NCS)_3^{4-} + 8H^+ + 6NCS^- \quad (5)$$

We observe first-order kinetics (k_{obsd} ca. 7 s^{-1}) for disappearance of $Mo(NCS)_6^{2-}$; this is consistent with a mechanism for reaction 5 that involves initial rate-limiting aquation of $Mo(NCS)_6^{2-}$.

We have therefore shown for the first time that molybdenum(III) complexes can undergo facile photoredox reactions and that photoinitiated two-electron oxidations can be accomplished by disproportionation of the initial electron-transfer products.[15] Experiments now in progress include nanosecond flash photolysis[16] and selective irradiation of $Mo(NCS)_6^{3-}$ in its weak low-energy absorption bands, in order to examine the redox-active excited states more directly. These results are of particular interest because of the possibility that electron transfer may be occurring from upper excited states. Also under study are the extension of these reactions to other second- and third-row d^3 complexes and the reactivity of the photogenerated oxo complexes toward organic and inorganic substrate molecules.

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Stereochemistry of Methylation in Thienamycin Biosynthesis: Example of a Methyl Transfer from Methionine with Retention of Configuration

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The carbapenem antibiotic thienamycin[1] (I) is derived biosynthetically from glutamic acid, which provides the pyrroline ring,[2] acetate and cysteine, providing C-6 and C-7 of the β-lactam ring and the cysteamine side chain, respectively,[3] and the methyl group of methionine, which gives rise to both carbon atoms of the hydroxyethyl side chain.[3] In a double-labeling experiment, Williamson et al.[3] demonstrated that [methyl-^{14}C,^{3}H]methionine is incorporated with 58% tritium retention, relative to ^{14}C, corresponding to 87% of the maximum value for retention of four of the six hydrogens of the two methyl groups.

In order to obtain more information on this intriguing double-methylation sequence, we examined the steric course of the transfer of the methionine methyl group. We first confirmed the incorporation of an intact methyl group into C-9 by using L-[methyl-^{13}C,^{2}H$_3$]methionine. This material, synthesized[4] from $^{13}C^2H_3I$ (Merck, 99% ^{13}C, 98% ^{2}H), was fed at a concentration of 0.74 mM to 1.2 L (3 × 40 mL) of a resting cell suspension of *Streptomyces cattleya*.[3] The fermentation was terminated 19 h later and I (3.2 mg) was isolated as described earlier.[3,5] The ^{13}C NMR spectrum of the sample was recorded at 4 °C at 75.5 MHz (Bruker WM 300) with proton broad-band decoupling and with and without deuterium broad-band decoupling. The results (Figure 1) clearly show that ^{13}C is incorporated into C-9 with retention of all three deuterium atoms and into C-8 with retention of one atom of deuterium. There seems to be little or no washout of deuterium from either position.

With this information at hand, we fed (*methyl-R*)- and (*methyl-S*)-[methyl-^{2}H$_1$,^{3}H]-L-methionine[6] (*R*, 2.79 mCi/mmol, max 80% ee *methyl-R*; *S*, 1.10 mCi/mmol, max 75% ee *methyl-S*[7]) to 80-mL cultures of *S. cattleya* (15 μCi per experiment). When tritium incorporation into I had reached a maximum, as determined by HPLC and liquid scintillation counting, 2 mg of unlabeled I was added and the labeled I was isolated and purified[3,5] (1-4% tritium incorporation). Kuhn-Roth oxidation of the products gave acetic acid samples which were analyzed for their chirality by the method of Cornforth[8] and Arigoni[9] using our previously described procedure.[10] The acetic acid obtained by

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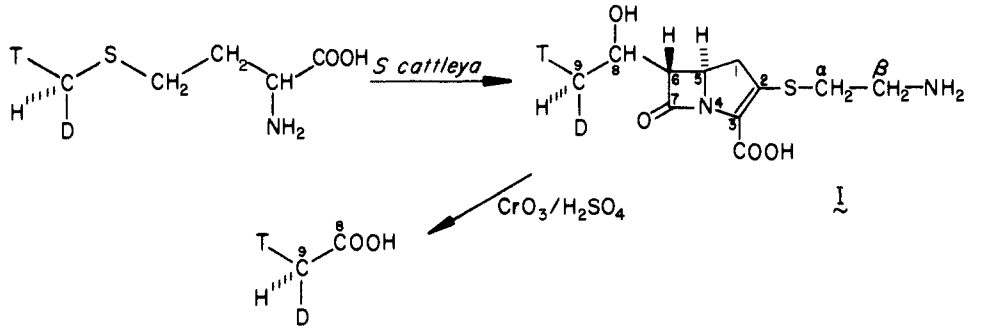
Scheme I



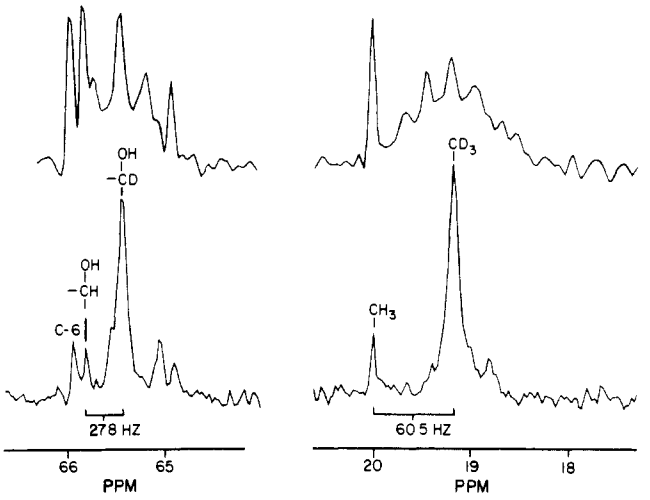


Figure 1. ^{13}C NMR spectrum of thienamycin biosynthesized from [methyl-^{13}C,$^{2}H_3$]methionine. Signals for C-8 (left) and C-9 (right) with broad-band ^{1}H decoupling (top tracings) and with broad-band ^{1}H and ^{2}H decoupling (bottom tracings).

degradation of I from (*methyl-R*)-methionine had an *F* value[10] of 69 indicating 66% ee *R* configuration of the thienamycin methyl group. Conversely, the acetate from the (*methyl-S*)-methionine experiment had $F = 35$ corresponding to 52% ee *S* configuration of the thienamycin methyl group. A complete repetition of the experiments confirmed these results.

The above results demonstrate that the biosynthesis of thienamycin involves transfer of a methyl group from methionine or, most likely, its activated form, *S*-adenosylmethionine[11] (AdoMet), to an acceptor carbon with net retention of configuration (Scheme I). This is in marked contrast to the findings with all other AdoMet-dependent methyltransferases studied to date which, without exception, have been found to catalyze methyl transfer with inversion of configuration. The 11 examples include enzymes catalyzing methyl transfer to oxygen,[12-14] nitrogen,[6,13,15,16] and sulfur[13] as well as to carbon.[6,13,17] This stereochemical uniformity has been interpreted to indicate a single transfer of the methyl group directly from the sulfur of AdoMet to the acceptor nucleophile in an S_N2 transition state.[12] Methyl transfer to C-8 of I could be followed by hydride migration from C-8 to C-6 and proton loss from the methyl group to give a C-9 methylene group, in analogy to the side-chain methylation of sterols.[13] Such a methylene group could be reduced to give either an *R* or an *S* methyl group. However, the full retention of three atoms of deuterium from [^{13}C,$^{2}H_3$]methionine at C-9 argues against this possibility. It seems more likely, then, that C-9 of I is derived by a mechanistically different methylation reaction involving two sequential methyl transfers, each proceeding with inversion. Since the thienamycin fermentation has been noted to have a cobalt requirement,[3] one may tentatively speculate that a corrin could serve as an intermediate carrier. This would have an analogy in the formation of methionine from 5-methyltetrahydrofolate by B_{12}-dependent methionine synthase, which we have recently shown to proceed with net retention of methyl group configuration.[18]

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Enhancement of Radioactivity of ^{14}C–^{12}C Mixtures via Partial Reduction

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Observable nuclear transmutation reactions have occupied an extremely important position in nuclear medicine, nuclear energy, and geological and anthropological dating. Further, the concentration of radioactive materials (enhancement of radioactivity) has grown to be very important in the treatment and storage of radioactive waste and in the development of techniques for reactivating spent nuclear fuel. These facts coupled with our observation[1] that the solution electron affinities of perdeuterated polyaromatics are less than that of the protiated materials led us to investigate the possibility of increasing the radioactivity of benzophenone-*carbonyl*-^{14}C (BZO-14C)–cold benzophenone (BZO-12C) mixtures via the partial reduction of these mixtures to the ketyls.

When 0.6–5.0-mmol samples of a radioactive (0.02–0.16 μCi)[2] mixture of BZO-14C and BZO-12C are reduced with deficient amounts of sodium metal in liquid ammonia (20–40 mL), the concentrations of the cold and hot anion radicals and neutral molecules are controlled via reaction 1.

$$\text{BZO-12C}^{\bullet-} + \text{BZO-14C} \rightleftharpoons \text{BZO-12C} + \text{BZO-14C}^{\bullet-} \quad (1)$$

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