Degradation of a VX Analogue: First Organometallic Reagent To Promote Phosphonothioate Hydrolysis Through Selective P−S Bond Scission

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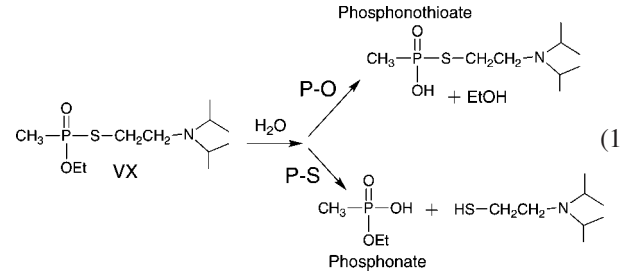
We report the first case of a metal complex that degrades a neurotoxin mimic under extremely mild conditions (pH 6.8, room temperature). The metallocene bis(η^5-cyclopentadienyl)molybdenum(IV) dichloride (Cp_2MoCl_2; Cp = η^5-C_5H_5) efficiently hydrolyzes the compound *O,S*-diethyl phenylphosphonothioate (DEPP), whose core functional group mimics the neurotoxin VX. Moreover, this is one of the few examples where phosphonothioate degradation yields exclusively the desired P−S bond scission under mild aqueous conditions (pH 7.2, 30 °C). Activation parameters for DEPP hydrolysis by Cp_2MoCl_2 in aqueous THF/acetone indicate (E_a = 86 kJ/mol, $\Delta H^{\ddagger}$= 83 kJ/mol, and $\Delta S^{\ddagger}$ = −10 J/(mol K)) an intramolecular hydrolytic process that goes through an ordered transition state. Alteration of the cyclopentadienyl ligand showed that *ansa*-Cp_2MoCl_2 with enhanced Mo(IV) electrophilicity significantly decreased DEPP hydrolysis, while $(CpMe)_2MoCl_2$ with increased Mo(IV) electron density had the opposite effect. These structure–activity relationships as well as the activation parameters indicate DEPP hydrolysis is achieved by nucleophilic attack of a Cp_2Mo-bound hydroxide on the phosphonothioate.

Introduction

Organophosphates, such as phosphonothioates, are the key functional group in chemical warfare (CW) nerve agents.[1] Among them are the nonvolatile and persistent V-type such as *O*-ethyl *S*-[2-(diisopropylamino)ethyl] methylphosphonothioate (VX), of which the U.S. has stockpiled several thousand tons.[2] The degradation of these CW neurotoxins include incineration,[3] alkaline hydrolysis,[4] perhydrolysis,[5] and adsorption.[6] Hydrolytic degradation of phosphonothioates may proceed through either P−S or P−O bond scission to yield the respective phosphonate [RP(O)(OR′)(OR″)] and phosphonothioate [RP(O)(SR′)(OR″)]. In the case of alkaline hydrolysis of VX, degradation occurs with both P−O (13%) and P−S (87%) bond scission and the phosphonothioate ion is nearly as toxic as the parent VX (eq 1).[7] Therefore, there is a major incentive to find reactions that selectively cleave the P−S bond of phosphonothioates. To this end, there are several reports of oxidative hydrolytic cleavage of phosphonothioates with oxone[8] and micellar complexes,[9] and the U.S. Army is currently pilot-testing alkaline hydrolysis in conjunction with biodegradation of stockpiled VX.



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Despite the urgency to degrade CW organophosphate neurotoxins, there are few reports that use metals or metal complexes[10] to achieve this goal. This is particularly curious, in light of the fact that the active site of the phosphotriesterase from *Pseudomonas diminuta* used to hydrolyze organophosphate insecticides consists of two chelated zinc atoms.[11] We therefore report the first case of a metal complex that selectively cleaves

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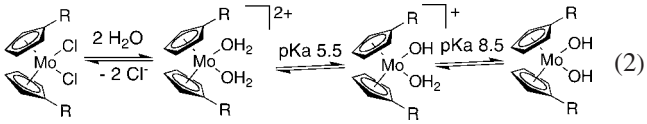
the P−S bond of a phosphonothioate that models the VX nerve gas. While there are other findings of selective P−S scission of phosphonothioates,[5,8,9] this is the first hydrolytic one assisted by a metal under mild aqueous conditions.

The metallocene bis(cyclopentadienyl) molybdenum(IV) dichloride (Cp_2MoCl_2; Cp = η^5-C_5H_5)[12] was chosen because of its many hydrolytic reactions, which include aqueous C−H activation and[13] nitrile[14] and ester[15] hydrolysis. Structurally, Cp_2MoCl_2 resembles a clamshell where both cyclopentadienyl ligands flank a pseudotetrahedral Mo(IV) coordinated to two chlorides. In water, the cyclopentadienyl rings remain bound to the Mo(IV) center even at neutral pH, while both chlorides are rapidly hydrolyzed off ($t_{1/2} \approx 20$ min) to form aquated species, as shown in eq 2.[16] A number of studies have shown that in aqueous solution the molybdocene species exist as an equilibrium mixture of the aquated monomer and μ-OH dimer[17] wherein the active complex is the monomer (eq 3).[18]



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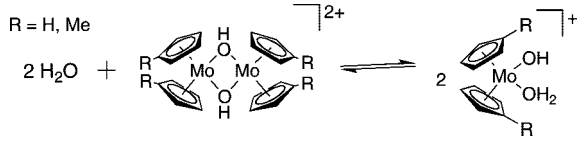

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We have reported that the metallocene bis(cyclopentadienyl)-molybdenum(IV) dichloride (Cp_2MoCl_2; Cp = η^5-C_5H_5) effectively degrades the phosphate triester pesticides parathion and paraoxon[19] as well as thiophosphinates[20] in aqueous media. In both cases we found a hydrolytic process with a large negative entropy of activation suggestive of a bimolecular mechanism or one that goes through an ordered transition state. We now extend these findings to phosphonothioate hydrolysis with the key goal of achieving selective P−S versus P−O bond scission.

Results and Discussion

The title compound for this analysis, *O*,*S*-diethyl phenylphosphonothioate (DEPP),[21] allows us to interrogate whether the molybdenum metallocenes exhibit any selectivity in cleaving the P−S versus the P−O bond. Hydrolysis of DEPP in 0.10 M NaOH yields the ethanolate and mercaptoethanolate products associated with the respective P−O and P−S scission (equation in Figure 1), as determined by ^{1}H NMR with addition of the corresponding alcohol/thiol (Supporting Information, Figure S1). The ratio of mercaptoethanol to ethanol was ∼4:1, which corresponds to the ratio of the two product signals in the ^{31}P NMR spectrum (Figure 1). In the alkaline hydrolysis of DEPP, the two product signals correspond to *O*-ethyl phenylphosphonate (P−S cleavage) and *S*-ethyl phenylphosphonothioate (P−O cleavage) which appear at 13 and 31 ppm, respectively. That the PhP(O)(SEt)(O$^-$) phosphonothioate signal is 4 times smaller than the PhP(O)(OEt)O$^-$ phosphonate species signal and is displaced ∼20 ppm downfield is consistent with similar findings in the alkaline hydrolysis (0.1 M NaOH) of VX, which also yields both phosphonate and phosphonothioate products in a 76:24 ratio.[22] The initial findings on the alkaline hydrolysis of DEPP indicate that this phosphonothioate serves as a reasonable model of the VX neurotoxin in delineating P−O versus P−S bond cleavage.

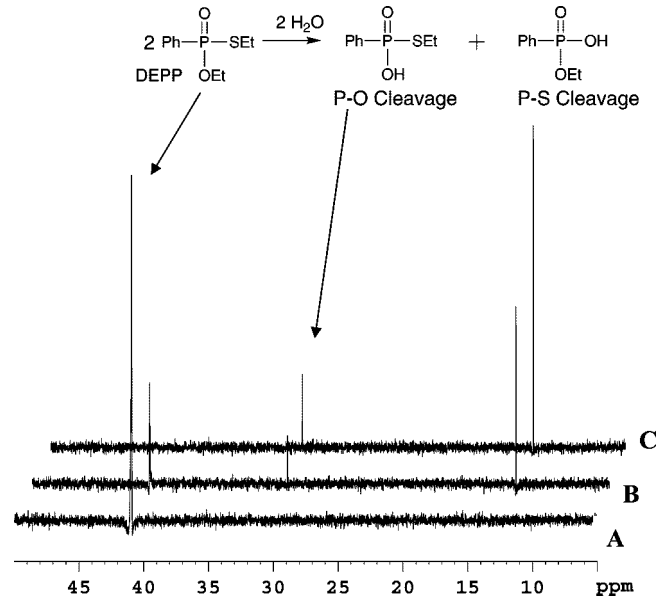

Figure 1. ^{31}P NMR of DEPP in 0.1 M NaOH reaction (25 °C): (A) time = 0; (B) intermediate; (C) final.

The initial molybdenum metallocene we used to hydrolyze DEPP was Cp_2MoCl_2. The poor water solubility of the phosphonothioate required the addition of 1 mL of THF to a 1 mL buffered (pH 7.2, 270 mM MOPS) aqueous solution of Cp_2MoCl_2 (67 mM) and DEPP (34 mM). In the ∼20 min for the DEPP to dissolve completely in the aqueous THF solution, both chlorides would be hydrolyzed off[16] the Cp_2MoCl_2 to yield an equilibrium mixture of monomeric and dimeric Cp_2Mo(aq) species.[17,23] Figure 2 clearly shows the disappearance of the starting phosphonothioate (44 ppm) and the appearance of only *one* new upfield signal at 12 ppm. Attempts to gauge the rate *acceleration* of DEPP degradation by Cp_2MoCl_2 were unsuccessful, as the phosphonothioate in the absence of the metallocene exhibited no change in the ^{31}P NMR spectra under identical conditions (pH 7.2) for 2 months, even at 50 °C.

Initially the closeness of the chemical shift of this product peak to the phosphonate product from the alkaline hydrolysis

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(23) In addition, the Cp_2MoCl_2 was initially made as a 67 mM stock solution in a 270 mM MOPS buffer prior to DEPP addition, which further hydrolyzed off both chloride ligands.

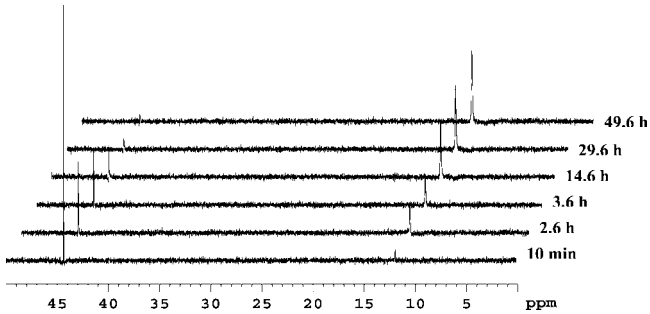

Figure 2. ^{31}P NMR stacked plot of DEPP (17 mM) hydrolysis by Cp_2MoCl_2 (33 mM) at 25 °C, showing degradation of the starting 44 ppm signal, while a 12 ppm resonance, due to P−S scission, grows in. Spectra were run in a 2 mL 1:1 THF−D_2O solution buffered in 135 mM MOPS (pH 7.2).

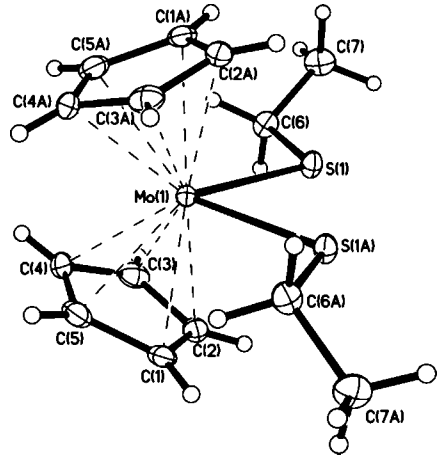

Figure 3. ORTEP of $Cp_2Mo(SEt)_2$ obtained from the addition of Cp_2MoCl_2 with mercaptoethanol. Selected bond distances (Å) and angles (deg): Mo–S = 2.4725(9); S–Mo–S = 76.91(4); Cp(centroid)–Mo–Cp(centroid) = 134.7; Cp(centroid)–Mo = 2.00. Thermal ellipsoids are drawn at the 30% probability level.

of DEPP (Figure 1) leads to the hypothesis that Cp_2MoCl_2 hydrolysis of DEPP yields exclusively the desired P−S scission. Identification of this product at 12 ppm as the phosphonate was done by authentic addition of the sample from the alkaline hydrolysis of DEPP, which yielded both the $PhP(O)(OEt)O^-$ phosphonate and $PhP(O)(SEt)O^-$ phosphonothioate anions. Addition of these alkaline hydrolysis products to the final spectrum in Figure 2 (Cp_2MoCl_2 + DEPP) enhanced only the signal at 12 ppm with no additional ^{31}P NMR signals (Supporting Information, Figure S2).

Attempts to confirm exclusive P−S scission through ^{1}H NMR face the issue of the thiophilic nature of Cp_2Mo. Prior synthetic studies show that Cp_2MoCl_2 and thiols yield discrete $Cp_2Mo(SR)_2$ complexes.[24] Therefore, the thiol produced from P−S scission of DEPP would be expected to bind the Cp_2Mo, which precludes identifying thiolate products through simple authentic addition of β-mercaptoethanol. Indeed, a simple Cp_2MoCl_2 + EtSH reaction alone in the MOPS buffer showed no free EtSH but rather a new complex that subsequently crystallized out and its structure (Figure 3) was determined by X-ray diffraction methods. The $Cp_2Mo(SEt)_2$ complex has C_2 symmetry, and its parameters are unexceptional (Supporting Information and Figure 3) with regard to the Mo−S bond distance and bond angle. Sandwich complexes of the form $Cp_2Mo(SR)_2$ are well-known,[24] but this is the first example

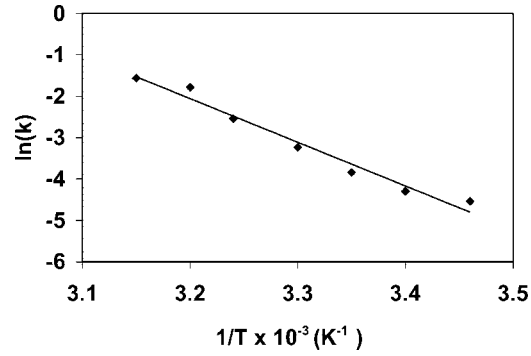

Figure 4. Arrhenius plot compiled from hydrolysis of DEPP (17 mM) by Cp_2MoCl_2 (33 mM) buffered in 2 mL of 135 mM MOPS/THF (pH 7.2) with 0.5 mL of added acetone. E_a = 86 kJ/mol. The Supporting Information (Figure S3) shows a representative kinetics plot for the hydrolysis of DEPP by Cp_2MoCl_2 at 35 °C.

where the Cp_2Mo moiety is bound to two separate mercaptoethanol ligands.

Although confirmation of P−S scission through ^{1}H NMR was problematic, we see no evidence of P−O scission, as no ethanol was detected in all the Cp_2Mo + DEPP reactions. This, coupled with the ^{31}P NMR data (Supporting Information) showing authentic addition of the DEPP + hydroxide reaction enhances only the upfield 12 ppm signal of the DEPP + Cp_2MoCl_2 reaction, indicates that this Mo metallocene selectively yields P−S scission of phosphonothioates. The selectivity in P−S scission by Cp_2Mo may be due to the metallocene's thiophilicity, as evidenced by the many $Cp_2Mo(SR)_2$ structures;[24] it is possible that the Cp_2Mo coordinates to the sulfur atom of the departing ethanethiolate upon P−S bond scission.

Attempts to measure the activation parameters for DEPP hydrolysis by Cp_2MoCl_2(aq) were beset by solubility difficulties. At temperatures >35 °C, the DEPP + Cp_2MoCl_2 in the MOPS buffer separated into two phases which required the presence of additional acetone to maintain a homogeneous solution. This in turn restricted the upper temperature at which kinetic studies could be performed, due to the low boiling points of acetone and THF. Nevertheless, a limited 20−45 °C temperature range gave a reasonable Arrhenius plot (Figure 4), from which the following activation parameters were obtained: E_a = 86 kJ/mol, $\Delta H^{\ddagger}$ = 83 kJ/mol, and $\Delta S^{\ddagger}$ = −10 J/(mol K). To a first approximation, the activation energy and $\Delta H^{\ddagger}$ value are within 5% of the values for the hydrolysis of *p*-methoxythiophenyl diphenylphosphinate ($Ph_2P(O)Ar$; Ar = *p*-$CH_3O-C_6H_4-S$) by Cp_2MoCl_2(aq) that we obtained in prior studies.[20] The major difference between DEPP and $Ph_2P(O)Ar$ hydrolyses lies with the entropy of activation, where the latter exhibited $\Delta S^{\ddagger} = -77$ J/(mol K), suggesting the phosphonothioate DEPP has a less ordered transition state in Cp_2Mo-promoted hydrolysis. Alternatively, it could be argued that phosphinate hydrolysis of $Ph_2P(O)Ar$ by Cp_2MoCl_2 is a bimolecular process, whereas DEPP hydrolysis is an intramolecular process that proceeds through an ordered transition state.

It is interesting to note that Yang and co-workers report the E_a values for P−S and P−O hydrolysis of the phosphonothioate

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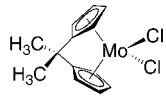
VX to be 60.6 and 61.0 kJ/mol at pH 12. This is in contrast to our much larger activation energy (86 kJ/mol) for DEPP hydrolysis by Cp_2MoCl_2 at pH 7.2, which suggests the metallocene-promoted process is more selective but not faster than alkaline hydrolysis. Indeed, DEPP hydrolysis in 0.1 M NaOH proceeds 8–10 times faster than Cp_2MoCl_2-promoted hydrolysis.

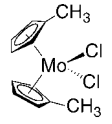
Prior studies with molybdocene compounds indicate that thiophosphinate[20] and nitrile[14] hydrolysis reactions are promoted by the withdrawal of electron density from the substrate. As such, we set out to enhance the electrophilicity of the molybdenum center with the bridged cyclopentadienyl ligand system, otherwise known as the *ansa*-Cp ligands, specifically the 2,2-bis(η^5-cyclopentadienyl)propane ligand. Work on *ansa*-zir-



isopropyl *ansa*-Cp_2MoCl_2

conocene systems showed the electron-withdrawing nature of the bridged cyclopentadienes results from the enhanced back-donation from the metal to the low-energy Cp_2 acceptor orbital.[26] Further work on Cp_2MoH_2 and its *ansa*-[2,2-bis(η^5-cyclopentadienyl)propane] derivative showed a substantially lower Mo–H stretch for the bridged compound consistent with the ligand's electron-withdrawing nature.[27] While the isopropyl-bridged *ansa*-Cp_2MoCl_2 exhibited P−S bond scission, it did not show any improvement in the rates of hydrolysis of DEPP compared to those for the parent Cp_2MoCl_2. In fact, the stacked ^{31}P NMR plots in the Supporting Information show *ansa*-Cp_2MoCl_2 to be almost 2 orders of magnitude slower in hydrolyzing DEPP under the best conditions (Supporting Information, Figure S4). Consistent with the finding on the poor performance of an electrophilic metal center was that the Mo(V) metallocene $Cp_2MoCl_2^+$ degraded DEPP no better than *ansa*-Cp_2MoCl_2.

To that end, we set out to see if adding an electron-donating methyl group would alter the rate of DEPP hydrolysis by using the complex (η^5-C_5H_4−CH_3)$_2MoCl_2$ (Cp'_2MoCl_2). Surprisingly,



Cp'_2MoCl_2

the rate of DEPP degradation dramatically improved with Cp'_2MoCl_2 and an intermediate ^{31}P NMR signal at 25 ppm was seen.

Initially the signal at 25 ppm after 1.5 h of reaction suggests P−O cleavage takes place to yield a phosphonothioate. However, key results show that this signal is due to a Cp_2Mo−phosphonate species. Upon anaerobic addition of hydroxide base, this 25 ppm signal completely and instantly goes away. Confirmation (or disconfirmation) of this signal in Figure 5 as the phosphonothioate through authentic addition with the DEPP + OH reaction then becomes problematic, as the additional hydroxide of the latter reaction decomposes the 25 ppm signal. It is highly unlikely that this intermediate signal is the $PhP(O)(SEt)O^-$ compound, as we have shown the phosphonothioate product to be highly stable in alkaline solution (Figure 1). We believe this signal is due to a Cp'_2Mo−phosphonate adduct, for when we add $PhP(O)(OEt)O^-$ [28] with Cp'_2MoCl_2 in a similar THF/MOPS buffer, a signal at 25 ppm appears. Moreover, prior work with $Ph_2P(O)SAr$[20] showed an intermediate signal displaced ~15 ppm downfield of the final phosphinate product $Ph_2P(O)O^-$, which, like the case in Figure 5, goes away under alkaline addition or at longer reaction times.

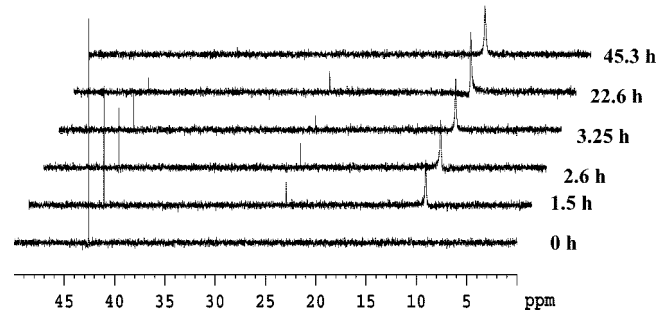


Figure 5. ^{31}P NMR of Cp'_2MoCl_2 (33 mM)+ DEPP (17 mM) at 35 °C in pH 7.2 MOPS/THF buffer. Note that the last time spectrum is also seen when 0.1 M NaOH is added to the prior (22. Six h) sample.

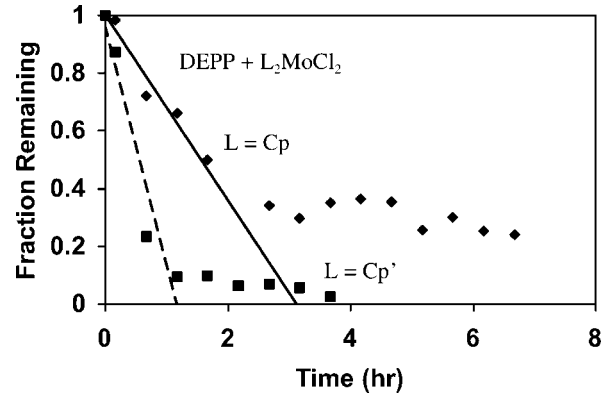


Figure 6. Hydrolysis of 17 mM DEPP with 33 mM Cp'_2MoCl_2 () and Cp_2MoCl_2 (◆) at 35 °C in 135 mM pH 7.2 MOPS buffer. Linear fits to the initial hydrolysis rates gave 0.83 and 0.32 h^{-1} for Cp'_2MoCl_2, and Cp_2MoCl_2, respectively.

Ideally, a comparison of DEPP hydrolysis by Cp_2MoCl_2(aq) versus Cp'_2MoCl_2(aq) required first-order rate constants for both metallocenes under identical conditions. This is problematic, for the limited Cp_2MoCl_2 solubility in aqueous THF precluded the high concentrations necessary for pseudo-first-order kinetics. Instead, we obtained only initial rates of DEPP hydrolysis by identical concentrations of Cp_2MoCl_2 and Cp'_2MoCl_2. Moreover, to discount any solubility and monomer–dimer equilibration issues, both metallocenes (67 mM in 1 mL) were first completely dissolved and stirred anaerobically in the aqueous MOPS (pH 7.2 270 mM) buffer for ~3 h prior to the addition of the DEPP/THF (1 mL of 34 mM) solution. Figure 6 is a summary of three trials showing the fraction remaining of the original DEPP (43 ppm) signal as it undergoes hydrolysis by either Cp_2MoCl_2 or Cp'_2MoCl_2. When the initial rates are fitted to a linear decay, it clearly shows the methylated molybdocene degrades the DEPP faster and more completely than the parent Cp_2MoCl_2. In spite of this enhanced rate of DEPP hydrolysis by Cp'_2MoCl_2, we saw no evidence for any turnover by the Mo metallocenes.

Our initial hypothesis on phosphonothioate hydrolysis treated the Mo(IV) center as a Lewis acid that activated the

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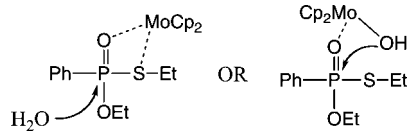
Scheme 1



phosphorus center of DEPP. However, results with *ansa*-$(CH_3)_2C-Cp_2MoCl_2$(aq) and with $Cp_2Mo^{V}Cl_2^{+}$, which have the more electrophilic molybdenum center, reveal that DEPP hydrolysis is actually deactivated. A similar observation was recently made by Ahmed and Tyler,[29] wherein they compared ester hydrolysis by $Cp_2Mo(OH)(OH_2)^{+}$ and the *ansa*-tetramethylethylene $(C_2Me_4(C_5H_4))_2Mo(OH)(OH_2)^{+}$ complex. In the case of *p*-nitrophenyl phosphate and ethyl acetate, they saw significantly slower rates of hydrolysis (5–12 fold) by the *ansa* molybdocene compared to the rates for the parent nonbridged $Cp_2Mo(OH)(OH_2)^{+}$ compound. This was indicative that the unsubstituted molybdenocene was the more reactive agent in promoting ester hydrolysis. The authors suggested the changes in the electronic environment of the cyclopentadienyl ligand counteract one another; the enhanced substrate activation by a more electrophilic Mo metal is offset by possible deactivation of the metal-bound hydroxyl nucleophile. The negligible hydrolysis of DEPP by the isopropyl *ansa*-Cp_2MoCl_2 and the Mo(V) $Cp_2MoCl_2^{+}$ is consistent with the ester hydrolysis findings of Ahmed and Tyler. While electrophilic deactivation may to a first approximation rationalize the decreased DEPP hydrolysis by *ansa*-Cp_2MoCl_2, one cannot overlook how the *ansa* ligand affects the monomer–dimer equilibrium (eq 3), especially in light of the fact that the monomer is the active species. Further studies on the effect of *ansa*-$Cp_2Mo(aq)^{2+}$ dimerization on phosphonothioate hydrolysis are underway.

The one major difference in our results with those of Tyler and Ahmed lies with the DEPP hydrolysis by the methylated Cp'_2MoCl_2 complex. As mentioned before, we allowed the dichloride forms of Cp_2MoCl_2 and Cp'_2MoCl_2 to completely dissolve in the aqueous MOPS (pH 7.2) buffer and to reach equilibrium with ~3 h of stirring prior to the addition of the DEPP. Ahmed and Tyler found that *p*-nitrophenyl phosphate and ethyl acetate hydrolysis (and to a lesser extent 3-hydroxypropionitrile hydration) was significantly retarded by $Cp'_2Mo(OH)(OH_2)^{+}$ relative to $Cp_2Mo(OH)(OH_2)^{+}$. When the chloride forms of the parent and methylated molybdocene complexes are allowed to equilibrate in aqueous solution, the latter complex actually hydrolyzes the phosphonothioate DEPP 2.5 times faster; initial rates of DEPP hydrolysis by Cp_2MoCl_2(aq) and Cp'_2MoCl_2(aq) are 0.32 and 0.83 h^{-1}, respectively. While this modest enhanced DEPP hydrolysis by Cp'_2Mo^{2+}(aq) correlates with the dimer−monomer equilibrium, the large 100-fold difference in K_{eq}[30] in favor of Cp'_2Mo^{2+}(aq) indicates that phosphonothioate activation by an electrophilic metal center plays a key role in DEPP hydrolysis (Scheme 1).

Summary

The phosphonothioate DEPP contains both P−SEt and P−OEt linkages and serves to mimic the core functionality of neurotoxins, including the chemical warfare agent VX. Many past studies on DEPP degradation sought to selectively convert the phosphonothioate to the less toxic phosphonate through selective P−S bond scission. The results in this contribution report the first case of an organometallic complex that promotes this selective phosphonothioate degradation. While there are many hydrolytic and C−H activation reactions promoted by Cp_2Mo(aq), this is the first one that exhibits chemoselectivity in bond scission that has practical implications. Moreover, the results with several derivatives of the parent Cp_2MoCl_2 complex indicate phosphonothioate degradation occurs most likely through nucleophilic activation of the Mo-bound hydroxyl group by the monomeric form of Cp_2Mo^{2+}(aq). As such, we are currently investigating avenues to shift the equilibrium population toward the monomer as well as enhance the nucleophilicity of the Cp_2Mo-bound hydroxo ligand.

Experimental Section

^{31}P and ^{1}H NMR spectra were obtained on a Bruker Avance-300 spectrometer at 121 and 300 MHz, respectively, and phosphorus spectra were acquired with ~$4T_1$ delay. The compounds Cp_2MoCl_2 and $Cp_2MoCl_2^{+}$ were obtained from Strem Chemical Co. (Newburyport, MA), and Aldrich (Milwaukee, WI), respectively. All reagents for the synthesis of phosphonothioates were purchased from Aldrich and used without further purification. The phosphonothioate DEPP was prepared according to the procedure of DeBruin and co-workers.[21] Manipulations with the various metallocenes were done in an Innovative Technology System One glovebox or with standard Schlenk techniques. Cp'_2MoCl_2[31] and *ansa*-$(CH_3)_2C(Cp_2MoCl_2)$[27] were made according to literature protocols. All solvents used in the hydrolysis studies were purged with N_2 for >10 min, and the reported pH readings in D_2O are uncorrected. Stock solutions of Cp_2MoCl_2 (67 mM) in D_2O containing 270 mM MOPS ($pK_a = 7.2$) were made and adjusted to pH 7.2 prior to kinetic measurements.

Typical kinetics with the molybdocenes involved adding DEPP to a 1 mL aqueous stock solution of Cp_2MoCl_2 (67 mM) in the 270 mM MOPS buffer (pH 7.2) such that the phosphonothioate concentration was 34 mM. Due to the poor aqueous solubility of DEPP, 1 mL of THF was added to help solubilize the molybdocene and phosphonothioate to yield the final concentrationd 135 mM MOPS, 34 mM Cp_2MoCl_2, and 17 mM DEPP.

X-ray -quality crystals were grown anaerobically in 5 mm NMR tubes containing Cp_2MoCl_2 (33 mM) and mercaptoethanol (17 mM) in D_2O. X-ray diffraction experiments were carried out on a Bruker Smart Apex diffractometer at 173 K using Mo Kα radiation (λ = 0.710 73 Å). Absorption corrections were done with SADABS. Crystallographic data and details of the X-ray diffraction study of the $Cp_2Mo(SEt)_2$ complex are given in the Supporting Information. The structure was solved using direct methods and refined by full-matrix least-squares methods based on F^2. All non-hydrogen atoms were refined with anisotropic thermal parameters. H atoms were located on the *F* map and refined with isotropic thermal parameters. All calculations were performed with the Bruker SHELXTL package.

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Supporting Information Available: CIF files and tables giving crystallographic data for $Cp_2Mo(SEt)_2$ and figures giving NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

OM7012887

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(30) It was found that the monomer−dimer equilibrium constants for reaction 3 were $(2.7 \pm 0.1) \times 10^{-4}$ and $(2.5 \pm 0.1) \times 10^{-2}$ M for Cp_2Mo^{2+}(aq) and Cp'_2Mo^{2+}(aq), respectively, at pH 6.8 (130 mM MOPS) and 25 °C.[28]

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