Use of an Organometallic Palladium Oxazoline Catalyst for the Hydrolysis of Methylparathion

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Reaction of (*S*)-4-carbomethoxy-2-phenyl-2-oxazoline with $Pd(OAc)_2$ leads to the formation of the *ortho*-palladated complex (*S,S*)-di-μ-(acetate)-bis{2-[2-(4-carbomethoxy)oxazolinyl]-phenyl-*C,N*}dipalladium(II) (**1**). In the presence of water, this complex reacts with methylparathion to produce *p*-nitrophenol as well as two oxazoline palladium dimethylthiophosphate complexes (**2** and **3**), which have been observed in solution by ^{31}P NMR. This reaction is accompanied by racemization of the oxazoline ligand and ultimately produces the dinuclear complex (*R,S*)-di-μ-(dimethylthiophosphate-*S,S*)-bis{2-[2-(4-carbomethoxy)oxazolinyl]phenyl-*C,N*}dipal-ladium(II) (**4**), which features bridging dimethylthiophosphate ligands. At pH 9−10, complex **1** serves as a precatalyst for the hydrolysis of methylparathion. The reaction rate has a first-order dependence in substrate and palladium catalyst with a second-order rate constant of 726 ($\pm$ 30) M^{-1} s^{-1} at pH 9.0.

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Introduction

Organophosphorus pesticides are acetylcholinesterase inhibitors whose structure and properties parallel those of chemical warfare agents.[1] These agents, which were introduced to replace organochlorine pesticides, have become widely used in the agricultural industry both in the United States and around the world. While most of these pesticides have been designed to decompose rapidly, their high solubility in water facilitates transport into groundwater, streams, and estuaries.[2] Moreover, because these pesticides are chemically related to G- and V-type nerve agents, any advances made in their environmental remediation could have an impact on the development of methods for the mitigation of nerve agents.[3,4] These organophosphorus pesticides are for the most part thiophosphate triesters and undergo oxidation to yield the more toxic oxon derivatives. As a result, their destruction is typically achieved by hydrolysis, which leads to the formation of the corresponding thiophosphate diesters. The hydrolysis reaction takes up to several months in water under neutral pH condition[5] but is greatly accelerated in the presence of the metalloenzyme phosphotriesterase (PTE).[6] Academic research efforts have also been directed to the study of coordination and organometallic complexes as hydrolysis catalysts. While the coordination complexes typically display only marginal activity,[7−11] recent reports indicate that organometallic catalysts can be remarkably active.[12−16] In particular, kinetic data gathered on platinum organometallic complexes bearing oximate functionalities[13] indicate that such species parallel the catalytic performance of PTE on a mass basis. In this contribution, we would like to report on the activity of a phenyloxazoline palladium(II) complex (**1**) as a precatalyst for the hydrolysis of methylparathion.

Results and Discussion

(*S*)-2-Phenyl-4-carbomethoxy-2-oxazoline[17] constitutes a polar ligand, which should promote the water solubility of the corresponding metal complexes. Palladation

(1) *Pesticides remediation in soils and water*; Keaney, P. C., Roberts, T., Eds.; Wiley: New York, 1998.
(2) Alegria, H. A.; Shaw, T. J. *Environ. Sci. Technol.* **1999**, *33*, 850−856.
(3) Yang, Y.-C. *Acc. Chem. Res.* **1999**, *32*, 109−115.
(4) Yang, Y.-C.; Baker, J. A.; Ward, J. R. *Chem. Rev.* **1992**, *92*, 1729−1743.
(5) Lartiges, S. B.; Garrigues, P. P. *Environ. Sci. Technol.* **1995**, *29*, 1246−1254.
(6) Donarski, W. J.; Dumas, D. P.; Heitmeyer, D. P.; Lewis, V. E.; Raushel, F. M. *Biochemistry* **1989**, *28*, 4650−4655. Dumas, D. P.; Durst, H. D.; Landis, W. G.; Raushel, F. M.; Wild, J. R. *Arch. Biochem. Biophys.* **1990**, *277*, 155−159. Caldwell, S. R.; Newcomb, J. R.; Schlecht, K. A.; Raushel, F. M. *Biochemistry* **1991**, *30*, 7438−7444.
(7) Morales-Rojas, H.; Moss, R. A. *Chem. Rev.* **2002**, *102*, 2497−2522.
(8) Ketellaar, J. A. A.; Gersmann, H. R.; Beck, M. *Nature* **1956**, *177*, 392−393.
(9) Zeinali, M.; Torrents, A. *Environ. Sci. Technol.* **1998**, *32*, 2338−2342. Smolen, J. M.; Stone, A. T.; Smolen, J. M.; Stone, A. L. *Environ. Sci. Technol.* **1997**, *31*, 1664−1673. Wan, H. B.; Wong, M. K.; Mok, C. Y. *Pestic. Sci.* **1994**, *42*, 93−99.
(10) Hartshorn, C. M.; Singh, A.; Chang, E. L. *J. Mater. Chem.* **2002**, *12*, 602−605. Moss, R. A.; Morales-Rojas, H. *Langmuir* **2000**, *16*, 6485−6491. Menger, F. M.; Gan, L. H.; Johnson, E.; Durst, D. H. *J. Am. Chem. Soc.* **1987**, *109*, 2800−2803. Morrow, J. R.; Trogler, W. C. *Inorg. Chem.* **1989**, *28*, 2330−2333. Moss, R. A.; Gong, P. K.; Morales-Rojas, H. *Org. Lett.* **2002**, *4*, 1835−1838. Hay, R. W.; Clifford, T.; Richens, D. T.; Lightfoot, P. *Polyhedron* **2000**, *19*, 1485−1492.
(11) Hendry, P.; Sargeson, A. M. *Aust. J. Chem.* **1986**, *39*, 1177−1186.
(12) Kuo, L. Y.; Perera, N. M. *Inorg. Chem.* **2000**, *39*, 2103−2106.
(13) Kazankov, G. M.; Sergeeva, V. S.; Efremenko, E. N.; Alexandrova, L.; Varfolomeev, S. D.; Ryabov, A. D. *Angew. Chem., Int. Ed.* **2000**, *39*, 3117−3119.
(14) Tao, J. C.; Jia, J.; Wang, X. W.; Zang, S. T. *Chin. Chem. Lett.* **2002**, *13*, 1170−1173.
(15) Um, I.-H.; Jeon, S.-E.; Baek, M.-H.; Park, H.-R. *Chem. Commun.* **2003**, 3016−3017.
(16) For recent related studies: Keizer, T. S.; De Pue, L. J.; Parkin, S.; Atwood, D. A. *J. Am. Chem. Soc.* **2002**, *124*, 1864−1865.
(17) Chandrakumar, N. S.; Hajdu, J. *Tetrahedron Lett.* **1982**, *23*, 1043−1046.

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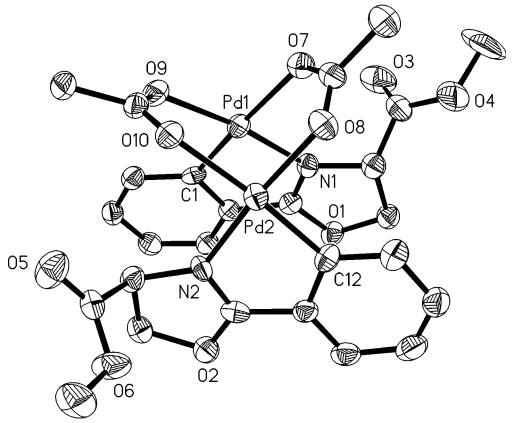
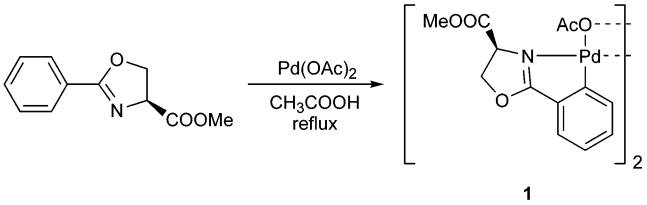


Figure 1. Structure of complex **1** in the crystal (50% ellipsoids). Selected bond lengths [Å] and angles [deg]: Pd(1)−C(1) 1.975(8), Pd(1)−N(1) 2.005(6), Pd(1)−O(9) 2.039(6), Pd(1)−O(7) 2.149(6), Pd(1)−Pd(2) 2.8536(9), Pd(2)−C(12) 1.963(8), Pd(2)−N(2) 2.016(6), Pd(2)−O(8) 2.026(6), Pd(2)−O(10) 2.137(6); C(1)−Pd(1)−N(1) 80.9(3), C(1)−Pd(1)−O(9) 90.5(3), N(1)−Pd(1)−O(9) 171.2(3), C(1)−Pd(1)−O(7) 172.0(3), N(1)−Pd(1)−O(7) 92.9(3), O(9)−Pd(1)−O(7) 95.9(2), C(12)−Pd(2)−N(2) 81.4(3), C(12)−Pd(2)−O(8) 92.2(3), N(2)−Pd(2)−O(8) 172.7(2), C(12)−Pd(2)−O(10) 174.9(3), N(2)−Pd(2)−O(10) 93.9(2), O(8)−Pd(2)−O(10) 92.6(3).

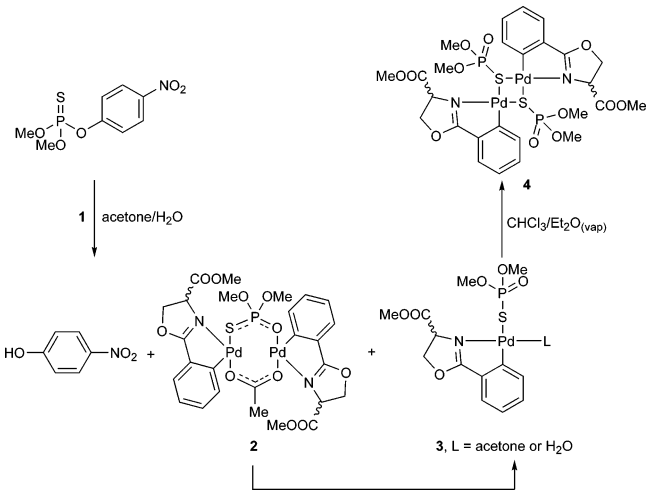
Scheme 1



1

of this ligand was carried out with $Pd(OAc)_2$ in acetic acid as previously described for other oxazoline complexes[18] and afforded a 84% yield of (*S,S*)-di-μ-(acetate)-bis{2-[2-(4-carbomethoxy)oxazolinyl]phenyl-*C*,*N*}-dipalladium(II) (**1**) (Scheme 1). Compound **1** is an orange, air-stable complex that can be recrystallized from benzene. It has been characterized by NMR, mass spectrometry, and X-ray analysis. The ^{1}H NMR spectrum of **1** features the expected resonances whose chemical shifts differ from those of the free ligand.[17] The successful palladation of the ligand leads to the appearance of four distinct signals in the aromatic region of the spectrum, in agreement with the existence of an ABCD spin system. Formation of **1** also results in a 0.9 ppm upfield shift of the CH_2 signal of the oxazoline ring. Single crystals of **1** were grown by slow evaporation of a benzene solution. Compound **1** crystallizes in the orthorhombic $P2_12_12_1$ space group with four molecules in the unit cell (Figure 1).[19] The two palladium moieties are linked by two bridging acetate ligands. As expected, both palladium centers are tetracoordinated and adopt a square-planar coordination geometry, as shown by the sum of the angles at Pd(1) (360.2(3)°) and Pd(2) (360.1(3)°). Two of the adjacent coordination sites are occupied by the carbon and nitrogen donor atoms of the phenyloxazoline ligands. The resulting Pd−C (av 1.97 Å) and Pd−N (2.01 Å) bond distances fall within the range observed in cyclopalladated phenyloxazoline palladium derivatives.[20−23] Finally, the absolute configuration of the molecule stereocenter in **1** is *S* and corresponds to that of the serine methyl ester used as starting material.

Scheme 2



The hydrolysis reaction of methylparathion in the presence of complex **1** in acetone-d_6/D_2O solution has been studied by NMR spectroscopy. While methylparathion is stable for several weeks in this aqueous solvent mixture, addition of **1** results in the rapid production of *p*-nitrophenol, as shown by ^{1}H NMR spectroscopy (Scheme 2). This reaction is also accompanied by the appearance of two new phosphorus-containing compounds (**2** and **3**), whose ^{31}P NMR resonance in acetone-d_6/D_2O appears at 30 and 51 ppm, respectively (Figure 2). Both of these signals are upfield from the ^{31}P resonance of methylparathion, which appears at 66 ppm,[24] and do not correspond to the thiosphosporic acid $HSP(=O)(OMe)_2$ derivative, which gives rise to a resonance at 65 ppm.[25] Compound **2**, whose resonance appears at 30 ppm, is an intermediate that disappears after approximately 90 min. It most likely corresponds to a derivative that contains a dimethylthiophosphate moiety acting as a bidentate ligand. For comparison, the ^{31}P chemical shift of the *O,S*-bridging thiophosphate ligand in $[Me_3PPtCl(SOP(O\text{-}i\text{-}Pr)_2)_2]_2Zn$ appears at 32 ppm.[26] As a result, **2** is tentatively described as the mixed acetate thiophosphate binuclear palladium com-

(18) Peterson, D. L.; Keuseman, K. J.; Kataeva, N. A.; Kuz'mina, L. G.; Howard, J. A. K.; Dunina, V. V.; Smoliakova, I. P. *J. Organomet. Chem.* **2002**, *654*, 66−73. Ohff, M.; Ohff, A.; Milstein, D. *Chem. Commun.* **1999**, 357−358.

(19) Crystal data for **1** and **4**: $C_{26}H_{26}N_2O_{10}Pd_2$, M_r = 739.29, orthorhombic, space group $P2_12_12_1$; a = 11.171(2) Å, b = 15.149(3) Å, c = 16.419(3) Å, V = 2778.4(10) Å^3, Z = 4, ρ_{calc} = 1.767 g cm^{-3}, F(000) = 1472, T = 110(2) K, 12 890 measured reflections, 4721 unique (R_{int} = 0.0417), μ = 1.353 mm^{-1}, empirical abs correction, T_{min}/T_{max} 0.4602/0.6607, R1 ($I > 2\sigma(I)$ = 0.0529, wR2 ($I > 2\sigma(I)$) = 0.1310 for 361 parameters. **4**: $C_{19}H_{21}N_4O_9SPPd$, M_r = 590.81, triclinic, space group $P\bar{1}$; a = 9.668(6) Å, b = 11.233(6) Å, c = 11.733(6) Å, α = 104.60(1)°, β = 111.45(1)°, γ = 100.01(1)°, V = 1096.41(11) Å^3, Z = 2, ρ_{calc} = 1.790 g cm^{-3}, F(000) = 596, T = 110(2) K, 6859 measured reflections, 4781 unique (R_{int} = 0.0288), μ = 1.070 mm^{-1}, R1 ($I > 2\sigma(I)$) = 0.0245, wR2 ($I > 2\sigma(I)$) = 0.0658 for 421 parameters.

(20) Churchill, M. R.; Wasserman, H. J.; Young, C. J. *Inorg. Chem.* **1980**, *19*, 762−770;

(21) Zocchi, M.; Tieghi, G.; Albinati, A. *J. Chem. Soc., Dalton Trans.* **1973**, 883.

(22) Wong-Ng, W.; Cheng, P. T.; Kocman, V.; Luth, H.; Nyburg, S. C. *Inorg. Chem.* **1979**, *18*, 2620.

(23) Navarro-Ranninger, C.; Zamora, F.; Martinez-Cruz, L. A.; Isea, R.; Masaguer, J. R. *J. Organomet. Chem.* **1996**, *518*, 29−36.

(24) Kuivalainen, T.; El-Bahrauoui, J.; Uggla, R.; Kostiainer, R.; Sundberg, M. R. *J. Am. Chem. Soc.* **2000**, *122*, 8073−8074.

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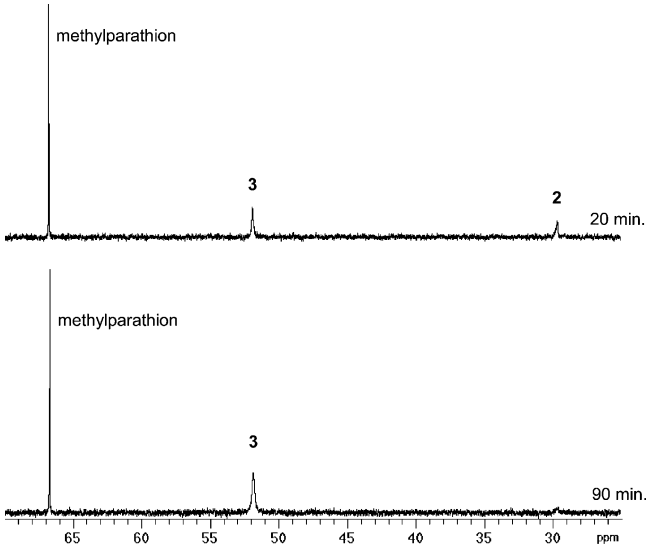

Figure 2. $^{31}P\{^{1}H\}$ NMR spectra of a solution obtained by mixing **1** (0.07 mmol) with methylparathion (0.14 mmol) and water (0.42 mmol) in acetone-d_6 solution (1.5 mL) after 20 and 90 min.

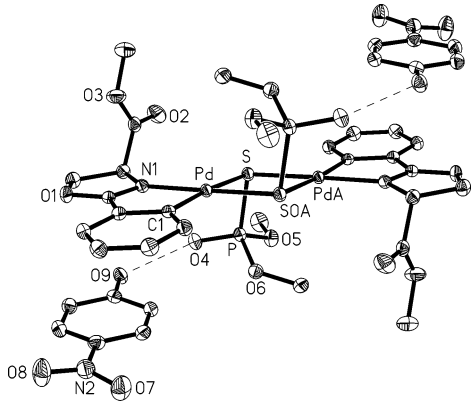

Figure 3. Structure of complex **4** in the crystal (50% ellipsoid). The hydrogen bonds are represented by dotted lines Selected bond lengths [Å] and angles [deg]: Pd−C(1) 2.015(2), Pd−N(1) 2.0543(19), Pd−S(A) 2.3239(11), Pd−S 2.4617(14), S−P 2.0645(12), S−Pd(A) 2.3239(11), P−O(4) 1.4746(16), P−O(6) 1.5665(19), P−O(5) 1.5734(18); C(1)−Pd−N(1) 80.76(8), C(1)−Pd−S(A) 95.69(7), N(1)−Pd−S(A) 175.80(5), C(1)−Pd−S 174.87(5), N(1)−Pd−S 98.71(6), S(A)−Pd−S 85.03(4), P−S−Pd(A) 103.07(5), P−S−Pd 94.46(3), Pd(A)−S−Pd 94.97(4).

plex **2** (Scheme 2). Upon standing, compound **2** disappears and converts into **3**. The ^{31}P chemical shift of **3** (51 ppm) suggests that this derivative contains a sulfur-bound dimethyl thiophosphate group as a terminal ligand (Scheme 2).[27] For comparison, the ^{31}P chemical shift of the thiophosphate ligand in $[Me_2Sn(SP(=O)(OBu)_2)_2]$ appears at 48.8 ppm.[28] The ^{31}P chemical shift of **3** is sensitive to the amount of water present in the deuterated solvent and will move from 58 ppm in dry acetone-d_6 to 51 ppm in acetone-d_6 solution containing 10% D_2O. This observation suggests that acetone and water compete as ligands for the palladium center.

Attempts to isolate crystals of **3** by diffusion of ether vapors into a $CHCl_3$ solution led to the slow crystallization of (*R,S*)-di-μ-(dimethylthiophosphate-*S,S*)-bis{2-[2-(4-carbomethoxy)oxazolinyl]phenyl-*C,N*}dipalladium(II) (**4**), which could be isolated as an orange-yellow crystalline product in the form of the hydrogen-bonded aggregate **4**-(*p*-nitrophenol)$_2$. The composition of **4**-(*p*-nitrophenol)$_2$ was confirmed by ^{1}H NMR, which allowed for the detection of the signals corresponding to the *p*-nitrophenol group, the phenyl oxazoline ligand, and the dimethylthiophosphate ligand. When dissolved into acetone, **4** converts into **3**, as indicated by ^{31}P NMR spectroscopy. Complex **4**-(*p*-nitrophenol)$_2$ crystallizes in the triclinic space group $P\bar{1}$ as a centrosymmetrical dinuclear complex (Figure 3).[19] In this complex, the two square-planar palladium moieties (sum of angles of Pd = 360.2(6)°) are linked by the sulfur atoms of the bridging dimethylthiophosphate ligands. The Pd−S distances of 2.324(1) Å and Pd−S distances of 2.461(1) Å are comparable to those observed in related complexes such as $[Pd_2((t\text{-}BuNH)_2P(=O)S)_4]$ (av Pd−S = 2.34 Å), which also features bridging thiophosphate groups.[29] The remaining coordination sites of the palladium center are occupied by the phenyloxazoline carbon and nitrogen donor atoms. The resulting Pd−C(1) (2.015(2) Å) and Pd−N(1) (2.054(2) Å) bonds are comparable to those observed in **1**. Finally, as indicated by the O(4)−O(9) distance of 2.62 Å, a molecule of *p*-nitrophenol is hydrogen bonded to the terminal phosphoryl oxygen atom of each dimethylthiophosphate ligand. The formation of **4** indicates racemization of the chiral oxazoline during the reaction. This has been confirmed by monitoring the CD spectrum of the reaction mixture as a function of time. The mechanism of this racemization remains at this time unclear, and we have not been able to confirm deuterium incorporation when the reaction is carried out in D_2O.

While all reactions involving **1** and methylparathion in mixtures of organic solvent and water are stoichiometric, we observed that catalytic hydrolysis of methylparathion is observed in aqueous media under basic conditions. This reaction can be conveniently followed by monitoring the release of *p*-nitrophenol, which features an absorption band at 400 nm (ϵ = 17 000 cm^{-1} M^{-1}). For example, when this experiment was carried out on a solution containing 9.41×10^{-5} M of methylparathion and 4.02×10^{-6} M of palladium at pH 9, the hydrolysis reaction was 50% complete after 4.4 min, yielding a turnover number of 11.7 and a turnover frequency of 4.4×10^{-2} s^{-1}. After 28 min, the reaction was >95% complete. To obtain more detailed insight into the kinetics, experiments carried out at various methylparathion and catalyst concentrations in the 9−10 pH range (CHES, 10 mM) were analyzed using the initial rate methods. As indicated by this kinetic analysis, the reaction rate follows second-order kinetics with a first-order dependence on both substrate and palladium catalyst ($v = k_2$[Pd][parathion]). The k_2

(25) The chemical ^{31}P shift of dimethylthiophosphate salt has been previously reported. Mahajna, M.; Quistad, G. B.; Casida, J. E. *Chem. Res. Toxicol*. **1997**, *10*, 64−69. Jamer, P. C. J.; Roelen, H. C. P. F.; van den Elst, H.; van der Marel, G. A.; van Boom, J. H. *Tetraherdon Lett*. **1989**, *30*, 6757−6760.

(26) Poat, J. C.; Slawin, A. M. Z.; Williams, D. J.; Woollins, J. D. *Polyhedron* **1992**, *11*, 2125−2126.

(27) Hua, L.; Quing-Ian, X.; Ji-tao, W.; Mazhar, M. *Heteroat. Chem.* **1998**, *9*, 299−305.

(28) Jain, V. K.; Kesavadas, T.; Vasta, C. *Spectrochim. Acta* **1992**, *48a*, 1583−1587.

(29) Scherer, O. J.; Forstinger, K.; Kaub, J.; Sheldrick, W. S. *Chem. Ber.* **1986**, *119*, 2731−2747.

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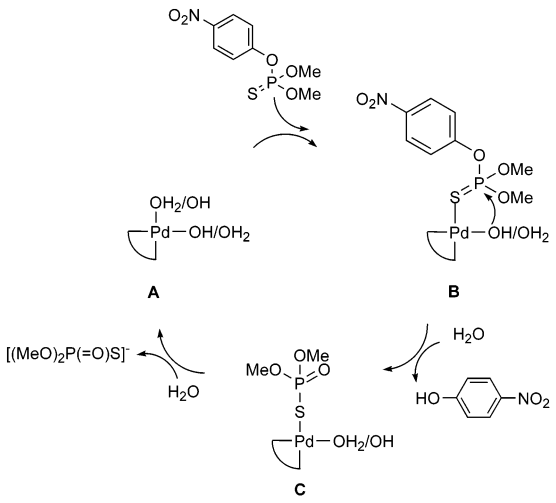
Scheme 3



values obtained from these measurements range from 726 (± 30) M^{-1} s^{-1} at pH 9.0 to 792 (± 47) M^{-1} s^{-1} at pH 10.0. These values are the highest ever recorded for palladium-based catalysts in this type of reaction.[13,14] By comparison with the uncatalyzed hydrolysis of parathion in the same buffer solution (k_1 = 3.5 (± 0.2) × 10^{-6} s^{-1} at pH 9 and 4.07 (± 0.2) × 10^{-6} s^{-1} at pH 10),[30] the palladium catalyst in 2 × 10^{-6} M concentration accelerates the reaction by a factor of 414 at pH 9.0 and 389 at pH 10.0. In fact, the k_2 values reported herein are comparable to those reported by Ryabov for organoplatinum oximate catalysts.[13] While the exact nature of the palladium catalyst in the presence of substrate and buffer remains to be confirmed, an NMR experiment carried out on **1** in a 50% D_2O/50% acetone-d_6 solution saturated with $Ca(OH)_2$ shows that the acetate ligand is dissociated and the methylester functionality hydrolyzed. Presumably, the resting state of the catalyst corresponds to a cyclometalated palladium aqua species of type **A** (Scheme 3).[31] The large rate increase observed in this reaction also supports a mechanism in which the metal center is involved in the activation of the substrate as well as in the delivery of a hydroxide ion via an intermediate of type **B** (Scheme 3). Since the pK_a values of cyclometalated palladium aqua complexes fall in the 4−5 range, it can be expected that, under the conditions of the reaction, the aqua ligand of **B** will be deprotonated.[32] A similar mechanism has been proposed for the hydrolysis of sarin mediated by copper(II) catalysts (Scheme 3).[33] In the 7.5−8.5 pH range, with EPPS as a buffer, only stoichiometric release of *p*-nitrophenol is observed, suggesting that the catalyst is inhibited by the product. This inhibition can be explained by the formation of a thiophosphate complex such as **C**, which would not be labile in this pH range.

(30) The accelerations are equal to k_2[Pd]/k_1. The k_1 values for the uncatalyzed hydroysis of methylparathion have been measured independently.

(31) Similar di-aqua palladium complexes have been reported previously; see: Deeming, Antony J.; Rothwell, Ian P.; Hursthouse, Michael B.; New, L. *Dalton Trans.* **1978**, 1490−1496.

(32) Ryabov, A. D.; Kazankov, G. M.; Yatsimirskii, A. K.; Kuz'mina, L. G.; Burtseva, O. Y.; Dvortsova, N. V.; Polyakov V. A. *Inorg. Chem.* **1992**, *31*, 3083−3090.

(33) Hay, R. W.; Govan, N. *Polyhedron* **1998**, *17*, 2079−2085.

Conclusions

This report indicates that simple organopalladium acetate complexes are reactive toward thiophosphate triesters such as methylparathion. While stoichiometric reactions are observed at neutral or slightly basic pH, the data that we have gathered clearly indicate that catalytic hydrolysis occurs at pH's greater than 9. With k_2 values close to 800 M^{-1} s^{-1}, the activity displayed by the title palladium oxazoline catalyst is remarkably high and approaches the performance of the more expensive platinum catalysts described by Ryabov, who reported k_2 values in the 200−900 M^{-1} s^{-1} range at similar pH's.[13] Hence, the rate of hydrolysis is substantial and suggests that such complexes could be used for mitigating thiophosphate triester neurotoxins. We are currently studying the reactivity of organopalladium complexes toward phosphate triesters such as paraoxon.

Experimental Section

General Considerations. ***Methylparathion is highly toxic and should be handled in a well-ventilated fume hood. All glassware exposed to methylparathion should be decontaminated with bleach.*** Solvents were dried by standard methods. All NMR studies were carried out on an Inova 300 MHz NMR spectrometer (300 MHz for ^{1}H, 100.5 MHz for ^{13}C, 121.4 MHz for ^{31}P NMR). H_3PO_4 (85%) was used as an external standard for the solution ^{31}P NMR spectra. The proton and carbon signals of the deuterated solvent were used as internal standard for the ^{1}H and ^{13}C NMR spectra, respectively. Elemental analyses were performed by Atlantic Microlab Inc., Norcross, GA 30091. Melting points were measured on a Laboratory Devices Mel-Temp apparatus and were not corrected. All UV/vis absorption spectra and spectrophotometric measurements were recorded on a JASCO V530 UV/vis spectrometer equipped with an automatic cell changer. The circular dichroism experiments were performed on an Aviv circular dichroism spectrometer model 62DS. The methylparathion solution was provided by A/S Cheminova, Lemvig, DK-7620, Denmark, as a gift. (*S*)-4-Carbomethoxy-2-phenyl-2-oxazoline was synthesized by following the literature procedure.[17]

Synthesis of 1. A suspension of palladium acetate (224 mg, 1 mmol) in acetic acid (6 mL) was added to a solution of (*S*)-4-carbomethoxy-2-phenyloxazoline (205 mg, 1 mmol) in acetic acid (6 mL). The resulting orange-red solution was stirred overnight at room temperature and refluxed for 2 h. Following addition of water (10 mL), the product was extracted with chloroform (3 × 15 mL). The organic phase was washed with a saturated sodium bicarbonate solution and passed through a layer of Celite. Evaporation of the solvents yielded an orange-red oil, which was dissolved in benzene. Slow evaporation of the solvent led to the formation of bright orange crystals of **1**. Yield: 310 mg, 84%. Anal. Calcd for $C_{26}H_{26}N_2O_{10}Pd_2$: C 42.24, H 3.54. Found: C 42.34, H 3.50. Mp: 165 °C. ^{1}H NMR ($CDCl_3$): δ 2.11 (s, 3H, Pd-OCOCH_3), 3.69 (dd, J = 8.5 Hz, J = 10.5 Hz, OCH_2), 3.81 (s, 3H, CO_2CH_3), 3.82 (dd, 1H, J = 6.5 Hz, J = 10.5 Hz, NC*H*), 4.40 (dd, 1H, J = 6.5 Hz, J = 8.5 Hz, OCH_2), 7.04−7.60 m (aromatic H, 4H). ^{13}C NMR ($CDCl_3$): δ 23.9 (Pd-OCO*C*H$_3$), 53.0 (CO_2CH_3), 62.9 (N*C*H), 72.9 (O*C*H$_2$), 123.9, 126.1, 130.1, 131.1, 131.3 (*C*arom), 148.2 (*C*Pd), 169.9, 175.8, (CO_2CH_3, C=N(O)), 181.5 (Pd-O*C*OCH$_3$).

Isolation of 4-(*p*-Nitrophenol)$_2$ in the Reaction of 1 with Methylparathion. To a solution of complex **1** (81 mg, 0.22 mmol) in dioxane (40 mL) and water (10 mL) was added an 80% solution of methylparathion in xylenes (72 mg, 0.22 mmol). After 60 h, evaporation of the volatiles afforded an oily residue, which was dissolved in $CHCl_3$ (40 mL), dried over sodium sulfate, filtered, and concentrated to 5 mL. The

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resulting $CHCl_3$ solution was exposed to vapors of hexanes. Upon standing and over the course of two months, small orange-yellow crystals of **4**-(*p*-nitrophenol)$_2$ coated by a dark oily residue formed at the bottom of the vessel. These crystals were quickly washed with $CHCl_3$ and recovered in a pure form. Yield: 30 mg, 23%. Anal. Calcd for $C_{38}H_{42}N_4O_{18}P_2S_2Pd_2$: C 38.63, H 3.58. Found: C 38.16, H 3.53. Upon dissolution in acetone, **4** converts back into **3**, which has been characterized by NMR spectroscopy. ^{1}H NMR (acetone-d_6): δ 8.14 (d, 2H, J = 9.28 Hz, C*H*-arom, *p*-nitrophenol), 7.29, 7.18, 7.11 (m, 4H, C*H*-arom, phenyloxazoline), 7.00 (d, 2H, J = 9.28 Hz, C*H*-arom, *p*-nitrophenol), 5.17 (m, 1H, OCH_2), 5.02 (m, 1H, N*H*), 4.93 (m, 1H, OCH_2), 3.76 (s, 6H, CO_2CH_3), 2.79 (d, 6H, J = 15.6 Hz, CH_3OP). ^{13}C NMR (acetone-d_6): δ 23.9 (Pd-OCO*C*H_3), 53.6 (O*C*H_3), 53.2 (CO_2*C*H_3), 64.3 (N*C*H), 74.4 (O*C*H_2), 125.1, 127.6, 129.0, 130.2, 132.3 (*C*arom), 164.6, 172.8, (CO_2CH_3, *C*=N(O)), 126.6 and 116.2 (*C*H-arom, *p*-nitrophenol). ^{31}P NMR (acetone-d_6): δ 51 (s, S-*P*(=O)(OMe)$_2$).

Catalytic Hydrolysis of Methylparathion by 1 Complex. In a typical experiment, the cell was filled with 2.0 mL of a buffer solution (CHES, 10 mM, pH = 9 or 10) and 0.160 mL of a stock solution of catalyst **1** in dioxane ([Pd] = 2 × [**1**] = 8.8×10^{-5} M). Following addition of 0.278 mL of a stock solution of methylparathion ([methylparathion] = 2.42×10^{-4} M in water), the total volume of the solution was adjusted to 3.5 mL by addition of water, and the reaction was followed by monitoring the release of *p*-nitrophenol, which features an absorption band at 400 nm (ϵ = 17 000 M^{-1} cm^{-1}). The dependence of the reaction rate on methylparathion was established by varying the methylparathion concentration at constant catalyst concentration (([Pd] = 4.02×10^{-6} M). The dependence of the reaction rate on catalyst was established by varying the catalyst concentration at constant methylparathion concentration (1.92×10^{-5} M).

NMR Studies. 1 (0.07 mmol) was mixed with methylparathion (0.14 mmol) in acetone-d_6 (1.5 mL) inside a NMR tube. After mixing and in the absence of water, ^{31}P NMR of the resulting mixture allowed the detection of only a signal at 66 ppm, corresponding to methylparathion. The reaction was initiated by addition of D_2O (0.42 mmol). This resulted in production of *p*-nitrophenol, which was detected by ^{1}H NMR. It also resulted in the appearance of **2** and **3** with ^{31}P NMR chemical shifts of 30 and 51 ppm, respectively.

Circular Dichroism Spectroscopy. A dioxane solution containing **1** ([**1**] = 1.09 mM) and methylparathion ([methylparathion] = 2.17 mM) was placed in a cuvette (path length = 0.1 cm). The reaction was initiated by addition of 10 equiv of water. The CD spectrum of the solution was recorded at regular intervals.

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Supporting Information Available: Kinetic, CD, and X-ray crystallographic data for complexes **1** and **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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