

Transesterification of Phosphotriester Paraoxon Catalyzed by ZnCl₂ Supported on Silica Gel

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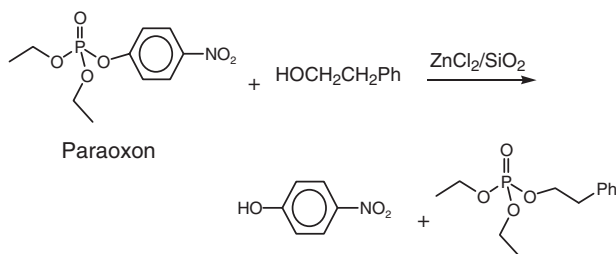
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ZnCl₂ supported on silica gel has shown to be an effective catalyst for transesterification of the organophosphate insecticide, paraoxon, in the presence of 2-phenylethanol. The kinetics of the reaction in acetonitrile was studied. Formation of the product diethyl 2-phenylethyl phosphate was confirmed by ³¹P NMR.

Processes involving phosphoryl transfer are of enormous importance in biological systems. In spite of the fact that phosphotriesters are not natural products, they are readily processed by the microbial *Pseudomonas diminuta* phosphotriesterase (PTE).¹⁻⁴ PTE, which contains two zinc centers in its active site, catalyzes the hydrolysis of a variety of phosphotriesters through a mechanism that is still not fully understood. Such phosphotriesters include insecticides and pesticides such as parathion, malathion, and paraoxon that accumulate in soil and are relatively stable at low temperature and low pH. These phosphotriesters are structurally related to chemical warfare agents, such as sarin, soman, and nerve agent VX. Therefore, considerable effort has been devoted toward developing methods for controlled degradation of such organophosphorous contaminants.

It is well known that transesterification reactions can generally be catalyzed by acids and bases.⁵ Although there have been few reports in recent years indicating that some metal complexes can catalyze transesterification of phosphotriesters,⁶⁻¹⁰ there have been no reports on the catalysis of such reactions by simple Lewis acids such as ZnCl₂. In our continuous effort in developing catalysts for phosphoryl-transfer reactions by metal ions and metal complexes, we found ZnCl₂ supported on silica gel to be efficient in catalyzing phosphotriesters transesterification. In this regard, we wish to present the results of our work involving catalysis of the transesterification of diethyl *p*-nitrophenyl phosphate (paraoxon) by SiO₂-supported ZnCl₂ (Scheme 1).

A solution of diethyl *p*-nitrophenyl phosphate (paraoxon, 2 mM) in anhydrous acetonitrile (100 mL) was stirred at 50 °C in the presence of 2-phenylethanol (10 mM) and ZnCl₂/SiO₂ (0.2 g, 2 mM)^{11,12} under dry argon atmosphere. Reaction



Scheme 1.

progress was monitored spectro-photometrically by observing the rate of formation of *p*-nitrophenol ($\lambda_{\text{max}} = 312 \text{ nm}$, $\epsilon_{\text{max}} \approx 10000 \text{ M}^{-1} \text{ cm}^{-1}$).¹³ Periodically (10 min intervals) the catalyst was allowed to settle to the bottom of the flask, 150- μL sample of the solution was withdrawn, diluted to 3 mL in acetonitrile, and the UV-vis spectrum was recorded using a Hitachi U-2000 spectrophotometer.¹⁴ The reaction was followed to at least five half-life times and found to exhibit pseudo-first-order kinetics. The observed rate constant (k_{obs}) was evaluated from the plot of absorbance (after background adjustment) versus time by fitting it into a standard exponential model (Figure 1).

³¹P NMR spectroscopy of the reaction mixture confirmed the formation of diethyl 2-phenylethyl phosphate product and showed complete disappearance of paraoxon starting material after 90 min of reaction time. In order to confirm that the supported catalyst has different activity than the non-supported one, control reactions were carried out using non-supported ZnCl₂ and/or SiO₂. Neither ZnCl₂ nor SiO₂ alone failed to give any reaction beyond background. However, when the reaction was carried out in the presence of unsupported ZnCl₂ and silica gel only minimal transesterification was observed (5% conversion was obtained in the presence of 2 mM ZnCl₂ and 0.2 g SiO₂, after 3 h). Thus, this solution was used for background correction when studying the reaction kinetics.

Catalyst turnover was confirmed by periodically monitoring the integrated spectra of a solution containing 4.0 mM paraoxon, 10.0 mM 2-phenylethanol, and 0.2 mM catalyst, over a period of 2 h. The time profiles of the disappearance of paraoxon and appearance of the product diethyl 2-phenylethyl phosphate indicated more than 20 turnovers of the catalyst.¹⁵

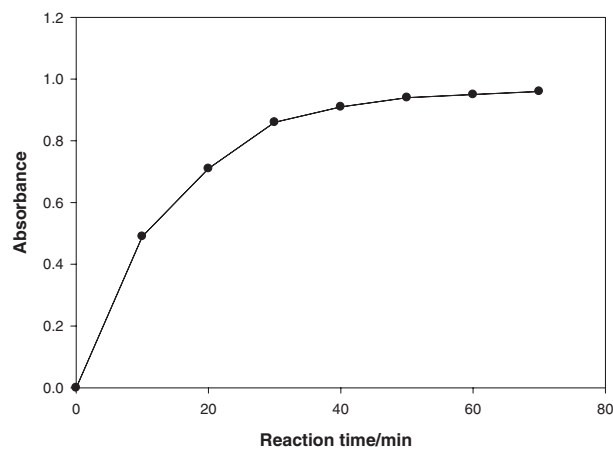


Figure 1. Release of *p*-nitrophenol from the reaction of paraoxon and 2-phenylethanol, in the presence of ZnCl₂/SiO₂ (1 mmol/g) at 25 °C.

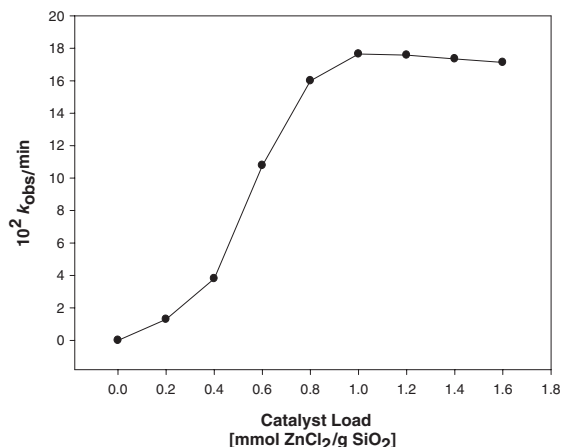


Figure 2. k_{obs} for the alcoholysis of paraoxon as a function of catalyst load.

Study of the effect of catalyst load on reaction rate showed that rate (k_{obs}) increases moderately upon increasing catalyst load up to 0.4 mmol ZnCl₂/g SiO₂, while a larger increase was observed between 0.4 and 1.0 mmol/g. Catalyst load higher than 1 mmol/g, however, seems to have an adverse effect (Figure 2). Such decrease in reaction rate at very high catalyst load may be attributed to the possible formation of a μ -phosphatozinc complex as the distance between the metal centers on the support decreases, this behavior was observed in some homogeneous metal-complex catalysts.⁸ However, no decrease in reaction rate was observed upon increasing the total amount of catalyst, when the amount of catalyst was doubled only moderate enhancement (20%) of reaction rate was observed, suggesting that cooperation between two Zn centers on the same support particle could play an important role in catalytic activity. Although at this time we do not have a clear evidence of the nature of the catalytic mechanism, it is likely that a phosphoester molecule is activated upon coordination to the metal, while either a free or a neighboring coordinated alcohol molecule acts as a nucleophile. The fact that moderate rate enhancement is observed when the average distance between metal centers is relatively large (at <0.4 mmol/g catalyst load), versus the more drastic enhancement when the inter-metal distance decreases (at higher catalyst loads), indicates that coordination of both reactants to adjacent metal centers seems to be a requirement for optimum catalytic activity.

This work represents the first example involving catalysis of a phosphoryl-transfer reaction by silica gel-supported ZnCl₂. In polar aprotic solvents, this catalyst has shown to be very effective for transesterification of the phosphotriester paraoxon. We are currently studying other phosphoryl-transfer reactions by supported catalysts. We are also exploring the catalytic activities of other Lewis acids on various supports.

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- 14 ZnCl₂ was supported on Fisher Scientific silica gel 60 by means of previously described methods (refs 11 and 12). Typically, silica gel was treated with acid by refluxing in excess 30% sulfuric acid for 30 min. The cold solution was filtered, washed thoroughly with distilled water and allowed to dry in air for 48 h. ZnCl₂ was deposited on the acid-washed support by evaporating a 1% suspension of the support in methanolic solution containing ZnCl₂ at a concentration equivalent to the desired catalyst load. Catalyst was activated prior to use by heating overnight at 150 °C.
- 15 Anhydrous acetonitrile (100 mL) containing 4.0 mM paraoxon and 10.0 mM 2-phenylethanol was stirred at 50 °C in the presence of 0.2 mM of catalyst (ZnCl₂/SiO₂, 1 mmol/g). Periodically (every 20 min, for 2 h), 0.4-mL samples were withdrawn, diluted with 0.1 mL of CD₃CN (for signal lock), and the ³¹P NMR spectrum was recorded. After 90 min of reaction time the spectrum indicated complete disappearance of the paraoxon signal (δ -6.35) and appearance of the product signal (δ 0.73).