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Selective oxidations of sulfides to sulfoxides using immobilised cerium alkyl phosphonate

Mohammed Al-Hashimi, Gopa Roy, Alice C. Sullivan* and John R. H. Wilson

Department of Chemistry, Queen Mary, University of London, Mile End Road, London El 4NS, UK

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Abstract—A range of sulfides can be selectively oxidised to the corresponding sulfoxides in good yields using catalytic quantities of immobilised cerium alkyl phosphonate and either sodium bromate or *tert*-butyl hydroperoxide as oxidants. © 2005 Elsevier Ltd. All rights reserved.

1. Introduction

The selective oxidation of sulfides to sulfoxides remains a challenge and is of interest because of the importance of sulfoxides as synthetic intermediates in organic synthesis.¹ Stoichiometric oxidation can be accomplished with reagents like HNO₃, KMnO₄, MnO₂ and *m*-CPBA¹ but cleaner methods based on catalytic promotion of oxidation using aqueous hydrogen peroxide, or tertbutyl hydroperoxide (TBHP) are preferred. Noyori and co-workers reported the use of various W catalysts (based on sodium tungstate, phenylphosphonic acid and methyltri-n-octylammonium hydrogensulfate, which acts as a phase-transfer catalyst) for the oxidation of aromatic and aliphatic sulfides using 30% H₂O₂.¹ Espenson reported the use of oxorhenium dithiolates and TBHP for the selective oxidation of a number of sulfides.² A number of studies have been reported on heterogeneous oxidation of sulfides. Titanium silicates TS-1 promote sulfide oxidation, however bulky sulfides were not oxidised due to limited access to the Ti active sites.³ Ti-beta³ and Ti-MCM-41⁴ allow the oxidation of bulky sulfides to mixtures of sulfoxide and sulfone. Better selectivity was observed for the oxidant UHP (crystalline urea adduct of H₂O₂).³ Mayoral and co-workers reported that $Ti(OPr^{i})_{4}$ supported on silica is an efficient and selective catalyst for the oxidation of sulfides to sulfoxides,⁵ but the Ti was gradually leached from the support. Product selectivity (i.e., sulfoxide/sulfone) was

better for H_2O_2 than for TBHP but the rate of reaction was faster with the latter. Choudary et al. reported the catalytic oxidation of sulfides selectively to sulfoxides with heterogeneous tungstate exchanged Mg-Al-LDH (layered double hydroxide) catalysts, 30% H_2O_2 as the oxidant and water as the solvent.⁶ These heterogeneous catalysts displayed superior activity over their homogeneous counterparts but were not always selective for sulfoxide formation.

Kropp and co-workers reported that silica gel and alumina mediate the oxidation of sulfides and sulfoxides by TBHP and a 2:1:1 mixture $KOSO_2OOH$, $KHSO_4$, K_2SO_4 (OXONE) with minimal over-oxidation to the sulfone. Mechanisms for the surface mediated oxygen atom transfer were proposed.^{7,8}

We recently reported^{9,10} the synthesis and characterisation of the first examples of phosphonate and phosphonic acid modified silicas, $[O_2Si]_x[O_{3/2}Si(CH_2)_2-PO(OH)_2]_y$; x:y = 1:1-10:1, that is, ethylphosphonate substituted silica 1:1 to 1:10, EPS1 to EPS10, obtained from diethyl phosphonatoethyltriethoxysilane (EtO)₃-Si(CH₂)₂PO(OEt)₂ and tetraethoxysilane, TEOS, in appropriate ratios.

In addition we have reported¹¹ on related phosphonate materials $[O_2Si]_x[O_{3/2}Si(CH_2)_2PO(OH)_2]_y[O_{3/2} SiCH-(CH_2PO(OH)_2)CH_2CH_2SiO_{3/2}]_z$, $Q_xTa_yTb_z$, x:y:z = 0.0: 0.5:0.5–10:0.5:0.5, obtained from TEOS (Q source) dimethyl phosphonatoethyltrimethoxysilane (Ta source) and 1-dimethylphosphonatobutyl-2,4-bis(trimethoxysilane), (MeO)_3SiCH(CH_2PO(OMe)_2)CH_2CH_2Si(OMe)_3, (Tb source). Since these materials have both *e*thylphosphonate and *butylp*hosphonate functionalities in a

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^{*} Corresponding author. Tel.: +44 20 7882 3274; fax: +44 20 7882 7794; e-mail: a.c.sullivan@qmul.ac.uk

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Table 1. Oxidation of sulfides by CeEPBPSS3-NaBrO3

| Substrate ^a | Temp (°C) | NaBrO ₃ (mmol) | Time (h) | Selectivity ⁱ sulfoxide:sulfone |
|------------------------------------|-----------------|---------------------------|----------|---|
| Ph-S | 30 | 0.8 | 1.3 | 96/4 |
| | 30 | 1.5 | 3 | 96/4 |
| | 40 | 0.8 | 0.7 | 96/4 |
| | 40 | 1.5 | 0.75 | 97/3 |
| | 50 | 0.8 | 0.5 | 98/2 |
| | 50 | 1.5 | 0.5 | 95/5 |
| | 60 | 1.5 | 0.25 | 96/4 |
| | 40 | 1.5 | 3 | 98/2 ^b |
| c | 40 | 1.5 | 0.75 | 98/2 [°] |
| d | 30 | 1.5 | 0.33 | 98/2 ^d |
| e | 40 | 1.5 | 24 | e |
| r c | 40 | 1.5 | 24 | 1 |
| Ph | 35 | 1.5 | 8 | 96/4 |
| c O () | 40 | 1.5 | 8 | 83/17 ^c |
| Me | 24 | 1.0 | 5.5 | 91/9 |
| 0 | 40 | 1.5 | 0.25 | 94/6 |
| Ь | 40 | 1.5 | 0.25 | 94/6 ^b |
| ° | Rt | 1.5 | 7 | 94/6° |
| Ph ^S Ph | 80 | 2 | 144 | 97/3 ^g |
| d A | 20 | 2 | 3 | 97/3 ^d |
| $\langle \rangle$ | 40 | 4 | 4 | 99 |
| ∕S∕ | 40 | 4 | 48 | 91 |
| | 50 | 1.5 | 1.75 | 99 |
| | 70 | 1.5 | 1.5 | 99 |
| ,S,CN O ∐ | 50 | 1.5 | 3 | 99 |
| S S | 50 | 1.5 | 0.75 | 99 |
| Me | 24 | 1.5 | 1 | 99 |
| Me ^S OH | 24 | 2.0 | 17 | 100 ^h |
| Me ^S CO ₂ Me | 24 | 1.5 | 1 | 87 |
| Ph ^S | 40 | 6 | 24 | 99/1 ^h |
| | 50 ^g | 6 | 23 | 99/1 |
| | 60 | 4 | 18 | 98/2 |
| $\mathbf{S}(\mathbf{A})$ | 70 | 2 | 16 | 98/2 |
| Me | 40 | 4 | 25 | 89/11 ^h |
| $\langle \mathbf{s} \rangle$ | 70 | 6 | 24 | 1/99 ^h |

^a All reactions were conducted using 1 mmol organic substrate in 3.5 cm³ acetonitrile–water 6:1, for the times and temperatures indicated in the table, using the quantities of catalyst and sodium bromate indicated.0.03 g CeEPBPSS3 $(Ce(IV) 0.7 \text{ mmol } g^{-1})^{17}$ was used unless otherwise indicated.

^b Recycled catalyst (reaction mixture decanted from the catalyst and fresh solvent and reagents added).

^c Used Ce(III)EPBPSS3 (0.03 g) prepared from Na₂-EPBPSS3 and aqueous cerium(III) nitrate.

^d CAN (0.03 g) used in place of CeEPBPSS3.

^e The reaction mixture was filtered from the catalyst at 40 °C after 0.2 h. NMR indicated a 90:10 ratio of sulfide to sulfoxide and this did not change after a further 24 h at 40 °C.

^f No Ce catalyst added and only sulfide recovered.

^gCeEPBPSS3 0.1 g used.

 $^{\rm h}\,TBHP$ used instead of NaBrO3.

ⁱ The NMR spectra of the products indicated no residual sulfide starting material except for the substrate methyl 3-methylmercaptopropionate, where 13% of the starting sulfide was still present after 1 h at room temperature.

silsesquioxane–silica matrix, we refer to them as EPBPSS. In this work we have used ceriumEPBPSS3 materials (where 3 refers to the Q/Ta + Tb ratio).



We have already reported on a range of metalEPS and metalEPBPSS derivatives, including cobalt(II), cerium(IV) and vanadyl derivatives and on their catalytic oxidation chemistry of allylic groups, primary and secondary alcohols and allylic alcohols.^{11–15} In this letter we report our initial work on the catalytic oxidation of a variety of sulfides utilising CeEPBPSS3 as catalyst and sodium bromate as oxidant. Similar reactions utilising TBHP as oxidant were carried out in a few cases for comparison.

2. Results

We reported earlier on the oxidation of alcohols with the related CeEPS-sodium bromate system where effective heterogeneous oxidation of alcohols was achieved. We now report on the oxidation of a range of sulfide substrates using the related system CeEPBPSS3-NaBrO₃. The results are shown in Table 1. As far as we are aware no cerium(IV) heterogeneous reagents have been reported for the oxidation of sulfides although the homogeneous system, CAN-NaBrO₄ (where CAN is cerium ammonium nitrate) has been reported as a reagent for the oxidation of alcohols.¹⁶ CeE-PBPSS3, was prepared by treating an aqueous suspension of the disodium phosphonate material, Na₂EPBPSS3,¹¹ with an aqueous solution of cerium ammonium nitrate. The yellow solid obtained was filtered, washed with copious amounts of water and then with ether and finally dried at 100 °C at 0.01 Torr.

3. Discussion

In all cases except one, the reactions resulted in 100% conversion of sulfide. Typical procedures are given.^{18,19} For thioanisole and the Ce(IV)EPBPSS3–NaBrO₃ system, increasing the reaction temperature from 30 to 50 °C using 0.8 mmol of the reoxidant,²⁰ resulted in a quicker reaction and a 2% improvement in selectivity for sulfoxide. Increasing the oxidant from 0.8 to 1.5 mmol had no effect at 30 °C and a 3% reduction in selectivity at 50 °C. Selectivity for the sulfoxide would appear to be slightly higher for reactions employing 0.8 mmol of the reoxidant. Oxidation of thioanisole with Ce(IV)EPBPSS3 and TBHP as reoxidant resulted in good selectivity but considerably slower reactions than those utilising NaBrO₃. The sulfoxide is

formed rapidly and selectively in substrates having a primary alcohol or ester group. We previously showed that primary alcohols are oxidised at a slow rate if the reaction mixture is stirred at the reflux temperature.¹³ Tetrahydrothiophene gave excellent selectivity for the sulfoxide with NaBrO₃ as reoxidant but gave only sulfone with TBHP. Confirmation that the Ce(IV)/Ce(III) couple is important in these reactions was obtained by demonstrating that the oxidation worked equally well starting with Ce(III)EPBPSS3. For all substrates tested with the Ce(IV)EPBPSS3-NaBrO₃ system, a good degree of selectivity for the sulfoxide could be obtained after some optimisation of conditions. The heterogeneous system competed well with homogeneous CAN-NaBrO₃ for reactive sulfides like thioanisole. The less reactive diphenyl sulfide however was converted to sulfoxide after 144 h, using the heterogeneous system at 80 °C, compared to 3 h using the homogeneous CAN-NaBrO₃ system at room temperature. Overall, the selectivities observed for heterogeneous oxidation of sulfides using the Ce(IV)EPBPS-NaBrO₃ system compare extremely well with reported selectivities for other heterogeneous catalysts and indicate that this system is more selective than the corresponding Ce(IV)EPBPSS3-TBHB system.

In a future paper we will report on further oxidation chemistry using other active redox metalEPBPSS3 catalysts and a variety of co-oxidants.

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- 17. Cerium content in CeEPBPSS3 was determined by titration of the remaining Ce⁴⁺ (using Fe²⁺/ferroin) in the combined filtrate and washings after treating the Na₂EPBPSS3 with aqueous cerium ammonium nitrate, CAN, and washing the product thoroughly.
- 18. Typical procedure using Ce-EPBPSS3–NaBrO₃ system. The catalyst and sulfide (see Table 1 for quantities) were added to acetonitrile, 3 cm³, and then sodium bromate and water 0.5 cm³ were added. This mixture was stirred at the temperature and for the time indicated in Table 1. The reaction was followed by TLC. The catalyst was separated by filtration and washed with ethyl acetate. The combined filtrate and and ethyl acetate washings were then washed with water and the organic phase separated and dried over magnesium sulfate. The product was obtained after removal of the solvent.
- 19. Typical procedure using CeEPBPSS3-TBHB system. To a solution of sulfide in acetonitrile (4 cm³) was added catalyst followed by a 70% aqueous solution of *tert*-butyl hydroperoxide (see Table 1 for quantities). This mixture was stirred at the temperature and for the time indicated and the progress of the reaction was monitored by TLC. After completion of the reaction, the catalyst was filtered and washed with diethyl ether. The combined organic fractions were washed with sodium sulfite 10% aq, 10 cm³, extracted with diethyl ether and the extract dried over magnesium sulfate. The solvent was evaporated to give the products.
- 20. The quantity of NaBrO₃ taken, 0.8 mmol, represents a 1.42-fold excess over that required to reoxidise cerium following the oxidation of 1 mmol sulfide (assuming that sodium bromide is formed in the process).