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Zinc-Catalyzed Deoxygenation of Sulfoxides to Sulfides Applying $[B(Pin)]_2$ as Deoxygenation Reagents

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Abstract In the present study, the zinc-catalyzed deoxygenation of aliphatic and aromatic sulfoxides in the presence of 4,4,4′,4′,5,5,5′,5′-octamethyl-2,2′-bi-1,3,2-dioxaborolane $[B(Pin)]_2$ as reducing reagent to produce the corresponding sulfides has been investigated. After examination of various reaction parameters the abilities of catalytic amounts of $Zn(OTf)_2$ has been proven in the deoxygenation of various sulfoxides. Especially, a high functional group tolerance was noticed for the $Zn(OTf)_2$/$B(Pin)_2$ system.

Keywords Catalysis · Zinc · Deoxygenation · Sulfoxide · Sulfide

1 Introduction

During the last decades several approaches have been accounted on the deoxygenation of sulfoxides to produce the corresponding sulfides. Especially, the deoxygenation of sulfur-based compounds is an essential process in biological systems (e.g., dimethylsulfoxide-, biotin-, and methionine sulfoxide reductase) and furthermore of importance in organic chemistry [1–39]. Nowadays for organic and industrial synthesis the application of cheap and low toxic metals is highly requested [40–68]. Recently, we have studied the deoxygenation of sulfoxides with silanes and different cheap and abundant metal catalysts (e.g., Mo, Fe, Cu, Zn) [69–72]. In case of zinc excellent yields have been realized under mild reaction conditions (Fig. 1). Noteworthy, the application of hydrosilanes displayed difficulties with respect to selectivity. In more detail, functional groups, e.g., alkenyl, alkinyl, carbonyl and amide are reduced along with the sulfoxide by the zinc catalyst and the hydrosilane. Moreover, we could demonstrate that hydroboranes are suitable reagents for the deoxygenation of sulfoxides [73]. To overcome the limitations in functional group tolerance novel systems are highly desired. Interestingly, as additional products siloxanes ($R_3SiOSiR_3$) or bisborane oxides (R_2BOBR_2) are obtained, which are containing the oxygen of the former sulfoxide. The structural motif can be rationalized as an insertion of oxygen in $R_3Si–SiR_3$ or $R_2B–BR_2$ bonds. Hence, the reaction of sulfoxides with $R_3Si–SiR_3$ or $R_2B–BR_2$ as reductants to form the sulfide and $R_3SiOSiR_3$ or R_2BOBR_2 could avoid the reduction of functional groups and increase the chemoselectivity.

Based on that concept we report herein our investigations on the zinc-catalyzed deoxygenation of sulfoxides to generate the corresponding sulfides with $[B(Pin)]_2$ as reductant.

2 Results and Discussion

Initially, the deoxygenation of *p*-tolyl sulfoxide (**1**) with an excess of hexamethyldisilane (TMS–TMS) was studied (Table 1, entry 1–3). For our initial study a catalytic loading of 5 mol% of $Zn(OTf)_2$ was used. However, no product formation was obtained under described conditions even in the presence of tetra *n*-butylammonium fluoride (TBAF) to activate the disilane. Replacement of the disilane by 1.2 equivalents 4,4,4′,4′,5,5,5′,5′-octamethyl-2,2′-bi-1,3,2-dioxaborolane $[B(Pin)]_2$ at 100 °C in toluene

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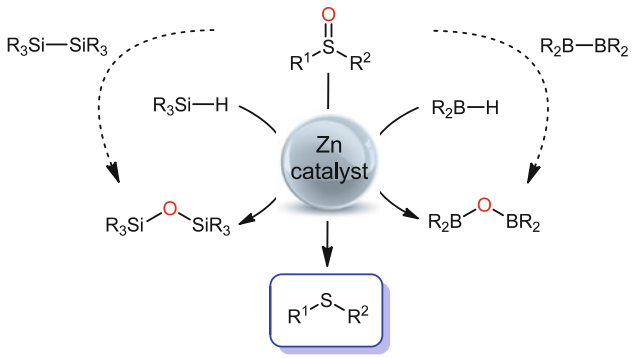


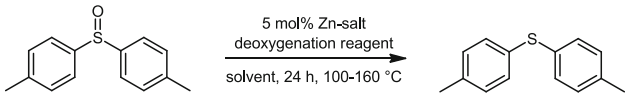
Fig. 1 Recent achievements in the zinc-catalyzed deoxygenation of sulfoxides to sulfides

resulted in the formation of sulfide **2** (Table 1, entry 4). An increased yield of 81–82 % was observed by increasing the temperature to 160 °C applying tetraglyme or mesitylene as solvent (Table 1, entries 6 and 8). Furthermore, a decrease of activity (51 %) was attained with $ZnCl_2$ as pre-catalysts, while in the absence the corresponding sulfide was formed in 23 % yield (Table 1, entries 7 and 9). In the absence of any zinc source and $[B(Pin)]_2$ small amounts of sulfide **2** (5 %) were detected (Table 1, entry 9). A similar result was observed in the presence of catalytic amounts of $Zn(OTf)_2$, but in the absence of $[B(Pin)]_2$ (Table 1, entry 11). To clarify the role of the zinc, the deoxygenation was performed in the presence of catalytic amounts of trifluoromethanesulfonic acid (TfOH), which can be potentially formed by decomposition of $Zn(OTf)_2$ (Table 1, entry 12). However, no product formation was observed; hence the zinc should play an important role during catalysis.

After investigation of the reaction conditions the scope and limitations of the zinc-catalyzed deoxygenation of various sulfoxides, including aromatic and aliphatic sulfoxides, using $[B(Pin)]_2$ as reducing reagent were studied (Table 2). For obtaining higher yields of the products the reaction time was elongated to 48 h. In case of our model substrate **1** full conversion was attained (Table 2, entry 1). In addition, biaryl sulfides **3a** and **4a** were obtained in good yields (Table 2, entries 2 and 3). Substitution of one aryl unit by an alkyl group demonstrated excellent performance of the combination of $Zn(OTf)_2$ and $[B(Pin)]_2$ (Table 2, entry 5). Noteworthy, in case of an olefin attached to the sulfur the desired product was not obtained (Table 2, entry 6). Furthermore, good to excellent yields were obtained for alkyl based sulfides (Table 2, entries 4, 7, 8 and 9).

In order to study the selectivity of the process different substrates containing functional groups sensitive to reduction in combination with the sulfoxide **1** were reacted with $[B(Pin)]_2$ in the presence of zinc(II) triflate (Table 3). Excellent selectivity (>99 %) for the deoxygenation of the S=O bond was observed in the presence of esters, amides sulfonyl, and alkynyl functional groups. Noteworthy, the application of hydrosilanes as reductant resulted in the attack of amides and alkynyl functions [70].

Table 1 Investigation of the influence of the reaction conditions in the zinc-catalyzed deoxygenation of sulfoxides



1 2

Entry	Pre-catalyst	Reagent	Solvent	T (°C)	Yield (%)[a]
1	$Zn(OTf)_2$	$MeSi–SiMe_3$[b]	–	100	<1
2[c]	$Zn(OTf)_2$	$MeSi–SiMe_3$[b]	–	100	<1
3[c]	–	$MeSi–SiMe_3$[b]	–	100	<1
4	$Zn(OTf)_2$	$[B(Pin)]_2$	Toulene	100	8
5	$Zn(OTf)_2$	$[B(Pin)]_2$	Tetraglyme	130	40
6	$Zn(OTf)_2$	$[B(Pin)]_2$	Tetraglyme	160	82
7	$ZnCl_2$	$[B(Pin)]_2$	Tetraglyme	160	53
8	$Zn(OTf)_2$	$[B(Pin)]_2$	Mesitylene	160	81
9	–	$[B(Pin)]_2$	Tetraglyme	160	23
10	–	–	Mesitylene	160	5
11	$Zn(OTf)_2$	–	Mesitylene	160	5
12	TfOH	–	Mesitylene	160	<1

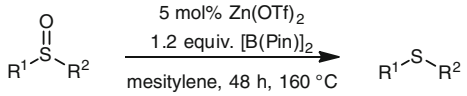
Reaction conditions: **1** (0.72 mmol), $Zn(OTf)_2$ (5 mol %), $[B(Pin)]_2$ (1.2 equiv. 0.80 mmol), solvent (2.0 mL), 24 h

[a] Determined by GC methods and ^1H NMR

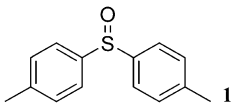
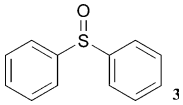
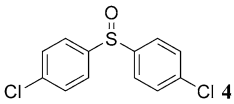
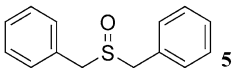
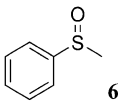
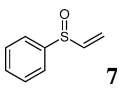
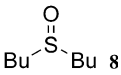
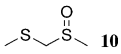
[b] 1.0 mL of $Me_3Si–SiMe_3$

[c] 10 mol% TBAF

Table 2 Scope and limitations of the zinc-catalyzed deoxygenation of sulfoxides



1, 11-17 **6, 11a-17a**

Entry	Substrates	Product	Yield (%)[a]
1	 **1**	**2**	98
2	 **3**	**3a**	83
3	 **4**	**4a**	92
4	 **5**	**5a**	89
5	 **6**	**6a**	98
6	 **7**	**7a**	<1[b]
7	 **8**	**8a**	97
8	 **9**	**9a**	85[c]
9	 **10**	**10a**	87[c]

Reaction conditions: substrate (0.72 mmol), $Zn(OTf)_2$ (5 mol%), $[B(Pin)]_2$ (1.2 equiv.), mesitylene (2.0 mL), 48 h, 160 °C

[a] Isolated yield

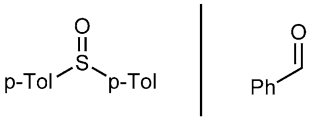
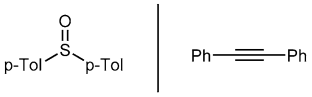
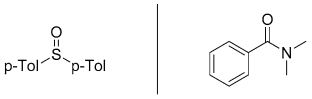
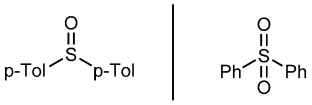
[b] Decomposition

[c] Determined by GC methods and ^{1}H NMR

Based on the obtained results we propose that the zinc acts as a Lewis-acid catalyst (Scheme 1). Initially, the sulfoxide coordinates to the zinc (intermediate **A**) thus an activation of the S=O bond occurs and enhances the susceptibility of the sulfur for reduction [70, 73, 74]. Subsequently, the $[B(Pin)]_2$ reacts with the intermediate **A** via the intermediate **B**. The sulfur is reduced by the $[B(Pin)]_2$ and the oxygen is transferred to the borons of the previous $[B(Pin)]_2$ to form the desired sulfide and the $O[B(Pin)]_2$. The formation of $O[B(Pin)]_2$ was clarified by ^{11}B NMR studies, since a characteristic signal was observed at $\delta = 22.4$ ppm. The chemical shift is in agreement to literature reports [75]. The sulfide is replaced by a substrate molecule to re-create the starting complex **A**.

In summary, we have set up a protocol for the deoxygenation of sulfoxides to the corresponding sulfide with $[B(Pin)]_2$ as oxygen scavenger in the presence of straightforward and abundant zinc(II) triflate. Noteworthy, various aryl and alkyl based sulfoxides were

Table 3 Zinc(II) triflate-catalyzed reduction of sulfoxide **1** in the presence of additional substrates sensitive to reduction

Entry	Substrates	Yield (%)[a]
1		>99/<1[b]
2		>99/<1[b]
3		>99/<1
4		>99/<1
5		98/<1
6		>99/<1
7		>99/<1
8		>99/<1
9		>99/<1[b]

Reaction conditions: sulfoxide **1** (0.72 mmol), $Zn(OTf)_2$ (5 mol%), $[B(Pin)]_2$ (1.2 equiv.), 0.72 mmol of the second substrate, mesitylene (2.0 mL), 48 h

[a] Determined by GC–MS

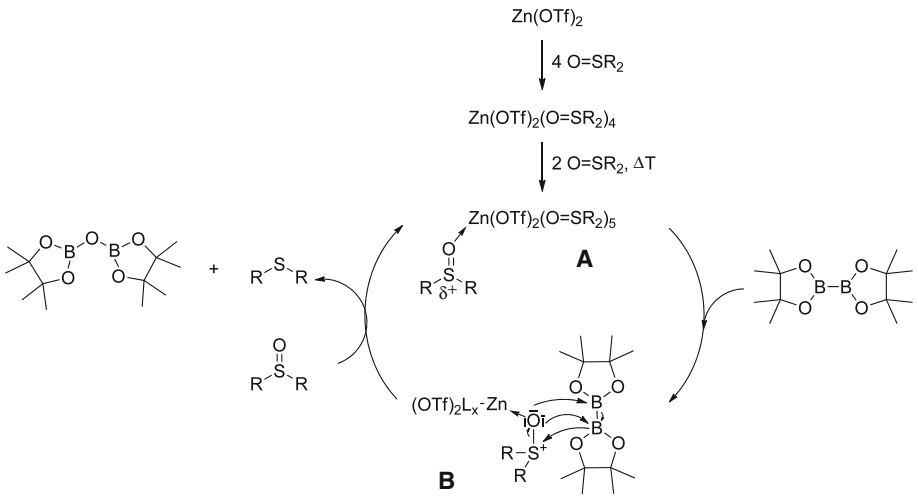
[b] The second substrate was not detectable, probably due to decomposition

converted to the corresponding sulfides in good to excellent yields.

3 Experimental Section

3.1 General Procedure for the Deoxygenation of Sulfoxides

A pressure tube was charged with an appropriate amount of $Zn(OTf)_2$ (0.036 mmol, 5.0 mol%), the corresponding sulfoxide (0.72 mmol) and the borane (1.2 equiv., 0.86 mmol). After addition of mesitylene (2.0 mL) the reaction mixture was stirred in a preheated oil bath at 160 °C for 48 h. The mixture was cooled on an ice bath and biphenyl (internal standard) was added. The solution was diluted with dichloromethane and an aliquot was taken for GC-analysis (30 m Rxi-5 ms column, 40–300 °C). The solvent was removed and the residue was purified by column chromatography. The analytical properties of the corresponding sulfides are in agreement with literature data [69–73].



Scheme 1 Proposed catalytic cycle for the reduction of sulfoxides with $[B(Pin)]_2$ in the presence of $Zn(OTf)_2$

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References

1. Hille R, Reètey J, Bartlewski-Hof U, Reichenbecher W, Schink B (1999) FEMS Microbiology Rev 22:489–501
2. Hille R (1996) Chem Rev 96:2757–2816
3. Kisker C, Schindelin H, Rees DC (1997) Annu Rev Biochem 66:233–267
4. Enemark JH, Cooney JJA, Wang J-J, Holm RH (2004) Chem Rev 104:1175–1200
5. McGarrigle EM, Myers EL, Illa O, Shaw MA, Riches SL, Aggarwal VK (2007) Chem Rev 107:5841–5883
6. Rickard D, Luther GW III (2007) Chem Rev 107:514–562
7. Nicolas E, Vilaseca M, Giralt E (1995) Tetrahedron 51:5701–5710
8. Nicolau KC, Kuombis AE, Synder SA, Simonsen KB (2000) Angew Chem 112:2629–2633
9. Nicolau KC, Kuombis AE, Synder SA, Simonsen KB (2000) Angew Chem Int Ed 39:2529–2533
10. Zhu Z, Espenson JH (1995) J Mol Catal A Chem 103:87–94
11. Reis PM, Costa PJ, Romão CC, Fernandes JA, Calhorda MJ, Royo B (2008) Dalton Trans 13:1727–1733
12. Bahrami K, Khodaei MM, Karimi A (2008) Synthesis 16:2543–2546
13. Khurana JM, Sharma VS, Chacko A (2007) Tetrahedron 63:966–969
14. Yoo BW, Park MC, Song MS (2007) Synth Commun 37:4079–4083
15. Yoo BW, Song MS, Park MC (2007) Bull Korean Chem Soc 28:171–172
16. Yoo BW, Song MS, Park MC (2007) Synth Commun 37:3089–3093
17. Pandey LK, Pathak U, Rao AN (2007) Synth Commun 37:4105–4109
18. Bahrami K, Khodaei MM, Khedri M (2007) Chem Lett 36: 1324–1325
19. Fernandes AC, Romão CC (2006) Tetrahedron 62:9650–9654
20. Roy CD, Brown HC (2006) J Chem Res 10:642–644
21. Raju BR, Devi G, Nongpluh YS, Saikia AK (2005) Synlett 2:358–360
22. Espenson JH (2005) Coord Chem Rev 249:329–341
23. Sanz R, Escribano J, Fernández Y, Aguado R, Pedrosa MR, Arnáiz FJ (2004) Synthesis 37:1629–1632
24. Harrison DJ, Tam NC, Vogels CM, Langler RF, Baker RT, Decken A, Westcott SA (2004) Tetrahedron Lett 45:8493–8496
25. Kukuskin VY (1995) Coord Chem Rev 139:375–407
26. Yoo BW, Choi KH, Kim DY, Choi KI, Kim JH (2003) Synth Commun 33:53–57
27. Arias J, Newlands CR, Abu-Omar MM (2001) Inorg Chem 40:2185–2192
28. Abu-Omar MM, Khan SI (1998) Inorg Chem 37:4979–4985
29. Arterburn JB, Perry MC (1996) Tetrahedron Lett 37:7941–7944
30. Abu-Omar MM, Appelman EH, Espenson JH (1996) Inorg Chem 35:7751–7757
31. Kukuskin VY (1990) Russ Chem Rev 59:844–852
32. Madesclaire M (1988) Tetrahedron 44:6537–6551
33. Bryan JC, Stenkamp RE, Tulip TH, Mayer JM (1987) Inorg Chem 26:2283–2288
34. Cha JS, Kim JE, Kim JD (1985) Tetrahedron Lett 26:6453–6456
35. Brown HC, Ravindran N (1973) Synthesis 1:42–43
36. Guidon Y, Atkinson JG, Morton HE (1984) J Org Chem 49:4538–4540
37. Sousa SCA, Fernandes AC (2009) Tetrahedron Lett 50:6872–6876
38. Mikami Y, Noujima A, Mitsudome T, Mizugaki T, Jitsukawa K, Kaneda K (2011) Chem Eur J 17:1768–1772
39. Cardoso JMS, Royo B (2012) Chem Commun 48:4944–4946
40. Enthaler S, Junge K, Beller M (2008) Angew Chem 120:3363–3367
41. Enthaler S, Junge K, Beller M (2008) Angew Chem Int Ed 47:3317–3321
42. Mimoun H, De Saint Laumer JY, Giannini L, Scopelliti R, Floriani C (1999) J Am Chem Soc 121:6158–6166
43. Mimoun H (1999) J Org Chem 64:2582–2589
44. Bette V, Mortreux A, Lehmann CW, Carpentier J-F (2003) Chem Commun 3:332–333
45. Bette V, Mortreux A, Ferioli F, Martelli G, Savoia D, Carpentier J-F (2004) Eur J Org Chem 14:3040–3045
46. Bette V, Mortreux A, Savoia D, Carpentier J-F (2004) Tetrahedron 60:2837–2842

47. Mastranzo VM, Quinterno L, Anaya de Parrodi C, Juaristi E, Walsh PJ (2004) Tetrahedron 60:1781–1789
48. Ushio H, Mikami K (2005) Tetrahedron Lett 46:2903–2906
49. Bette V, Mortreux A, Savoia D, Carpentier J-F (2005) Adv Synth Catal 347:289–302
50. Gérard S, Pressel Y, Riant O (2005) Tetrahedron Asymmetry 16:1889–1891
51. Park B-M, Mun S, Yun J (2006) Adv Synth Catal 348:1029–1032
52. Bandini M, Melucci M, Piccinelli F, Sinisi R, Tommasi S, Umani-Ronchi A (2007) Chem Commun 43:4519–4521
53. Inagaki T, Yamada Y, Phong LT, Furuta A, Ito J-i, Nishiyama H (2009) Synlett 2:253–256
54. Gajewy J, Kwit M, Gawroński J (2009) Adv Synth Catal 351:1055–1063
55. Das S, Addis D, Zhou S, Junge K, Beller M (2010) J Am Chem Soc 132:1770–1771
56. Bandini M, Cozzi PG, de Angelis M, Umani-Ronchi A (2000) Tetrahedron Lett 41:1601–1605
57. Locatelli M, Cozzi PG (2003) Angew Chem Int Ed 42:4928–4930
58. Marinos NA, Enthaler S, Driess M (2010) ChemCatChem 2:846–853
59. Enthaler S, Eckhardt B, Inoue S, Irran E, Driess M (2010) Chem Asian J 5:2027–2035
60. Enthaler S, Schröder K, Inoue S, Eckhardt B, Junge K, Beller M, Driess M (2010) Eur J Org Chem 25:4893–4901
61. Enthaler S (2011) Catal Lett 141:55–61
62. Someya CI, Inoue S, Irran E, Krackl S, Enthaler S (2011) Eur J Inorg Chem 2011:2691–2697
63. Enthaler S, Weidauer M, Schröder F (2012) Tetrahedron Lett 53:882–885
64. Enthaler S, Weidauer M (2012) Catal Lett 142:168–175
65. Enthaler S, Inoue S (2012) Chem Asian J 7:169–175
66. Enthaler S, Weidauer M (2012) Chem Eur J 18:1910–1913
67. Someya CI, Inoue S, Krackl S, Irran E, Enthaler S (2012) Eur J Inorg Chem 8:1269–1277
68. Haberberger M, Someya CI, Company A, Irran E, Enthaler S (2012) Catal Lett 142:557–565
69. Enthaler S (2011) ChemCatChem 3:666–670
70. Enthaler S (2011) Catal Sci Technol 1:104–110
71. Enthaler S, Weidauer M (2011) Catal Lett 141:833–838
72. Krackl S, Company A, Enthaler S, Driess M (2011) ChemCatChem 3:1186–1192
73. Enthaler S, Krackl S, Irran E, Inoue S (2012) Catal Lett. doi: 10.1007/s10562-012-0862-9
74. Drabowicz J, Mikolajczyk M (1976) Synthesis 8:527–528
75. Bae S, Lakshman MK (2008) J Org Chem 73:1311–1319