A Catalytic Deprotection of *S,S*-, *S,O*- and *O,O*-Acetals Using $Bi(NO_3)_3 \cdot 5\,H_2O$ under Air

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Abstract: *S,S*-Acetals are smoothly deprotected with air in the presence of a catalytic amount of $Bi(NO_3)_3 \cdot 5\,H_2O$ (1–50 mol %) under ambient conditions to regenerate the original carbonyl compounds in good to excellent yield. This mild, simple, and environmentally benign system is successfully applied to the deprotection of *S,O*- and *O,O*-acetals and is compatible with various functional groups. From the mechanistic study of the reaction, the catalytic cycle is considered to be composed of the following four steps: (1) the nitrososulfonium ion of the *S,S*-acetal is formed by attack of nitrosonium ion (NO^+) generated from $Bi(NO_3)_3 \cdot 5\,H_2O$ through the equilibrium with NO_2, (2) the nitrososulfonium ion is hydrolyzed to afford the hemithioacetal and thionitrite, (3) the hemithioacetal collapses to the original carbonyl compound and thiol, which is oxidized by NO^+ to give disulfide and NO via thionitrite, and (4) the NO captures molecular oxygen from air to regenerate NO_2.

Keywords: acetals; bismuth nitrate; deprotection; oxidation; protecting groups; reaction mechanisms

Introduction

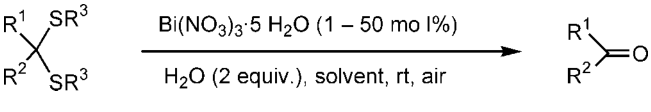
The *S,S*-acetal function finds wide use in organic synthesis as a carbonyl protecting group due to its easy access[1] as well as high stability under both acidic and basic conditions. In addition, this function is often employed as the acyl anion equivalent.[2] In particular, 2-lithio-1,3-dithiane derivatives have been widely used for the key reactions to combine the building blocks in natural product syntheses.[3] In spite of these synthetic utilities, the use of *S,S*-acetals is occasionally hampered by the lack of an efficient procedure for regenerating the original carbonyl functionality, although various methods have been developed. The methods reported so far may be classified into three categories; chemical, photochemical, and electrochemical.[4] The latter two need expensive equipment and are not amenable to scaling-up of the reaction. In addition, known chemical methods require the use of a *stoichiometric* or an *excess* amount of the demasking reagent,[2b,5,6] which usually includes heavy metal salts such as mercury(II), silver(I), and copper(II) salts as well as oxidizing agents such as molecular halogens, *N*-halosuccinimides, and MCPBA.

As part of our ongoing program on the use of the bismuth salts as catalyst for organic transformations,[7] we have reported preliminary results on the deprotection of simple *S,S*-acetals with air and a *catalytic* amount of $Bi(NO_3)_3 \cdot 5\,H_2O$ under ambient conditions.[8] This paper gives a full account of the deprotection, including (1) its compatibility with various functional groups on the *S,S*-acetals, (2) an extension to the deprotection of *S,O*- and *O,O*-acetals, and (3) the reaction mechanism. To our knowledge, the literature to date contains no precedent for such an economical, mild and environmentally benign[9] dethioacetalization.

Results and Discussion

Deprotection of *S,S*-Acetals

The *S,S*-acetals derived from aldehydes and ketones were smoothly deprotected in the presence of 1–50 mol % of $Bi(NO_3)_3 \cdot 5\,H_2O$ and 2 equivalents of water under air to regenerate the parent carbonyl



Scheme 1.

Table 1. Deprotection of *S,S*-acetals in benzene using a catalytic amount of $Bi(NO_3)_3 \cdot 5\,H_2O$ (Scheme 1).

Run	R^1	R^2	R^3	$Bi(NO_3)_3$ (mol %)	additive (mol %)	Reaction time (h)	Yield (%)[a]
1	p-$MeOC_6H_4$	H	$(CH_2)_2$	1	–	10	91
2	p-$MeOC_6H_4$	H	$(CH_2)_2$	2	–	5	94
3	p-$MeOC_6H_4$	H	$(CH_2)_2$	5	–	3	86
4[b]	p-$MeOC_6H_4$	H	$(CH_2)_2$	5	–	1	75
5[c]	p-$MeOC_6H_4$	H	$(CH_2)_2$	10	$BiCl_3$ (5)	2	89
6[d]	p-$MeOC_6H_4$	H	$(CH_2)_2$	20	–	2	89
7[d]	p-$MeOC_6H_4$	H	$(CH_2)_2$	20	NaN_3 (10)	5	Trace[e]
8	p-$MeOC_6H_4$	H	$(CH_2)_2$	-	NO_2 (20)	0.5	86
9	p-$MeOC_6H_4$	H	$(CH_2)_3$	2	–	4.5	91
10	p-$MeOC_6H_4$	H	Et	10	–	10	91
11	p-$MeOC_6H_4$	H	Ph	10	–	12	98[f]
12[b],[g]	p-$MeOC_6H_4$	H	Ph	5	–	24	99[f]
13	Ph	H	$(CH_2)_2$	2	–	6	72[h]
14[i]	Ph	H	$(CH_2)_2$	2	–	6	8[e],[h]
15	Ph	H	$(CH_2)_3$	2	–	4	91[h]
16	p-ClC_6H_4	H	$(CH_2)_2$	5	–	9	81
17	p-ClC_6H_4	H	$(CH_2)_3$	5	–	4	80
18	p-$AcOC_6H_4$	H	$(CH_2)_2$	5	–	4	98
19	p-$AcOC_6H_4$	H	$(CH_2)_3$	5	–	2	92
20	3,4-$(MeO)_2C_6H_3$	H	$(CH_2)_2$	5	–	5	92
21	3,4-$(MeO)_2C_6H_3$	H	$(CH_2)_3$	5	–	5	93
22	p-$O_2NC_6H_4$	H	$(CH_2)_2$	5	–	5	68[h]
23	2-Thienyl	H	$(CH_2)_2$	10	–	10	74[h]
24	2-Thienyl	H	$(CH_2)_3$	5	–	5	76[h]
25	*trans*-PhCH=CH	H	$(CH_2)_2$	40	–	24	Trace[e]
26	*trans*-PhCH=CH	H	$(CH_2)_2$	40	$BiCl_3$ (10)	4	90
27	*trans*-PhCH=CH	H	$(CH_2)_3$	30	–	2	70
28	$Me(CH_2)_6$	H	$(CH_2)_2$	20	–	4	98[h]
29	$Me(CH_2)_6$	H	$(CH_2)_3$	20	–	6	75[h]
30	$Me(CH_2)_6$	H	$(CH_2)_3$	20	$BiCl_3$ (5)	2	81[h]
31	$Me(CH_2)_6$	H	Et	20	–	6	96[h]
32	Ph	Me	$(CH_2)_3$	10	–	10	76[h]
33	Ph	Me	$(CH_2)_3$	10	$BiCl_3$ (5)	2	76[h]
34	Ph	Me	$(CH_2)_3$	10	$Bi_2(SO_4)_3$ (5)	3	76[h]
35	Ph	Me	$(CH_2)_3$	20	–	4	72[j]
36	$Me(CH_2)_5$	Me	$(CH_2)_2$	50	–	10	93[h]
37	$Me(CH_2)_5$	Me	$(CH_2)_3$	10	–	3	92[h]
38	$Me(CH_2)_4$	Et	$(CH_2)_2$	50	–	24	94[h]
39	$Me(CH_2)_4$	Et	$(CH_2)_3$	10	–	5	98[h]
40	$-(CH_2)_5-$		$(CH_2)_3$	20	–	5	98[h]

[a] Isolated yield unless otherwise noted.

[b] Under oxygen.

[c] In CH_2Cl_2 containing 1.4 equivalents of water.

[d] In MeCN containing 1.4 equivalents of water.

[e] Most of the substrate remained intact.

[f] In runs 9 and 10, diphenyl disulfide was obtained in 83% and 99% yields, respectively.

[g] Consumption of oxygen was measured volumetrically (see text).[10]

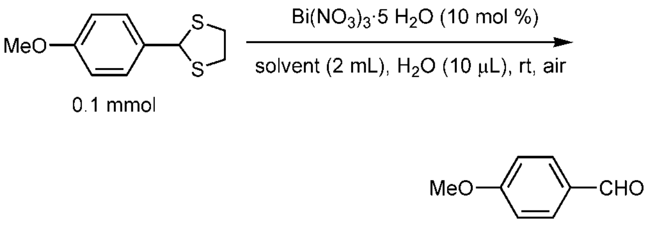
[h] GC yield.

[i] Under argon.

[j] α-Nitroacetophenone was obtained in 11 % yield, along with acetophenone (Equation 3).

compounds in good to excellent yield as shown in Table 1. Under an argon atmosphere, the reaction scarcely proceeded (run 14), while the reaction was complete within an hour under oxygen (run 4). These results suggest that oxidation by molecular oxygen is involved as a key step of the deprotection. This view is supported by the fact that an equimolar amount of molecular oxygen was consumed during the deprotection to produce diphenyl disulfide and *p*-anisaldehyde quantitatively (run 12).[10] Actually, $Bi(NO_3)_3 \cdot 5\,H_2O$ has been utilized as an oxidation catalyst for sulfide to sulfoxide[11] and thiol to disulfide[12] transformations under similar conditions.

In order to find a suitable solvent system for this dethioacetalization, several solvents were examined under the same conditions (Equation 1). The results are summarized in Table 2. Benzene was found to be the best solvent to proceed the fastest reaction rate (run 1). Toluene, dichloromethane, acetonitrile, 1,4-dioxane, and ethyl acetate can be used as alternative solvents, although longer reaction times were needed than for benzene to complete the deprotection of *S,S*-acetal (runs 2–6). A similar trend is observed in the amount of catalyst required; less than 5 mol % of $Bi(NO_3)_3 \cdot 5\,H_2O$ is sufficient for the dethioacetalization in benzene (runs 1–3 in Table 1), while 10 and 20 mol % are necessary in dichloromethane and acetonitrile, respectively (runs 5 and 6 in Table 1). In THF, DMF, hexane, CCl_4, and methanol, the reaction hardly proceeded.



(1)

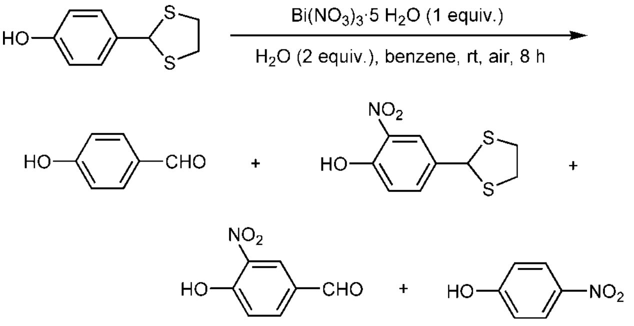
Table 2. Solvent effects in the deprotection of *S,S*-acetals (Equation 1).

Run	Solvent	Reaction time (h)	Yield (%)[a]
1	benzene	2	100
2	toluene	3	100
3	CH_2Cl_2	5	94
4	MeCN	6	93
5	1,4-dioxane	10	83
6	AcOEt	24	93
7	$CHCl_3$	24	39
8	THF	24	10

[a] GC yield.

As for the catalysts, other bismuth salts such as BiF_3, $BiCl_3$, BiOCl, $BiBr_3$, BiI_3, $Bi(OAc)_3$, and $Bi_2(SO_4)_3$, and other metal nitrates such as $Zn(NO_3)_2{\cdot}6\,H_2O$, $Pb(NO_3)_2$, and $La(NO_3)_3{\cdot}6\,H_2O$ showed little or no catalytic activity under the conditions used for runs 2 and 6 in Table 1. As for the added water, 2 equivalents gave the best result; larger and smaller amounts of water (1 and 3 equivalents) retarded the reaction considerably.

Under the optimized conditions, the cyclic dithioacetals derived from aromatic aldehydes were demasked using less than 5 mol % of the catalyst (runs 1–4 and 13–22 in Table 1) regardless of the functional groups on the aromatic ring such as –OMe, –Cl, –OAc, and $-NO_2$, and the thioacetal moieties (R^3) such as dithiane, dithiolane and acyclic acetals. Hydroxy and dimethylamino functions at *para*-positions made the catalytic reactions sluggish; an equimolar amount of $Bi(NO_3)_3{\cdot}5\,H_2O$ was needed to make these reactions proceed, affording a large amount of nitrated products along with the desired aldehydes (Equation 2). In these reactions, the yields of the products were not reproducible probably because a considerable amount of nitrogen oxides was generated by the decomposition of $Bi(NO_3)_3{\cdot}5\,H_2O$, which will be discussed below, and nitrated the substrates and the products indiscriminately. *S,S*-Acetals with a thiophene ring and conjugated double bond were deprotected to give the desired aldehydes in good yields with 5–10 and 30–40 mol % of the catalyst (runs 23–24 and 25–27), respectively.



(2)

The dithioacetals from ketones and aliphatic aldehydes needed a larger amount of the catalyst (10–50 mol %) (runs 25–40) than those from aromatic aldehydes. When the reaction was sluggish, it was considerably facilitated by the additional presence of a second bismuth salt, i.e., $BiCl_3$ and $Bi_2(SO_4)_3$, as an auxiliary additive (runs 26, 30, 33 and 34). Without $Bi(NO_3)_3{\cdot}5\,H_2O$, *S,S*-acetals remained intact even in the presence of the second bismuth salt.

A variety of *S,S*-acetals **1**–**5**[5c,13] (Figure 1) was successfully deprotected with the present system as shown in Table 3. The alcohols **1**–**3** derived from 2-lithio-2-methyldithiane and the corresponding methyl ketones[13c] were deprotected to give α-hydroxy ke-

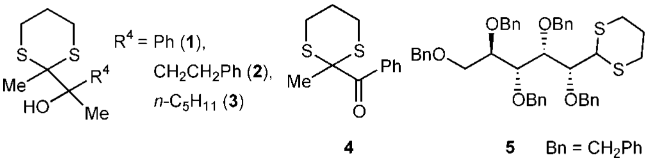


Figure 1. Structures of compounds **1** – **5**.

Table 3. Deprotection of various functionalized *S,S*-acetals in benzene using a catalytic amount of $Bi(NO_3)_3{\cdot}5\,H_2O$.

Run	*S,S*-acetal	$Bi(NO_3)_3$ (mol %)	$BiCl_3$ (mol %)	Reaction time (h)	Yield (%)[a]
1	**1**	10	–	2	77
2	**2**	10	–	5	75
3	**3**	20	–	5	60
4	**4**	20	5	24	NR[b]
5	**4**	50	50	7	43[c],[d]
6	**4**	50	30	7	39[c],[d]
7	**4**	50	10	7	22[c],[e]
8	**5**	20	–	24	92[f]
9	**5**	20	10	4	95[f]

[a] Isolated yield unless otherwise noted.

[b] No reaction.

[c] GC yield.

[d] Trace amount of substrate was recovered after work-up.

[e] Substrate (27 %) was recovered after work-up.

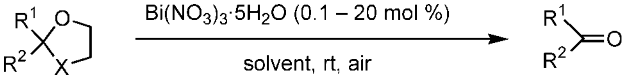
[f] Yield of a crude product, which was found almost pure on ^{13}C NMR spectra.

tones in good yields with 10–20 mol % of the catalyst (runs 1–3). Although the deprotection of the ketone 4[5c,13b,13d] to the 1,2-diketone required 50 mol % of $Bi(NO_3)_3\cdot 5\,H_2O$ together with bismuth(III) chloride (10–50 mol %) (runs 4–6), the *S,S*-acetal derived from D-glucose 5[13a] was deprotected almost quantitatively in the presence of 20 mol % of the catalyst (run 8). The copresence of 10 mol % $BiCl_3$ remarkably accelerated the deprotection of 5 (run 9).

Deprotection of *S,O*- and *O,O*-Acetals

The present method is found to be effective for the deprotection of *S,O*- and *O,O*-acetals (Scheme 2). *S,O*-Acetals have also been known to require harsh conditions and/or the use of a *stoichiometric* or an *excess* amount of reagent for their deprotection in spite of their synthetic importance similar to that of *S,S*-acetals.[5a,14] On the other hand, a simple chemoselective method for the deprotection of *O,O*-acetals has been developed using $Bi(NO_3)_3\cdot 5\,H_2O$ as a catalyst quite recently.[15]

The results of the deprotection of *S,O*- and *O,O*-acetals are summarized in Table 4. Acetonitrile/water (4/1 v/v) was found to be a complementary solvent to the wet benzene used for the deprotection of *S,S*-acetals; much better yields were obtained in acetonitrile/water (runs 8, 12 and 13) than in wet benzene (runs 7, 11 and 14), while the opposite trends were observed in runs 3–4 and 9–10. All the oxathiolanes derived from aldehydes and ketones were deprotected with 5–20 mol % of $Bi(NO_3)_3\cdot 5\,H_2O$ in wet benzene and/or acetonitrile/water to regenerate the carbonyl compounds in good to excellent yields. As for the deprotection of *O,O*-acetals (dioxolanes), 0.1 mol % of $Bi(NO_3)_3\cdot 5\,H_2O$ is sufficient to regenerate the parent carbonyl compounds quantitatively in acetonitrile/water (runs 13 and 15), while much larger amounts of the catalyst resulted in a poor yield in wet benzene (run 14).



Scheme 2.

Such a remarkable difference depending on the solvent system may imply the operation of a different reaction mechanism. In acetonitrile/water, C–O bond fission is considered to occur preferentially via hydrolysis under the catalysis of nitric acid generated by hydrolysis of $Bi(NO_3)_3\cdot\ 5\,H_2O$,[15] while the C–S bond may be cleaved in wet benzene via oxidation under the catalysis of NO^+ generated by decomposition of $Bi(NO_3)_3\cdot 5\,H_2O$, which will be discussed below. The recent report on a similar deprotection of *O,O*-acetals describes that a suspension of $Bi(NO_3)_3\cdot 5\,H_2O$ in water is acidic and that the resulting nitric acid promotes the deprotection.[15] An additional point to note in the report is that no reaction is observed with dioxolanes in dichloromethane even in the presence of 25 mol % of $Bi(NO_3)_3\cdot 5\,H_2O$, which is in marked contrast to our results (runs 13 and 15 in Table 4).

Reaction Mechanism

From the above discussion, it has been established that *S,S*-acetals were cleaved oxidatively by molecular oxygen. This poses the question: what is the oxidant? A hint towards the answer was obtained from

Table 4. Deprotection of *S,O*- and *O,O*-acetals using a catalytic amount of $Bi(NO_3)_3\cdot 5\,H_2O$ (Scheme 2).

Run	R^1	R^2	X	Solvent	$Bi(NO_3)_3$ (mol %)	Reaction time (h)	Yield (%)[a]
1	*p*-$MeOC_6H_4$	H	S	benzene[b]	5	24	64
2	*p*-$MeOC_6H_4$	H	S	$MeCN/H_2O$ (4/1)	9	24	68
3	Ph	H	S	benzene[b]	10	19	79
4	Ph	H	S	$MeCN/H_2O$ (4/1)	5	24	NR[c]
5	*p*-$NO_2C_6H_4$	H	S	benzene[b]	10	32	70
6	$Me(CH_2)_6$	H	S	benzene[b]	5	6	81
7	Ph	Me	S	benzene[b]	5	6	6[d],[e]
8	Ph	Me	S	$MeCN/H_2O$ (4/1)	10	24	93[d]
9	*p*-BrC_6H_4	Me	S	benzene[b]	20	20	74
10	*p*-BrC_6H_4	Me	S	$MeCN/H_2O$ (4/1)	5	36	24
11	$Me(CH_2)_5$	Me	S	benzene[b]	5	6	3[d],[e]
12	$Me(CH_2)_5$	Me	S	$MeCN/H_2O$ (4/1)	10	24	98[d]
13	Ph	H	O	$MeCN/H_2O$ (4/1)	0.1	3	95[d]
14	Ph	H	O	benzene[b]	5	4	16[d],[e]
15	$Me(CH_2)_5$	Me	O	$MeCN/H_2O$ (4/1)	0.1	3	100[d]

[a] Isolated yield unless otherwise noted.

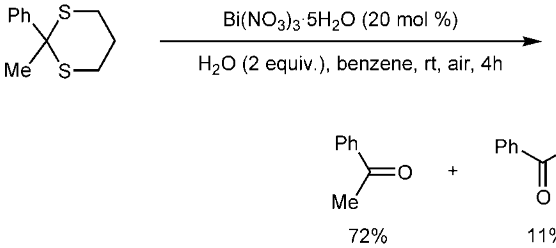
[b] Added 2 equivalents of H_2O.

[c] No reaction.

[d] GC yield.

[e] Most of substrate remained intact.

the by-products from the reactions. As we mentioned above, various nitrated products were obtained in the stoichiometric deprotection of 2-(4-hydroxyphenyl)-1,3-dithiolane (Equation 2) as well as in the catalytic deprotection of 2-methyl-2-phenyl-1,3-dithiane (Equation 3), implying the existence of nitrogen oxides generated *in situ*.



(3)

The following experimental observations support that this process involved NO_2 as a key compound. Light brown fumes were evolved when the *S,S*-acetal was mixed with $Bi(NO_3)_3{\cdot}5\,H_2O$ without a solvent in an open flask. The color was bleached immediately when the flask was capped. These observations may indicate the equilibrium between NO_2 and N_2O_4.[11] In addition, a catalytic amount of NO_2 completed the deprotection as with $Bi(NO_3)_3{\cdot}5\,H_2O$ (run 8 in Table 1). In the literature, $Bi(NO_3)_3{\cdot}5\,H_2O$ is reported to evolve nitrogen oxides (NO and NO_2) during its thermal decomposition[16] and has been employed for the nitration of aromatic compounds[17] and for the oxidation of sulfides,[11,18] alcohols,[17b,19] and dihydropyridine.[17c] NO_2 and nitrosonium salt are also used for the oxidative deprotection of *S,S*-acetals.[6b,20] These experimental observations, coupled with the reported evidence, lead to the inescapable conclusion that the *in situ* generated NO_2 from $Bi(NO_3)_3{\cdot}5\,H_2O$ works as the oxidant for the present dethioacetalization. More precisely, NO^+ is a most likely oxidizing agent, because it is a strong oxidizing agent produced via ionic dissociation of N_2O_4.[21] Actually, a catalytic amount of NaN_3, a known NO^+ quencher,[22] prevented the deprotection in the presence of a catalytic amount of $Bi(NO_3)_3{\cdot}5\,H_2O$ (run 7 in Table 1). In the nitration of phenols and oxidation of benzyl alcohol with supported metal nitrate, NO^+ generated from metal nitrate is accepted as the common active intermediate.[16]

A plausible catalytic cycle in the deprotection of *S,S*-acetals is illustrated in Figure 2. Similar mechanisms have been proposed by Jørgensen in the deprotection of *S,S*-acetals using $NaNO_2$,[20d] and by Olah in the desulfurative fluorination using $NO^+BF_4^-$.[20c]

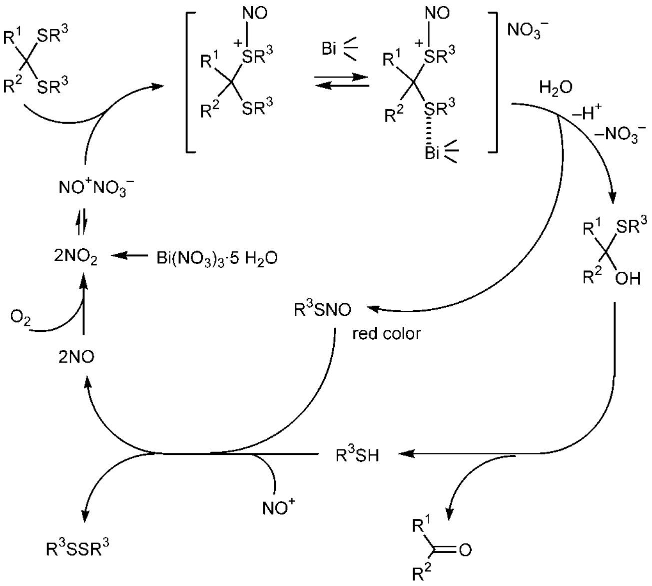


Figure 2. A plausible catalytic cycle for the deprotection of *S,S*-acetals using air and a catalytic amount of $Bi(NO_3)_3{\cdot}5H_2O$.

The catalytic cycle is initiated by the formation of the nitrososulfonium ion of the *S,S*-acetal by the attack of NO^+ generated from $Bi(NO_3)_3{\cdot}5\,H_2O$. The bismuth salt may shift the equilibrium to the nitrososulfonium ion by capture of nitrate ion (NO_3^-) as reported.[21a,23]

In the second stage, the nitrososulfonium ion is hydrolyzed to afford the thionitrite (R^3SNO) and the hemithioacetal. Since thionitrites, except for tertiary ones, are known to be red in solution,[24] the generation of thionitrite in our process is supported by the fact that the mixture colored red during the reaction in most cases. In the deprotection of *S,S*-acetals by direct use of NO_2, a pink-colored mixture is reported to be discharged on completion of the reaction,[20b] which also implies the formation of thionitrite as a transient intermediate. A similar process from *S,S*-acetal to thionitrite through hydrolysis of nitrososulfonium ion has been proposed by Jørgensen[20d] and Olah.[20c] Another role of bismuth salts may be as a soft Lewis acid to facilitate the nucleophilic attack of H_2O via coordination with the sulfur atom during hydrolysis.

In the third stage, the parent carbonyl compound and thiol are produced by the decomposition of the hemithioacetal. The thiol is readily oxidized by NO^+ to afford the corresponding disulfide and NO via thionitrite.[24]

In the final stage, NO_2 is regenerated via molecular oxygenation of NO in solution, completing the catalytic cycle. Under an argon atmosphere, however, NO_2 could not be regenerated, resulting in the low conversion as mentioned above (run 14 in Table 1). The same process from NO to NO_2 is proposed in the catalytic oxidation of sulfides with NO_2 and O_2.[23]

The stoichiometry in the catalytic cycle unequivocally agreed with that of the experimental result (run

12 in Table 1), where an equimolar amount of dioxygen was consumed to afford equimolar amounts of *p*-anisaldehyde and diphenyl disulfide.

Conclusion

The present method for the deprotection of *S,S*-acetals features the combined use of a catalytic amount of bismuth nitrate pentahydrate and molecular oxygen from air; the major advantages are simple manipulation, mild conditions, no use of toxic reagents, and economy. This method is successfully applied to the deprotection of a variety of functionalized *S,S*-acetals as well as *S,O*- and *O,O*-acetals. From the mechanistic point of view, NO^+ generated from $Bi(NO_3)_3 \cdot 5\,H_2O$ is considered to play a crucial role for this oxidative cleavage as a real catalyst. The catalytic cycle of NO^+ is composed of the following four steps as shown in Figure 2: (1) the nitrososulfonium ion of the *S,S*-acetal is formed by the attack of NO^+ generated from $Bi(NO_3)_3 \cdot 5\,H_2O$ through the equilibrium with NO_2, (2) the nitrososulfonium ion is hydrolyzed to afford the hemithioacetal and thionitrite, (3) the hemithioacetal collapses to the original carbonyl compound and thiol, which is oxidized by NO^+ to give disulfide and NO via thionitrite, and (4) the NO captures molecular oxygen from air to regenerate NO_2.

Experimental Section

General Procedures

^{1}H (200 MHz) and ^{13}C (50 MHz) NMR spectra were obtained with a Varian Gemini-200 for solutions in $CDCl_3$ with Me_4Si as an internal standard. Chemical shifts were reported in δ, and the coupling constants (*J*) are in Hz. IR spectra were recorded on a Shimadzu FTIR 8100S infrared spectrophotometer. Mass spectra were recorded on a Shimadzu GCMS QP5000 spectrometer. Melting points were determined with a Yanaco MP-J3 apparatus and are uncorrected. Flash chromatography was performed with Wakogel C-300. Solvents and reagents were used as commercially received unless otherwise noted.

Preparation of *S,S*-Acetals

All *S,S*-acetals except for **1–5**[5c, 13] were prepared according to our method.[1]

2-(1-Hydroxy-1-methyl-3-phenylpropyl)-2-methyl-1,3-dithiane (2)[13c]: Colorless oil; ^{1}H NMR: δ = 7.32–7.15 (m, 5H, ArH), 3.04–2.64 (m, 6H, CH_2), 2.38 (s, 1H, OH), 2.29–1.76 (m, 4H, CH_2), 1.81 (s, 3H, CH_3), 1.47 (s, 3H, CH_3); IR (neat). ν = 3490, 2980, 1497, 1455, 1277, 700 cm^{-1}; MS (CI, isobutane): *m/z* = 283 (M^++1); anal. calcd. for $C_{15}H_{22}OS_2$: C, 63.78; H, 7.85%; found: C, 63.82; H, 7.93%.

2,3,4,5,6-Penta-O-benzyl-D-glucose propane-1,3-diyl dithioacetal (5): D-Glucose propane-1,3-diyl dithioacetal was prepared according to the literature;[13a] yield: 98%; mp 142–143 °C.

Benzylation of the D-glucose propane-1,3-diyl dithioacetal was carried out as follows: to NaH (60% dispersion in oil, 2.5 g, 60 mmol) washed with dry hexane, D-glucose propane-1,3-diyl dithioacetal (1.35 g, 5.0 mmol) in 20 mL DMF was added over 0.5 h under an argon atmosphere. After stirring for 1 h at 25 °C, the mixture was cooled down to 10 °C, and benzyl bromide (6.0 g, 35 mmol) was added dropwise over 0.5 h. The resulting mixture was stirred at 10 °C for 12 h. After quenching the reaction by the addition of MeOH (10 mL) followed by H_2O (10 mL), the mixture was extracted with AcOEt three times. The combined extracts were washed with water three times and brine once, dried over Na_2SO_4, and concentrated. The residue was flash chromatographed on silica gel to give 2,3,4,5,6-penta-*O*-benzyl-D-glucose propane-1,3-diyl dithioacetal; yield: 2.56 g (71%); colorless syrup; ^{1}H NMR: δ = 7.32–7.25 (m, 25H, ArH), 4.91–3.70 (m, 17H, CH_2, CH), 2.89–2.53 (m, 6H, CH_2); ^{13}C NMR: δ = 138.42, 138.27, 138.05. 138.05, 137.96, 128.00, 127.88, 127.83, 127.41, 127.31, 127.10, 81.11, 79.75, 79.26, 78.29, 75.06, 73.84, 73.46, 72.94, 71.67, 69.34, 48.85, 29.56, 29.09, 25.69; anal. calcd. for $C_{44}H_{48}O_5S_2$: C, 73.30; H, 6.71%; found: C, 73.17; H, 6.71%.

Preparation of *S,O*-Acetals

All *S,O*-acetals were prepared according to the recent report.[25]

General Procedure for the Deprotection of *S,S*-Acetals in Benzene

To a solution of *S,S*-acetal (0.5 mmol) in dry benzene (10 mL) were added finely powdered $Bi(NO_3)_3 \cdot 5\,H_2O$ (1–50 mol %) followed by two equivalents of water (1 mmol). When needed, $BiCl_3$ was also added. The mixture was magnetically stirred in a stoppered flask for an appropriate time at ambient temperature, while the progress of the reaction was intermittently monitored by GLC. Since there was an induction period, the reaction time was sometimes not reproducible. The stopper was loosened at intervals in order to admit a fresh air into the reaction vessel. The reaction was quenched by the addition of water and the products were extracted with AcOEt three times. The yield of carbonyl compound was determined by isolation with flash column chromatography or GLC.

Typical Procedure for the Deprotection of 2-(*p*-Methoxyphenyl)-1,3-dithiolane in Dichloromethane (Run 5 in Table 1)

To a solution of 2-(*p*-methoxyphenyl)-1,3-dithiolane (106.1 mg, 0.50 mmol) in dry dichloromethane (10 mL) were added finely powdered $Bi(NO_3)_3 \cdot 5\,H_2O$ (25.8 mg, 0.053 mmol) and $BiCl_3$ (8.0 mg, 0.025 mmol) followed by water (13 μL, 0.72 mmol). The mixture was magnetically stirred for 3.5 h at room temperature. The stopper was loosened at intervals in order to admit a fresh air into the reaction vessel. The reaction was quenched by the addition of water and the products were extracted with AcOEt three times. After being dried with anhydrous $MgSO_4$, the combined extracts were concentrated and the residue was chromatographed on silica gel to give *p*-anisaldehyde; yield: 88%.

Typical Procedure for the Deprotection of 2-(*p*-Methoxyphenyl)-1,3-oxathiolane in Acetonitrile/Water (Run 2 in Table 4)

To a solution of 2-(*p*-methoxyphenyl)-1,3-oxathiolane (48.8 mg, 0.25 mmol) in acetonitrile/water (4 mL/1 mL) was added finely powdered $Bi(NO_3)_3 \cdot 5\,H_2O$ (10.9 mg, 0.022 mmol). The mixture was magnetically stirred for 24 h at room temperature. The stopper was loosened at intervals in order to admit fresh air into the reaction vessel. The work-up procedure was similar to that of the deprotection of 2-(*p*-methoxyphenyl)-1,3-dithiolane. *p*-Anisaldehyde was obtained in 68% yield after flash column chromatography on silica gel.

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