Oxidative *S*-Dealkylation Reaction of Sulfide Catalyzed by Co(II)(bzacen)

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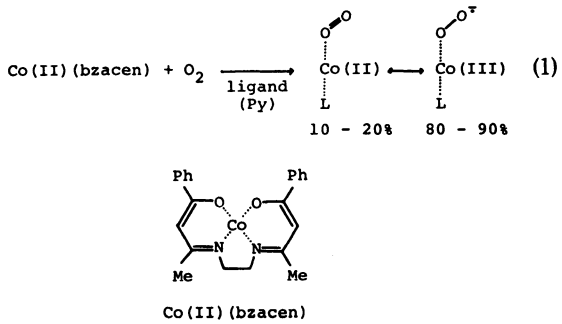
In the oxygenation reaction of alkyl sulfides with Co(II)(bzacen)–O_2 system, oxidative S–C bond cleavage (*S*-dealkylation) was found to take place exclusively. The reactivity of *S*-dealkylation reaction was dependent markedly on both acidity of α-methylene and steric hindrance of alkyl sulfide. The peroxo-Co(III) species is presumed to be the intermediate in this *S*-dealkylation reaction.

Although mechanisms of many reactions with hydrolytic enzymes have been understood fairly well now, those of the reactions with both mono- and di-oxygenases are by no means well-understood,[1-3] since many of the oxygenation intermediates in the reactions with oxygenases are unstable and hence not well-characterized. Therefore, numerous nonenzymatic models have been designed to investigate the nature of many enzymatic oxygenations.[4,5]

Meanwhile, as a model of the active site of myoglobin and oxymyoglobin "picket fence porphyrin"–iron(II) complexes have been synthesized and fully characterized by Mössbauer spectroscopy, magnetic susceptibility, and X-ray crystallography analysis.[6-8] These picket fence porphyrin–iron complexes can bond with molecular oxygen to give endo-on type complexes. Model oxygenation systems of another types are cobalt–Schiff base complexes.[9,10] However, only a few oxygenation reactions of aromatic compounds with metal-molecular oxygen complexes have been examined.[11,12] Meanwhile, sulfides bearing electron-withdrawing group were found recently by us to be oxygenated in the presence of a Co(II)–Schiff base complex affording exclusively the *S*-dealkylation products.[13]

In the meantime, in the oxygenation of divalent sulfur compounds with cytochrome P-450 monooxygenase, we have demonstrated that both dealkylation and *S*-oxygenation reactions take place *via* the sulfenium radical as the common intermediate formed in the rate-determing one electron transfer from sulfur atom to the "oxenoid" intermediate.[14,15] The "oxenoid" intermediate is believed to be the metal–mono-oxygen complex ($Fe{=}O^{3+}$).[16] Thus, it is of interest to examine the nature of the reaction with metal-molecular oxygen complex as compared to that with cytochrome P-450 in the oxygenation of various sulfides.

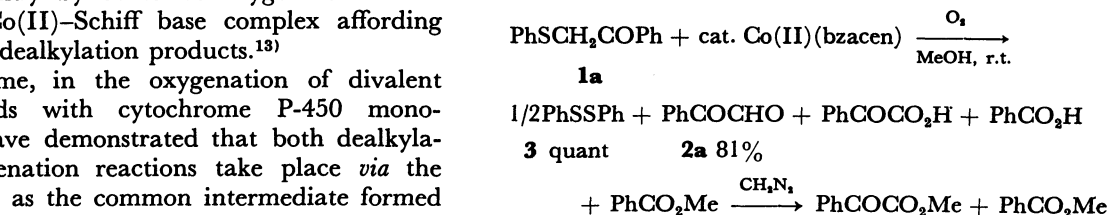
This report described a detailed account on the oxygenation of divalent sulfur compounds with Co(II)-(bzacen), [*N*,*N*′-bis(2-benzoyl-1-methylethylidene)ethylenediamine], which is known to ninteract with molecular oxygen to give ligand–Co(II)–O_2 complex that was found to be the endo-on type complex by X-ray study (Eq. 1).[17]



Co(II)(bzacen)

Results and Discussion

When a β-keto sulfide (**1a**, 0.40 mmol) was incubated aerobically in a 16 mL of methanol solution containing Co(II)(bzacen) (0.10 mmol) for 30 min at room temperature, the oxygenation was found to complete. The products were analyzed by GLC by removing the catalyst by adsorption through an ion exchange resin [Dowex 50W-8 (H^+ form)]. After GLC measurement and replacing methanol by dichloromethane, treatment of the mixture with an excess diazomethane to determine carboxylic acids gave methyl esters which were also analyzed by GLC (Scheme 1). In the oxygenation reaction, oxidative cleavage of S–C bond of the sulfide (**1a**) took place exclusively to afford only the corresponding carbonyl compound (**2a**) and diphenyl disulfide (**3**) in good yields (Scheme 1). The oxidative cleavage of other sulfides each having an acidic α-methylene (**1b—d**) was also found to proceed catalytically in methanol solution at room temperature but required a longer reaction time to complete the oxygenation reaction (Table 1). As shown in Table 1, the reaction proceeds faster with the sulfide bearing a higher acidic α-methylene group.[15] Benzyl phenyl sulfide (**1f**) and thioanisole (**1g**) were not oxygenated under these conditions. Thus, the reactivity of the oxidative *S*-dealkylation appears to depend strongly on the acidity of α-hydrogen of the alkyl sulfide.



Scheme 1.

Phenacyl phenyl ether (**6**), oxygen analogue of the keto sulfide (**1a**), was added into the methanol solution containing 1/2 equimolar amount of Co(II)(bzacen) was also found to be oxygenated aerobically and the corresponding phenol (**7**) and aldehyde (**2a**) were obtained (Table 2). The reactivity of ether (**6**) is quite

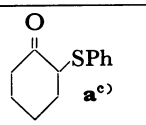
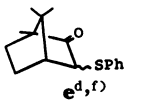
TABLE 1. THE OXYGENATION OF SULFIDES, SULFOXIDE, AND ETHER HAVING α-ACTIVE METHYLENES CATALYZED BY Co(II)(bzacen)

$$Ph\text{-}S\text{-}CH_2R + Co(II)(bzacen) \xrightarrow[r.t.]{O_2} PhSSPh + RCHO + RCO_2H$$

	1 R	(Equiv.)[a]	Time/h	Solvent	3	2 Yield/%[b]	
a	-COPh	1/4	30min	MeOH	quant[c]	81	13
b	-CN	1	15	MeOH	quant[c]	—[d]	
c	$-CO_2Et$	1/4	15	MeOH	52	—[d]	
d	$-C_6H_4NO_2$-*p*	1	72	MeOH	no reaction		
		1	48	MeOH-Py (1 : 1)	quant[c]	50	trace
e	$-CH_2CN$	1	120	MeOH (or MeOH-Py)	no reaction		
f	-Ph	1	120	MeOH	no reaction		
g	-H	1	120	MeOH	no reaction		
5	$PhS(O)CH_2CN$	1	120	MeOH	no reaction		
6	$PhOCH_2COPh$	1/2	16	MeOH	50	(PhOH) 93	

a) Based on the substrate used. b) Yield/% was calculated based on the substrate and was determined by GLC. c) Quantitative yield (>95%). d) Aldehyde was not observed in both TLC and GLC.

TABLE 2. PHYSICAL CONSTANTS OF α-SUBSTITUTED SULFIDES (4)

4	Bp θ_b/°C(mmHg)[b]	^{1}HNMR δ-values, *J*/Hz
 **a**[c]	145(2)[lit,[20] 150—153(5)]	1.5—2.5(7H,m) 2.5—3.1(1H,m) 3.75(1H,t,*J*=5.1) 7.1—7.5(5H,m)
PhCOCHSPh Ph **b**[c]	Mp 77—78 °C [lit,[21] 78—79]	5.85(1H,s) 7.0—7.53(8H,m) 7.8—8.05(2H,m)
PhCOCHSPh Me **c**[d]	195(3) [lit,[22] 110—115 (0.003)]	1.45(3H,d,*J*=6.6) 4.53(1H,q,*J*=6.6) 7.18—7.55(8H,m) 7.8—8.02 (2H,m)
PhCOCHSPh Et **d**[d,e]	181(2)	0.99(3H,t,*J*=7.2) 1.6—2.2(2H,m) 4.33(1H,t,*J*=7.8) 7.0—7.5(8H,m) 7.8—8.0(2H,m)
 **e**[d,f]	180(2)	0.90(6H,s) 0.96(3H,s) 1.2—2.1(4H,m) 2.2(1H,brs) 3.2(0.9H, s,H_{endo}) 3.8(0.1H,d,*J*=4.6 H_{exo}) 7.1—7.6(5H,m)

a) Recrystallized from EtOH. b) Bath temperature. c) In $CDCl_3$. d) In CCl_4. e) Found: C 74.62, H 6.21%. Calcd for $C_{16}H_{16}OS$: C 74.96, H 6.29%. f) Found: C 73.54, H 7.71%. Calcd for $C_{15}H_{20}OS$: C 73.80, H 7.74%.

$$Ph\text{-}O\text{-}CH_2COPh + Co(II)(bzacen) \xrightarrow{O_2} PhOH + PhCOCHO \quad (2)$$
6 **7** **2a**

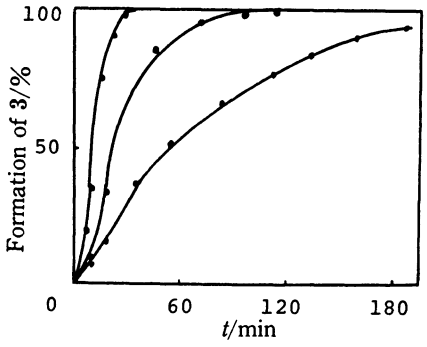
comparable to that of the sulfide (**1b**), seemingly supporting the hypothesis that one of the most important factors is the acidity of the α-methylene, since both pK_a's of methylene proton of **6** and **1b** are quite similar (pK_a; $PhCOCH_3$ 24.7, $NCCH_3$ 31.3, $PhS(O_2)CH_2OPh$ 27.9, $PhS(O_2)CH_2SPh$ 20.3).[18,19]

Meanwhile, the steric effect on the reactivity has been examined systematically with various α-substituted β-, keto sulfides (**4**) which are listed in Table 2. When 2-(phenylthio)cyclohexanone (**4a**) was incubated for 16h diphenyl disulfide (**3**) and 1,2-cyclohexanedione (**8a**) were obtained in good yields. The oxygenation of 2-(phenylthio)propiophenone (**4c**) with the Co(II)-(bzacen)-O_2 system required 23 h to be completed in methanol, eventually affording diphenyl disulfide (**3**) quantitatively and 1-phenyl-1,2-propanedione (**8c**) in 50% yields, respectively. Although phenyl group would activate the α-proton of **4b** which would hence be more

TABLE 3. THE OXYGENATION REACTION OF α-SUBSTITUTED SULFIDE (4) CATALYZED BY Co(II)(bzacen)[a]

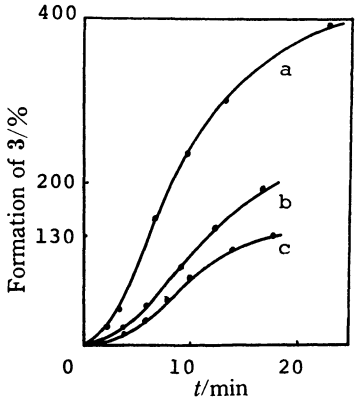
Sulfide 4	Co(II)(bzacen) (Equiv.)	Time h	PhSSPh 3 (%)[b]	RCOCOR′ 8
a	1/10	16	quant[c] (85)[d]	quant[c](60)[d]
b	1/4	4	quant[c]	quant[c]
c	1	23	quant[c]	50
d	1/4	24	10	—
e	1	48	no reaction[e]	

a) The reaction was carried out in MeOH at room temperature. b) Determined by GLC. c) Quantitative yield (95%). d) Isolated yield. e) In MeOH-Py system, sulfide (**4e**) was recovered.



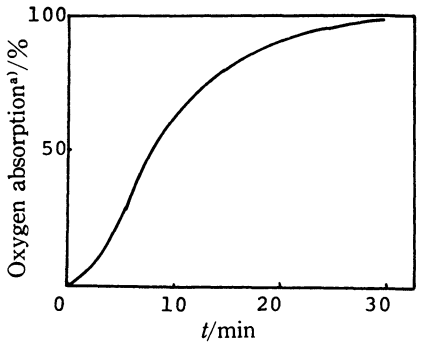
$$PhSCH_2COPh + Co(II)(bzacen) \xrightarrow{O_2} 1/2PhSSPh$$

Fig. 1. The effect of concentration of Co(II)(bzacen) on the formation of disulfide (**3**).
a: Co/**1a**=1/2, b: Co/**1a**=1/4, c: Co/**1a**=1/8, [**1a**]=2.5×10^{-2} mol/dm^3.



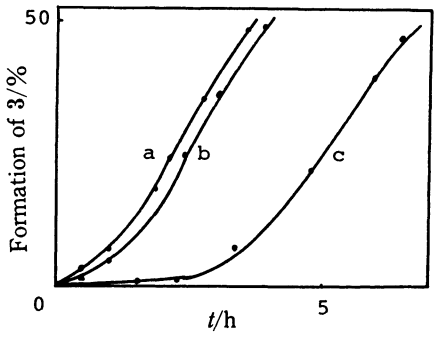
$$PhSCH_2COPh + Co(II)(bzacen) \xrightarrow{O_2} 1/2PhSSPh$$

Fig. 2. The effect of concentration of sulfides (**1a**) on the formation of disulfide (**3**).
a: Co/**1a**=1/4, b: Co/**1a**=1/2, c: Co/**1a** 1/1.3, [Co]=2.5×10^{-2} mol/dm^3.



$$PhSCH_2COPh + Co(II)(bzacen) \xrightarrow{O_2} 1/2\ PhSSPh$$

Fig. 3. Oxygen uptake in the oxygenation reaction of **1a** with Co(II) (bzacen).
Co/**1a**=1/4, [Co]=2.5×10^{-2} mol/dm^3.
a) 100 (%) means 1 equiv. oxygen absorption to sulfide (**1a**).



$$X\text{-}C_6H_4\text{-}SCH_2CN + Co(II)(bzacen) \xrightarrow{O_2} 1/2\ ArSSAr$$

Fig. 4. The effect of *para*-substituent on benzene ring of **1b** on the formation of disulfide (**3**).
a: X=CH_3, b: X=H, c: X=Cl, Co/**1b**=1, [Co]=5.0×10^{-1} mol/dm^3.

acidic than α-proton of **1a**, the reactivity of *S*-dealkylation of **4d** is substantially decreased. In the case of a most crowded β-keto sulfide, *i.e.*, 3-(phenylthio)-*dl*-camphor (**4e**), which is an *endo* and *exo* mixture, the oxygenation was not found to proceed for both *endo* and *exo* sulfides even though the reaction mixture was incubated for 48 h (Table 3).

These observations clearly indicate that the steric hindrance is second important factor for the *S*-dealkylation reaction. As shown previously, oxygenations catalyzed by cobalt(salen) are related to the electron donor character of the substrate and the steric hindrance would reduce the donor character of the substrates.[11]

In order to understand the whole feature of oxidative *S*-dealkylation reaction, several experiments have been carried out.[13] In the kinetic experiments of oxygenation of **1a** with Co(II) (bzacen) in methanol, the rate of the reaction was found to be of first order dependence both on the concentration of the sulfide (**1a**) and that of the catalyst; the plot of the amounts of the formation of the diphenyl disulfide (**3**) against time gave a sigmoidal curve shown in Figs. 1 and 2. On the other hand, an equimolar amount of molecular oxygen was found to be consumed by the reaction (Fig. 3).

These results suggest that the oxygenation reaction catalyzed by Co(II)(bzacen) has a pre-equilibrium which may be the process of coordination of sulfide to cobalt like a ES complex in the actual enzymatic reaction.

We cannot conclude whether or not the formation of the first complex (S·Co) involves the coordination of molecular oxygen, however, Fig. 3 suggests the participation of molecular oxygen in a ES like complex which eventually gave the products.

$$\underset{(E)}{S + Co} \overset{O_2}{\rightleftharpoons} \underset{(ES)}{S\cdot Co\cdot O_2} \longrightarrow P + Co \qquad (3)$$

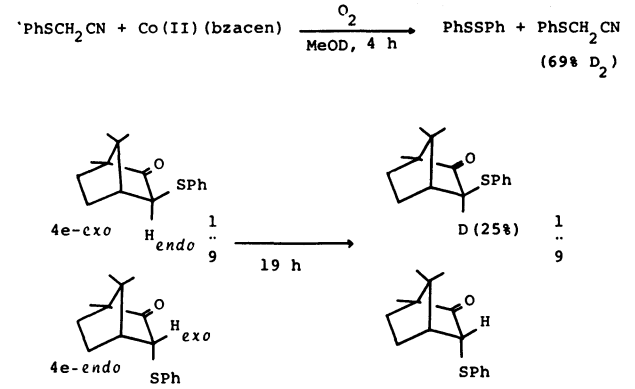
The effect of *p*-substituent on benzene ring of **1b** on this biomimetic oxygenation was examined to demonstrate the participation of divalent sulfur atom in the first equilibrium of the coordination. When the *p*-substituent was electron-donating group, the induction period of the oxygenation of **1b** was found to be shortened, however, the rate of formation of diaryl disulfide (**3**) after the induction period was not affected at all by the substituent. Meanwhile, an electron-withdrawing substituent prolonged only the induction period as shown in Fig. 4. The effect of *p*-substituent on benzene

ring may be explained in that the initial step of the oxygenation is the coordination of divalent sulfur atom to cobalt as an axial ligand.

Cyanomethyl phenyl sulfoxide (**5**) did not react at all under the same reaction conditions clearly suggesting that cobalt coordinates to divalent sulfur atom but not α-methylene position in the first step of oxygenation, since α-methylene proton is activated more by the sulfinyl group than sulfenyl group.

The effect of solvent was quite substantial; *e.g.*, the reaction in methanol was markedly faster than in pyridine. The reaction of **1a** in pyridine proceeded only 2% while the reaction in methanol was completed in the same period. These solvent and steric effects are similar to those in the oxygenation of indole derivatives by Co(II)(salen)–O_2 system.[11]

When the reaction of **1b** was carried out in methanol-d_1, the recovered sulfide was found to retain only 69% of deuterium at α-methylene carbon after 50% conversion of sulfide (**1b**) to diphenyl disulfide (**3**) (4 h, room temperature, Co(II)/**1b**=1). The H-D exchange reaction between the substrate and methanol-d_1 indicates that the reversible deprotonation step to give carbanion is involved in the oxygenation reaction. When an *endo* and *exo* mixture of very crowded 3-(phenylthio)-*dl*-camphor (**4e**) (*endo* : *exo*=1 : 9) was incubated with Co(II)(bzacen) in methanol-d_1 for 19 h to examine the H-D exchange, the starting sulfide (**4e**) was recovered quantitatively, however, 25% of *endo*-proton (less hindered proton) and 0% of *exo*-proton was deuterated (Scheme 2). The same reaction was found to take place when the reaction of sulfide (**4e**) with D_2O was carried out in the presence of pyridine as base, *i.e.*, only 28% of *endo*-proton was deuterated.



Scheme 2.

Meanwhile, oxidative dealkylation reaction of sulfides (**1a** and **1b**) was also found to take place with strong bases under oxygen atmosphere but very slowly without catalyst; *e.g.*, **1a** gave **2a** (10%), **3** (10%) and **1a** (85% recovered) upon treatment of **1a** with NaH in THF under oxygen atmosphere at room temperature for 20 min (Eq. 4).

In these reactions, peroxy intermediate (**9**) would be formed prior to give *S*-dealkylation products (Eq. 5). The products distribution in the autoxidation of sulfides supports that in the oxygenation of sulfides with Co(II)-(bzacen), a similar peroxy-intermediate (**10**) would be

$$\underset{\mathbf{1a}}{PhSCH_2COPh} + NaH \xrightarrow[\substack{THF,\ r.t.\\ 20\ min}]{O_2} PhSSPh + OHCCOPh + recov. \quad (4)$$

$$\mathbf{3}\ 10\% \qquad \mathbf{2a}\ 10\% \qquad 85\%$$

$$\underset{\mathbf{1b}}{PhSCH_2CN} + t\text{-}BuOK \xrightarrow[\substack{DMSO,\ r.t.\\ 30\ min}]{O_2} PhSSPh + recov.$$

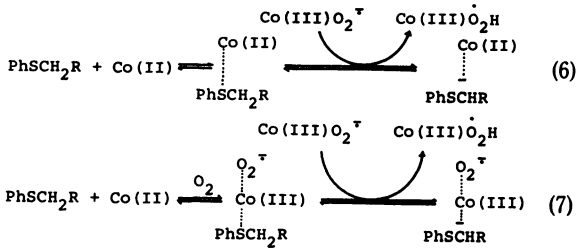
$$\mathbf{3}\ 30\% \qquad 70\%$$

formed as described in other cobalt-Schiff base induced oxygenations of *t*-butylsubstituted phenols and indoles.[11,12,23]

$$PhSCH_2R + :B \xrightarrow{Ar} PhS\dot{C}HR \xrightarrow{O_2} [PhS\dot{C}HR\ O_2^{\cdot}] \longrightarrow \left[\begin{matrix}PhSHR\\ |\\ O\text{-}O^-\end{matrix}\right] \rightarrow\rightarrow PhSSPh + RCHO \quad (5)$$

9

These observations suggest that the reaction proceeds through an initial formation of a dual or a ternary complex to activate α-methylene proton which may be abstracted by the superoxo-intermediate to give an α-carbanion



In the oxygenation of *t*-butyl-substituted phenols, Nishinaga *et al.* suggested the direct hydrogen abstraction by superoxo-Co(III) complex (Eq. 9) to be the rate-determining step, followed by subsequent fast electron transfer from the divalent Co(II) complex to the substrate radical (Eq. 10).[11,12,23]

$$Co(II) + O_2 \rightleftharpoons Co(III)O_2^{\cdot} \quad (8)$$

$$Co(III)O_2^{\cdot} + R\text{-}H \longrightarrow Co(III)^-O_2H + R\cdot \quad (9)$$

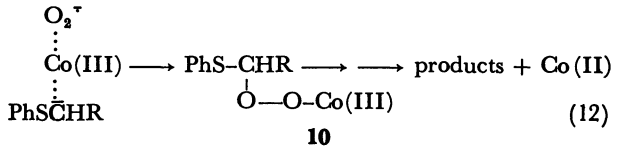
$$Co(II) + R\cdot \xrightarrow{fast} R^-Co(III) \quad (10)$$

$$R^-Co(III) + O_2 \longrightarrow ROO^-Co(III) \quad (11)$$

On the other hand, Jefford and Cadby[3] pointed out the cobalt–Schiff base complex to localize the π-anion charge into an orbital with more [sp^3] character; *i.e.*, cobalt–Schiff base complex catalyzes the reaction of carbanion with molecular oxygen to afford peroxy intermediate.

We cannot conclude which process is involved in the actual oxygenation pathway; *i.e.*, direct deprotonation or hydrogen abstraction and subsequent electron transfer to afford the carbanion, however, all these results would support the direct deprotonation mechanism as indicated in Eqs. 6 and 7.

Finally, the superoxo-Co(III)–carbanion complex is presumed to give peroxo-intermediate (**10**) and the products (Eq. 12).

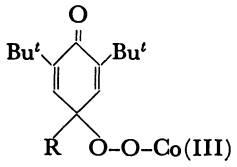


10 (12)

Although a few mechanisms are conceivable for the production of peroxy intermediate (**10**), Nishinaga *et al.* already isolated peroxy intermediates such as (**11**) and (**12**), which seem to support the formation of (**10**) in the oxygenation of sulfide with Co(II)(bzacen).[12,23]

After the oxygenation being carried out, a direct measurement of the ^{1}H NMR spectrum was attempted, however no clear signal was observed due to the presence of paramagnetic material which would be Co(II)(bzacen). Thus, Co(II)(bzacen) can catalyze the oxygenation reaction of sulfide. These results seem to support the mechanistic scheme shown in Eq. 12; *i.e.*, Co(II)(bzacen) is left after the reaction.

Incidentally, all these substrates (**1a—d**) are not susceptible to oxidation with superoxide with 18-crown-6 system.



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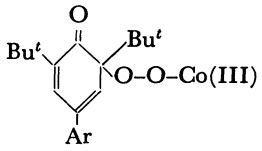

12

Experimental

Reagent. All reagents and solvents used in this study were of guaranteed grades and used without further purification. Methanol-d_1 (min. 99%) and deuterium oxide (min. 99.75%) were purchased from Merck.

General. Melting points were measured on a Yanaco instrument and uncorrected. The boiling points were observed on a Büchi K-R (Kugel Rohr). NMR spectra were recorded on a Hitachi Perkin Elmer R 20 spectrometer in $CDCl_3$ and CCl_4 using TMS as the internal standard. GLC analyses were taken with Hitachi 163 Gas Chromatography (10% SE 30, 2 m glass column). TLC and column chromatography were carried out with Kieselgel GF_{254} Type 60 and Kieselgel 60 (70—230 mesh) (Merck), respectively.

Preparation of Sulfides 1 and 4. Preparation of unsubstituted sulfides (**1a—e**) were already reported in our recent paper.[15] *p*-Substituted **1b**'s (methyl and chloro) were obtained by treatment of *p*-substituted thiophenol with chloroacetonitrile in the presence of potassium hydroxide according to the ordinary procedure described previously,[24] and isolated through SiO_2 column chromatography (eluent; benzene). Mp and ^{1}H NMR (δ-value, ppm): *p*-$CH_3C_6H_4SCH_2CN$; 160 °C/2 mmHg** (lit, 120.5—127.5 °C/1.0 mmHg),[25] 2.31 (3H, s) 3.41 (2H, s) 7.00 (2H, d, J=8.3) 7.29 (2H, d, J=8.3). *p*-$ClC_6H_4SCH_2CN$; 88—99 °C (from hexane) (lit, 88—90 °C),[26] 3.48 (2H, s) 7.25 (2H, d, J=9.6) 7.33 (2H, d, J=9.6). α-Substituted β-keto sulfides (**4a—e**) were synthesized by treating benzenesulfenyl chloride with corresponding alkyl ketones in the presence of butyllithium or sodium hydride in tetrahydrofuran.

Benzenesulfenyl Chloride. Chlorine gas was bubbled into a dichloromethane solution of diphenyl disulfide at 0 °C for 20 min to give benzenesulfenyl chloride quantitatively.[27] The reaction mixture was condensed by evaporation of both solvent and excess chlorine *in vacuo* without warming. Benzenesulfenyl chloride was used without further purification.

Preparation of 3-(Phenylthio)-DL-camphor (4e). A solution of butyllithium (0.2 mol) in 10 mL of dry hexane was added to a solution of DL-camphor (4.5 g, 0.03 mol) in dry tetrahydrofuran (40 mL) at −72 °C and stirred for 10 min. After introduction of benzenesulfenyl chloride (2.8 g, 0.02 mol) into the reaction mixture at −72 °C, the solution was warmed to room temperature slowly for 1 h and stirred for 1 h additionally. The solution was evaporated under reduced pressure and the mixture was washed with water and extracted with chloroform. The chloroform layer was dried over anhydrous magnesium sulfate. The recovered DL-camphor was separated by distillation at 110 °C (bath temp)/2 mmHg. 3-(Phenylthio)-DL-camphor (**4e**) was isolated through SiO_2 column chromatography (2.9 g, 50% yield). From the ^{1}H NMR spectroscopic analysis, 90% of phenylthio group in **4e** was found to be substituted at *exo* position. When the reaction was carried out at −20 °C, the ratio of *exo* : *endo* was 65 : 35. Other sulfide (**4**) were also prepared similarly and their physical data were listed in Table 2.

Phenylglyoxal and Benzoylformic Acid. Phenylglyoxal and benzoylformic acid were synthesized according to the procedure described in Organic Synthesis.[28,29]

Synthesis of Phenacyl Phenyl Ether (5). A mixture of phenacyl chloride (6.0 g, 0.039 mmol) and phenol (4.0 g, 0.042 mol) in benzene (40 mL) was added to a solution of sodium hydroxide (1.6 g, 0.067 mol) and tetrabutylammonium chloride (140 mg, 0.5 mmol) in water (40 mL). The solution was refluxed for 10 h and acidified with 6 mol dm^{-3} HCl (pH 4). The solution was extracted with chloroform and the extract was washed with water and dried over anhydrous magnesium sulfate. After evaporation of solvent, the residue was chromatographed on SiO_2, using hexane–benzene (4 : 5) as eluent. The desired product was recrystallized from ethanol. Mp and ^{1}H NMR in $CDCl_3$; 73—74 °C (lit, 71—72 °C),[30] 4.93 (2H, s) 6.7—7.0 (3H, m) 7.0—7.5 (2H, m) 7.3 (5H, brs).

Preparation of Co(II)(bzacen). *Bzacen*; N,N′-*Bis(2-benzoyl-1-methylethylidene)ethylenediamine*: A solution of benzoylacetone (20 g, 0.2 mol) in abs. ethanol (25 ml) was refluxed for 5 min and ethylenediamine (6.0 g, 0.1 mol) in 6 mL of abs. ethanol was added dropwise slowly. After additional reflux for 15 min, the reaction mixture was cooled to room temperature to give a white precipitate in a quantitative yield. The product was recrystallized from ethanol (mp 182—184 °C; lit, 180.5 °C).[31]

Co(II)(bzacen): After refluxing a solution of bzacen (2.0 g, 5.7 mmol) in dry acetone for 2 h under argon atmosphere, anhydrous cobalt(II) chloride (0.75 g, 5.7 mmol) was added and the solution turned green at once. Then, sodium hydroxide (0.75 g, 5.7 mmol) was added to the reaction mixture which was refluxed until the precipitate turned red completely (about 7 h). The reaction mixture was cooled to 0 °C and filtrated. The precipitate was washed with cold water and decantation with methanol 3 times gave Co(II) bzacen) in 60% yield (mp 262—263 °C decomp; lit. 265 °C decomp).[31]

Oxygenation Reaction of Phenacyl Phenyl Sulfide (1a) with Co(II)-(bzacen). A solution of 105 mg of sulfide (**1a**) (0.46 mmol) in 16 mL of methanol was added to 44 mg of Co(II)-(bzacen) and the mixture was stirred, monitoring time to time the decrease of sulfide (**1a**) by TLC (benzene : hexane= 1 : 1). The reaction mixture was stirred for 30 min and poured into an ion exchange resin (Dowex-50W H^+ form, methanol suspension) and then stirred for 5 min. After filtration, the filtrate was evaporated. The residue was diluted

** 1 mmHg≈133.322 Pa.

with dichloromethane (8 mL) and products [phenylglyoxal (**2a**), methyl benzoate, and diphenyl disulfide (**3**)] were analyzed by GLC. Then the solution was cooled with ice bath and excess diazomethane (ether solution) was added to the solution which was then kept standing for 2 h at 0 °C. Then the reaction mixture was analyzed by GLC again (methyl benzoate and methyl benzoylformate) by comparison with those of authentic samples. PhSSPh (quant), $PhCOCHO$ (81%), $PhCOCO_2H$ (13%), $PhCO_2H$ (4.5%), and $PhCO_2Me$ (1.2%).

The other sulfides were oxygenated in the same procedure.

The Reaction of Sulfide (1) with KO_2. To a solution of sulfide (**1**) (0.1 mmol) in chloroform, 7 mg, of KO_2 (0.1 mmol) was added at room temperature under argon atmosphere and 26 mg of 18-crown-6 (0.1 mmol) in 4 mL of chloroform. The mixture was stirred for 26 h at room temperature. TLC and GLC measurements showed that sulfide (**1**) was inert to KO_2.

The Autoxidation of Sulfides (1a) and (1b) in the Presence of Base. Oxygenation of Phenacyl Phenyl Sulfide (1a): To a solution of **1a** (110 mg, 0.5 mmol) in 30 mL of dry tetrahydrofuran, sodium hydride (17 mg, 0.7 mmol) was added at −72 °C under argon atmosphere and the mixture was stirred for 30 min. Then the mixture was warmed to room temperature slowly and oxygen was bubbled for 20 min with stirring. After evaporation of solvent, the residue was extracted with chloroform. The extract was washed with 2 mol dm^{-3} HCl solution and dried over anhydrous magnesium sulfate. The products were determined by GLC [PhSSPh (10%), PhCOCHO (10%), and recovered (85%)].

Oxygenation of Cyanomethyl Phenyl Sulfide (1b). A solution of **1b** (149 mg, 1 mmol) and potassium *t*-butoxide (157 mg, 1.4 mmol) in 30 mL of dry dimethyl sulfoxide was stirred at −72 °C under argon atmosphere for 30 min and was warmed to room temperature. Oxygen was bubbled then into the reaction mixture for 30 min and the solution was evaporated. The products were analyzed by GLC. [PhSSPh (30%) and recovered (70%)].

The H-D Exchange Reaction of Sulfides (1b) and (4e) with Co(II)(bzacen). A mixture of sulfide (**1b**) (60 mg, 0.4 mmol) and Co(II)(bzacen) (162 mg, 0.4 mmol) in 2 mL of methanol-d_1 was incubated for 4 h at room temperature under oxygen atmosphere. Co(II)(bzacen) was removed by ion exchange resin and the supernatant was evaporated. The residue was extracted with chloroform and washed with water. The chloroform layer was dried over anhydrous magnesium sulfate and evaporated. The residue was subjected to SiO_2 column chromatography and eluted with hexane. The ^1H NMR spectrum of the recovered sulfide (**1b**) (*ca.* 50%) was determined to estimate the content of deuterium [$PhSCH_2$-$(D_2)CN$; 69% deuterated]. A mixture of sulfide (**4e**) (110 mg, 0.42 mmol, *exo* : *endo*=9 : 1) and Co(II)(bzacen) (100 mg, 0.25 mmol) in 10 mL of methanol-d_1 was stirred for 19 h. After the usual work-up, the extent of the H-D exchange was also estimated by ^1H NMR (25% of *endo*-proton was deuterated).

The H-D Exchange Reaction of Sulfide (4e) in the Presence of Pyridine. A solution of sulfide (4e) (110 mg, 0.42 mmol *exo* : *endo*=9 : 1) and deuterium oxide (10 mmol) in pyridine, (20 mL) was stirred for 40 h under argon atmosphere at room temperature. The solution was acidified then to pH 4 by adding 4 mol dm^{-3} HCl into the solution at 0 °C which was extracted with chloroform. The chloroform layer was washed with 1 mol dm^{-3} HCl to remove a small amount of residual pyridine and dried over anhydrous magnesium sulfate. Chloroform was removed under reduced pressure and the deuterium content was determined by ^1H NMR (28% of *endo*-proton was deuterated).

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