Hypervalent Compounds

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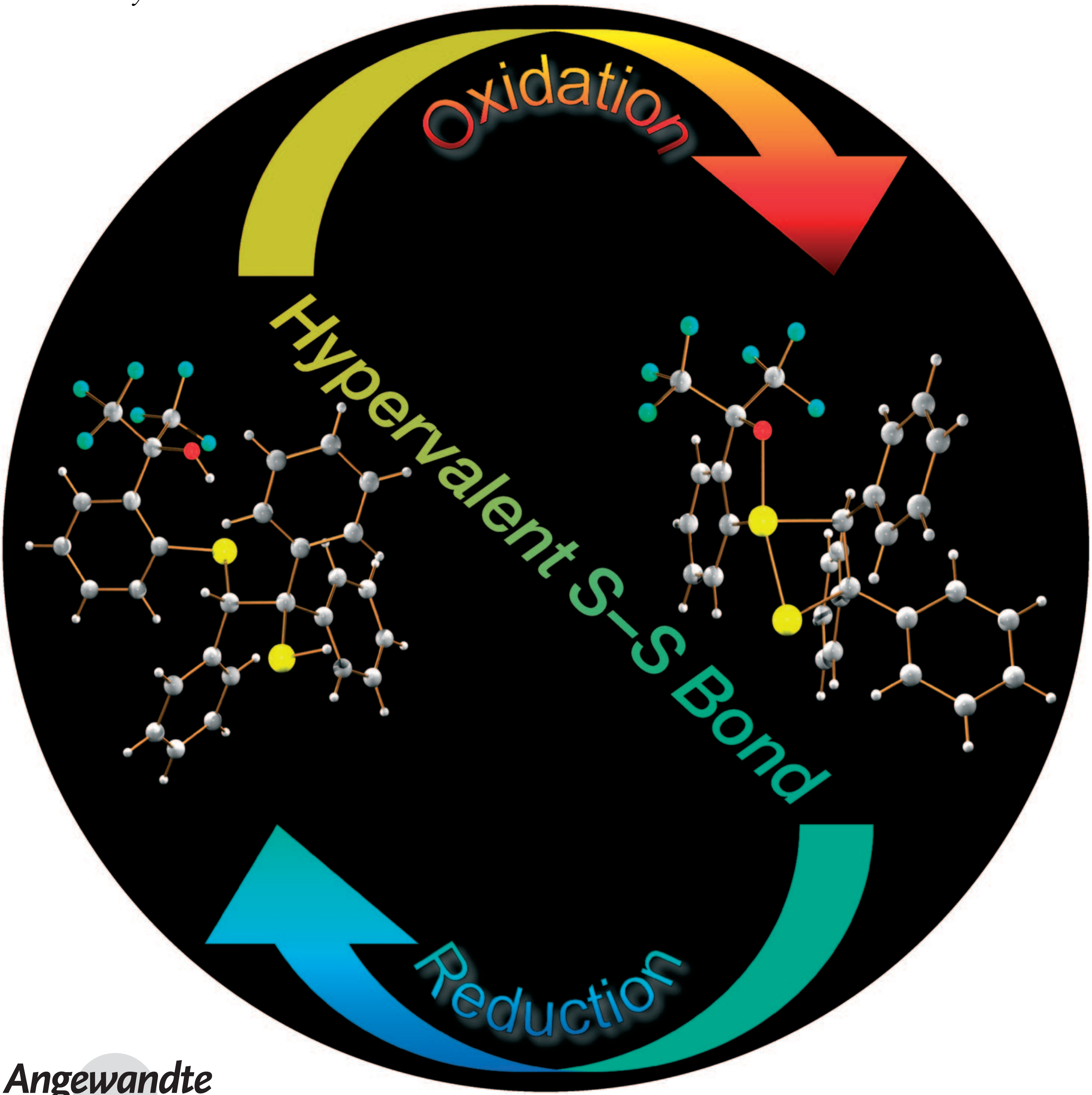
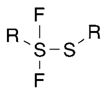
Structure and Properties of a Sulfur(IV)–Sulfur(II)-Bond Compound: Reversible Conversion of a Sulfur-Substituted Organosulfurane into a Thiol**

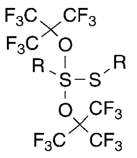
Naokazu Kano, Yusuke Itoh, Yuki Watanabe, Shinpei Kusaka, and Takayuki Kawashima**



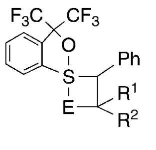
Catenation of divalent sulfur atoms, which easily bind to each other to form a sulfur(II)–sulfur(II) disulfide bond, is one of the characteristics of sulfur. The disulfide bond is found in disulfide complexes and some proteins, and the reversible S^{II}–S^{II} bond cleavage to form thiolates or thiols by redox processes plays a significant role in protein systems and both organic and inorganic chemistry. Meanwhile, sulfur can have a tetravalent tetracoordinate state in a few cases, in which the valence of sulfur formally expands beyond the octet, and such a hypervalent sulfur compound is known as a sulfurane. Although thiosulfonic esters, such as a 1,2-dithietane dioxide, have both a S–S bond and tetracoordinate sulfur, the valence electron of the sulfur atom is eight, and thus they are not hypervalent compounds.[1] As the hypervalent state of the sulfurane is effectively stabilized by at least one electron-withdrawing group, such as fluorine and/or alkoxy groups,[2] sulfur-substituted sulfuranes, which have an S^{IV}–S^{II} bond, are usually unstable owing to inefficient electronegativity of sulfur(II) as a stabilizing group for a sulfurane. Thus, there have been only a few reports on synthesis of sulfur-substituted sulfuranes and their structures and properties. For example, F_3SSF (**1a**), a thermally unstable liquid,[3] has a distorted pseudo trigonal bipyramidal (Ψ-TBP) structure around the central sulfur atom, which has the SF group in an equatorial position (an S-equatorial configuration), according to ab initio calculations.[4] Organosulfuranes **1b**, **1c**, and **2** react with water or glass vessels, leading to decomposition.[5,6] Neither redox reactivities nor crystal structures of the sulfur-substituted organosulfuranes have been studied well, which is partly due to their instability. A sulfur-substituted sulfurane is postulated to be an intermediate in the reduction of sulfoxides by thiols, for example in reactions involving the methionine sulfoxide reductases,[7] so that elucidation of the crystal structure and properties of the unique S–S bond are important. Our group previously reported the synthesis of sulfuranes **3**[8] and **4**[9] (R^1, R^2 = Ph, CF_3) by taking advantage of a bidentate ligand, 2-[bis(trifluoromethyl)oxidomethyl]phenyl,[10] and by integrating the sulfur–heteroatom bond in a ring framework. Herein we report the synthesis and the first X-ray crystallographic analysis of a sulfur-substituted sulfurane and the reversible formation–cleavage process of a bond between tetracoordinate sulfur(IV) and dicoordinate sulfur(II) atoms.



1a: R = F
1b: R = CF_3
1c: R = CF_2Cl

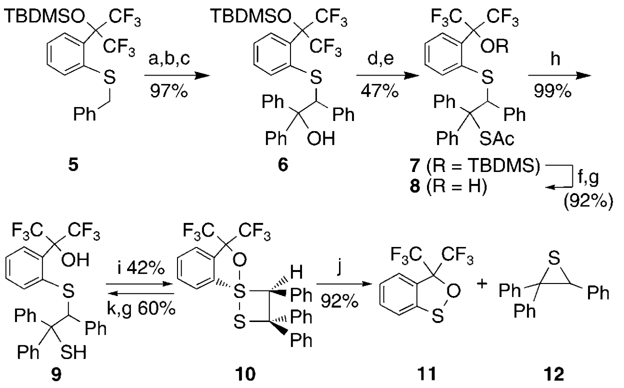


2: R = CF_3, C_6F_5



3: E = O
4: E = NPh

We considered that β-mercaptoalkyl sulfide **9** could be a precursor for the sulfur-substituted sulfurane **10** (Scheme 1). Attempted conversion of β-hydroxyalkyl sulfide **6**,[8a] which was prepared from benzyl sulfide **5**[8c] to the mercapto analogue **9** with the Lawesson's reagent resulted in no reaction. Instead, **6** could be converted into the corresponding thioacetyl ester **7** by the reaction with butyllithium and chlorodiphenylphosphine in THF at −78°C followed by treatment with 2,6-dimethylbenzoquinone and thioacetic acid (AcSH) in dichloromethane at room temperature.[11] After desilylation of **7** with tetra-*n*-butylammonium fluoride, deacetylation of the resulting alcohol **8** with hydrochloric acid in refluxing methanol quantitatively afforded β-mercaptoalkyl sulfide **9**. Treatment of **9** with *N*-bromosuccinimide (NBS) and triethylamine in CCl_4 at 0°C gave 1,2-dithietane **10** in 42% yield after recrystallization. The formation mechanism of **10** is considered as follows: The thiol moiety of **9** was converted into the corresponding sulfenyl bromide by NBS.[12] Intramolecular attack of the central sulfur atom to the brominated sulfur atom and the subsequent attack of the hydroxy group in the presence of triethylamine at the central sulfur atom lead to the formation of **10** with elimination of triethylammonium bromide.



Scheme 1. a) lithium diisopropylamide, THF, −78°C; b) $Ph_2C{=}O$, −78°C; c) aq NH_4Cl; d) *n*BuLi, Ph_2PCl, THF, −78°C; e) 2,6-dimethylbenzoquinone, AcSH, CH_2Cl_2, RT; f) $(nBu)_4NF$, THF, 0°C; g) H_3O^+; h) aq HCl, MeOH, reflux; i) NBS, Et_3N, CCl_4, 0°C; j) $CDCl_3$, 55°C; k) $LiAlH_4$, THF, 0°C. TBDMS = *t*BuMe₂Si.

In $CDCl_3$, the aromatic proton at the *ortho* position (H1) was detected at $\delta = 8.37$ ppm, which was close to the values of

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[*] Prof. Dr. N. Kano, Y. Itoh, Y. Watanabe, S. Kusaka,
Prof. Dr. T. Kawashima
Department of Chemistry, Graduate School of Science
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 (Japan)
Fax: (+81) 3-5800-6899
E-mail: takayuki@chem.s.u-tokyo.ac.jp
Homepage: http://www.chem.s.u-tokyo.ac.jp/users/hetero/index-e.html

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the tetracoordinate 1,2-oxathietanes and 1,2-thiazetidine, suggesting the similar conformation of the four-membered ring; that is, the divalent sulfur atom takes the apical position of the tetracoordinate sulfur atom in solution at room temperature.

The crystal structure of **10** was determined by X-ray crystallographic analysis (Figure 1).[13] The tetracoordinate S1 atom has ψ-TBP geometry, with atoms O1 and S2 at the apical positions and atoms C1 and C10 at the equatorial positions.

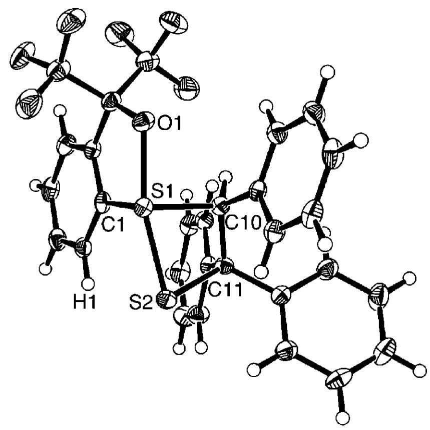

Figure 1. ORTEP of **10** with thermal ellipsoids set at 50% probability. Selected bond lengths (Å) and angles (°): S1–O1 1.9959(15), S1–S2 2.2138(10), S1–C1 1.806(2), S1–C10 1.870(2), S2–C11 1.856(2), C10–C11 1.554(3); O1-S1-S2 165.27(5), O1-S1-C1 84.90(8), O1-S1-C10 88.53(8), C1-S1-S2 98.60(7), C1-S1-C10 107.80(9), S2-S1-C10 76.77(6), S1-S2-C11 79.42(6), S1-C10-C11 99.16(12), S2-C11-C10 96.40(12).

The configuration of the divalent sulfur atom of **10** is different from that of F_3SSF. The difference is partly ascribed to the almost identical electronegativities of sulfur and carbon. The S1–S2 bond (2.2138(10) Å) is considerably longer than that of usual disulfide bonds (1.97–2.08 Å), and that of the previously reported divalent 1,2-dithietanes (2.084–2.0855 Å).[14] The bond length is quite reasonable for the hypervalent apical bond of a sulfurane.[2,8,9] The S1–O1 bond (1.9959(15) Å) is also longer than sum of the covalent bond radii (1.70 Å). The C10-S1-S2 and C11-S2-S1 angles (76.77(6) and 79.42(6)°, respectively) are slightly narrower than the C-S-S angles in the divalent 1,2-dithietanes (80.7(1)–82.2(1)°) as a result of the elongation of the S1–S2 bond. The torsion angle of C10-S1-S2-C11 (18.04(8)°) indicates that the 1,2-dithietane ring is slightly puckered.

The stability of the conformation of the 1,2-dithietane and its bonding properties were investigated by the DFT calculations with basis set of B3LYP/6-311G + (d,p). The optimized molecular structure, the S-apical configuration, which matches well with the X-ray crystal structure, is calculated to be more stable than the S-equatorial configuration by 15.9 kcal mol^{-1}. The HOMO (energy level −6.50 eV) of **10** is localized mainly on the two different lone pairs of both the dicoordinate and tetracoordinate sulfur atoms (see the Supporting Information, Figure S2). The LUMO (energy level −2.0 eV) is an unoccupied in-plane orbital localized on the dicoordinate sulfur atom. For the LUMO + 1 (energy level −1.7 eV), there is contribution by the antibonding orbitals of the 3-center 4-electron bonds for the apical S–O and S–S bonds. The natural population analysis showed the positive charge for the tetravalent sulfur (+ 0.88) and the negative charge for the divalent sulfur (−0.07), the oxygen (−0.78), and the carbon (−0.18, −0.28), suggesting polarity of the S–S, S–O, and S–C bonds. Formation of the 3-center 4-electron bonds and polarity of the S–S bond should be characteristics of the sulfur-substituted sulfurane with the S-apical configuration.

Sulfurane **10** is stable to oxygen and the solid is able to be handled in the air at room temperature, but it decomposes rapidly in the presence of water in solution. In solution, **10** decomposed gradually at room temperature even in the absence of water, and its thermolysis at 55 °C for 100 min in $CDCl_3$ gave the corresponding cyclic sulfenate **11** (quantative yield) and triphenylthiirane (**12**) (92 %). The reaction mode of **10** to give the corresponding three-membered ring compound is similar to the cases of the pentacoordinate 1,2-oxathietanes and the 1,2-thiazetidine oxide,[8b,c,9] which are thermally much more stable than **10**. Thus, the relative thermal instability of sulfurane **10** compared to the dicoordinate 1,2-dithietanes should be attributed to the existence of the S^{IV}–S^{II} bond.

The S–S bond of **10** can be cleaved by hydride reduction without cleavage of the S–C bond. Reaction of **10** with $LiAlH_4$ gave **9** in 60 % yield after quenching with aqueous NH_4Cl (Scheme 1). The formation of **9** shows reductive cleavage of the S^{IV}–S^{II} bond accompanying the S^{IV}–O bond cleavage under the hydride reduction conditions. Considering that **9** can be converted into **10**, the reductive cleavage and the oxidative formation of the S^{IV}–S^{II} bond is similar to the formation–cleavage processes of disulfide and thiol systems.

In summary, we succeeded in the synthesis and X-ray crystallographic analysis of the tetracoordinate 1,2-dithietane, which is the first example of a crystallographically analyzed sulfur-substituted sulfurane. A fairly long S–S bond and S-apical configuration were revealed. As the sulfur-substituted sulfurane was converted into the corresponding thiol reversibly by redox reactions, the S^{IV}–S^{II} bond formation–dissociation process may be found in biological systems.

Experimental Section

N-Bromosuccinimide (0.16 g, 0.90 mmol) and triethylamine (0.25 mL, 1.9 mmol) were added to thiol **9** (0.50 g, 0.89 mmol) in CCl_4 (25 mL) at 0 °C. The solution was stirred for 15 min, filtered through Celite, and the solvent was evaporated. Recrystallization from CCl_4/hexane gave 1,2-dithietane **10** (0.21 g, 42 %) as colorless crystals. **10**: m.p. 71.0–72.8 °C (dec.). ^1H NMR (400 MHz, $CDCl_3$): δ = 6.82 (s, 1 H), 6.96–7.33 (m, 15 H), 7.40–7.54 (m, 3 H), 7.68 (d, J = 7.6 Hz, 1 H), 8.37 ppm (d, J = 8.0 Hz, 1 H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$): δ = 60.33 (s), 83.17 (sept, $^2J(C,F)$ = 30.5 Hz), 94.70 (s), 122.85 (q, $^1J(C,F)$ = 230 Hz), 123.11 (q, $^1J(C,F)$ = 232 Hz), 126.36 (s), 126.38 (s), 126.51 (s), 126.89 (s), 127.60 (s), 128.02 (s × 2), 128.54 (s), 129.26 (s), 130.30 (s), 130.42 (s), 132.14 (s), 132.37 (s), 132.57 (s), 134.21 (s), 135.00 (s), 143.41 (s), 148.02 ppm (s); ^{19}F NMR (376 MHz, $CDCl_3$): δ = −78.4 (q, $^4J(F,F)$ = 8.6 Hz, 3F), −76.6 ppm (q, $^4J(F,F)$ = 8.6 Hz, 3F); MS (FAB): m/z: 563 $[M+H]^+$; HRMS (FAB): m/z calcd for $C_{29}H_{21}F_6OS_2$ $[M+H]^+$: 563.0938; found: 563.0927; UV (Et_2O): $\lambda(\varepsilon)$ = 214 (49000), 222 (sh), 248 (sh), 253 (sh), 258 nm (sh); IR (KBr): ν =

522, 555, 570, 608, 625, 643, 695, 738, 745, 772, 868, 952, 1001, 1033, 1052, 1078, 1129, 1145, 1181, 1223, 1255, 1281, 1446, 1456, 1492, 1583, 1597, 3031, 3069 cm^{-1}.

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[13] **10**: $C_{29}H_{20}F_6OS_2$, $M_r = 562.57$, monoclinic, $C2/c$, $a = 22.241(9)$, $b = 13.666(5)$, $c = 16.284(6)$ Å, $\beta = 99.0381(19)°$, $V = 4888(3)$ Å^3, $Z = 8$, 15526 measured and 4307 independent reflections, 343 parameters, GOF = 1.053, $R1(I>2\sigma(I)) = 0.0352$, $wR2$(all data) = 0.0906 (see the Supporting Information). CCDC-665669 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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