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In Pursuit of Stable, Strained Smallring Sulfur Heterocycles

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IN PURSUIT OF STABLE, STRAINED SMALL-RING SULFUR HETEROCYCLES

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(Received 17 January 1997)

Stable, strained small-ring sulfur heterocycles constitute an intriguing challenge for synthesis and study in organic chemistry. In pursuit of this class of compounds, the intermediacy of several three-membered hypervalent thiaheterocycles has been unequivocally established whereas the as yet elusive 2,4,5-trithia[1.1.1]propellane was predicted—via high-level *ab initio* calculations—to be a tightly bound molecule which should be experimentally accessible. The use of rhodium-SO and iridium-SO complexes for the generation of “SO”—to be trapped by multiple bonds to form the corresponding three- or four-membered small-ring sulfur heterocycles—turned out to be unproductive, while the use of palladium-SO complexes appeared to be more promising with respect to the targeted systems. Thiranes, in the PAHs series are accessible, synthetically, via the Lewis acid-aided catalysis of the reaction of the corresponding epoxide precursors with nucleophilic “S”-transfer agents.

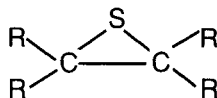
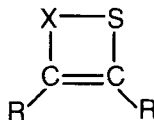
Keywords: Small-ring sulfur heterocycles

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1. HISTORICAL PERSPECTIVE

Small-ring compounds represent a fair portion of strained organic systems in which the geometries of sp^3 and that of sp^2 carbons have been distorted from the ideal configurations.^[1] Foremost among these reactive molecules are the small-ring heterocycles, such as **1**^[2] and **2**.^[3]

**1****2**

a, X = S

b, X = O

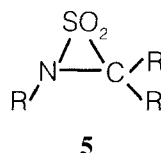
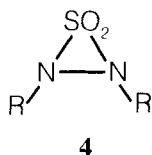
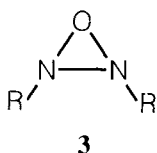
The introduction of heteroatoms into cyclic systems produces significant variations in the molecular geometry that reflect the changes in covalent radii, relative electronegativity and effective hybridization. Consequently, there are changes in the bonding and the physico-chemical characteristics of these heterocyclic systems—particularly in small-ring systems.

Cyclic systems have frequently been used in studies of chemical bonding and reactivity, reaction mechanisms and a variety of other problems of interest to chemists.^[3] Their utility depends on the changes in the carbon-carbon and the carbon-heteroatom bonds as well as on steric and electronic effects that result from the introduction of heteroatoms into the system. Thus, small rings and the associated concepts of distorted hybridization and strain have fascinated organic chemists for more than a century and this interest shows no sign of abating; if anything, it is growing.^[4] Indeed, three- and four-membered rings, over the years, have received great attention from both experimental and theoretical perspectives. However, the consequences of replacing one or more of the cyclic carbon atoms in these systems by heteroatoms, on bonding and structure, strain energies, chemical reactivity and reaction mechanisms are still being extensively explored in an attempt to bridge the gap between theoretical predictions and experimental tests.^[5,6]

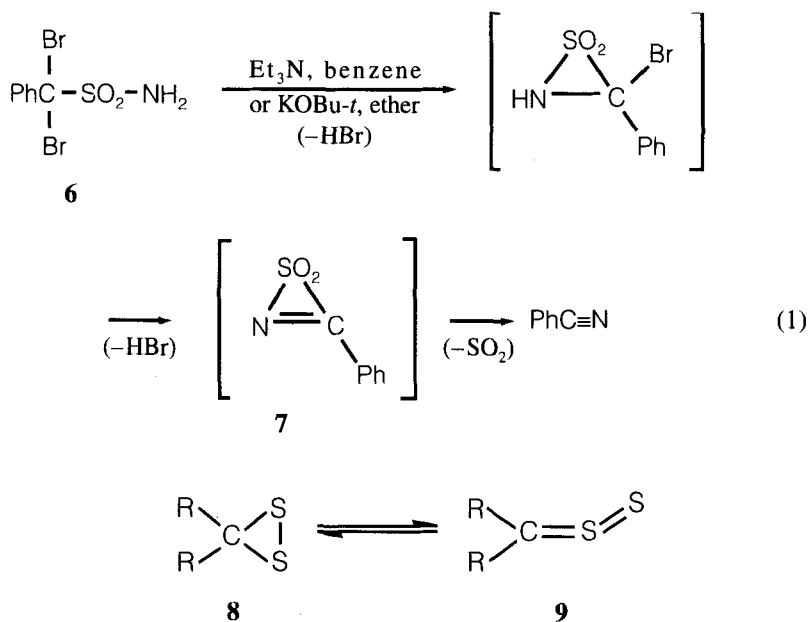
The history of three-membered rings containing sulfur begins more than 80 years ago with the synthesis of 2,2,3,3-tetraphenylthiirane by Staudinger and Pfenninger.^[7,8] Following the preparation of the first pure aliphatic thiirane—ethylene sulfide—by Delépine^[9] in 1920, the importance of this group of compounds as reactive substances suitable for a variety of chemical transformations was recognized. The chemistry of this class of compounds gained momentum when in 1934 Dachlauer and Jackel discovered a simple method for their synthesis from epoxides and alkali thiocyanates or thiourea.^[10] The comprehensive studies conducted by Culvenor and Davies during the late 1940s and early 1950s revealed significant and important aspects involved in the chemistry of thiiranes.^[11–14]

Excluding a few isolated cases of earlier reported preparations of thiirane oxides, thiirane dioxides, and thiiranium salts, the chemistry of these classes of stable three-membered rings containing sulfur was developed and established within the last four decades, beginning in the early 1960's.^[6,15]

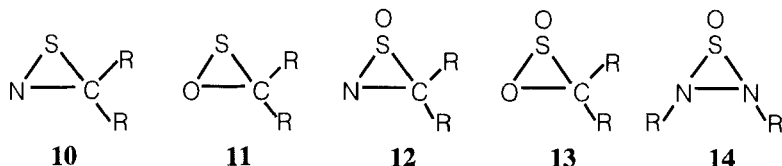
Although no three-membered ring with two heteroatoms had been prepared before the fifties, several insoluble compounds incorporating at least two heteroatoms, one or both sulfur, are known to date.^[16–18] Later, following the synthesis of the first three-membered ring comprised solely of heteroatoms (i.e., oxadiaziridines **3**),^[19] the synthesis of the thiadiaziridine dioxides **4** was reported,^[20] followed by the successful isolation and characterization of the thiaziridine dioxide systems.^[21]



In the early seventies, the intermediacy of **7**, an aza vinylog of thiirene dioxide (an unsaturated three-membered ring containing sulfur), has been established via the base-induced successive dehydrohalogenations of the α,α -dibromophenylmethanesulfonamide **6** (Eq. 1),^[22] followed by the reported experimental proof of the existence of the dithiirane **8** in equilibrium with **9**.^[23]



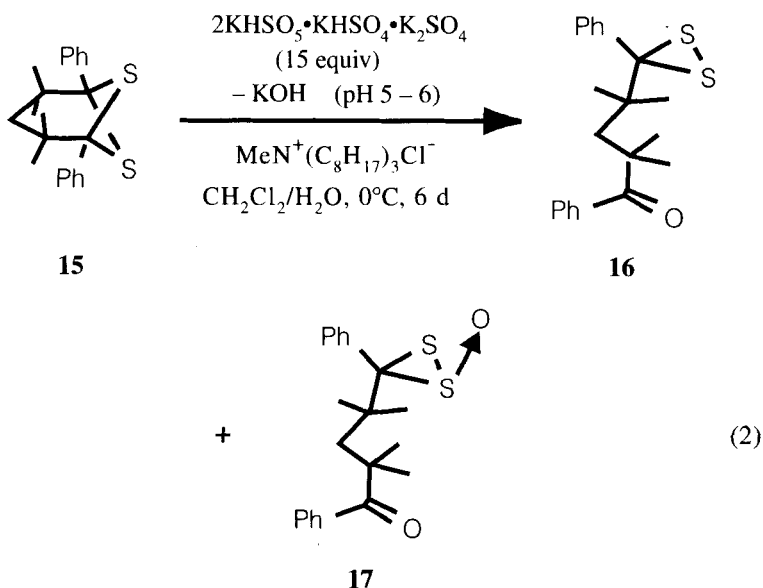
Interestingly, except as proposed reaction intermediates, the saturated three-membered ring systems **10–14** have not been synthesized thus far.



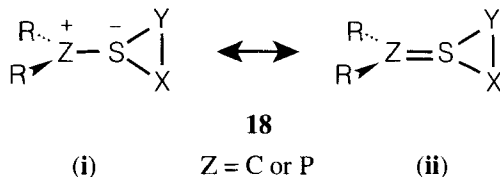
The high energy inherent in the sulfur-containing three-membered ring systems such as **4**, **5**, and **10–14**, turned them by and large into very reactive species, which are sensitive both chemically and thermodynamically, particularly to nucleophiles.^[15–17]

In contrast, examples of virtually all four-membered rings with two heteroatoms, including those with two sulfur atoms, have been prepared.^[24] In this series, however, four-membered rings containing two sulfur atoms such as derivatives of the 1,3-dithietane system have been known for over 120 years.^[25]

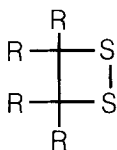
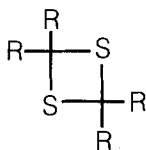
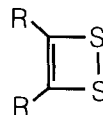
It is well established that the introduction of heteroatoms into small rings produces significant variations in the molecular geometry which reflect changes in the bonding and hybridization of these heterocyclic systems compared to that of the hydrocarbon analogues. Indeed, the carbon-heteroatom bond length shows an effective increase with increasing heteroatom electronegativity, in line with potentially facile ring opening involving the carbon-heteroatom bonds. This, coupled with the ring strain, makes the three- and four-membered rings containing two heteroatoms thermally unstable and highly reactive: carbon-heteroatom and heteroatom-heteroatom bonds are weak compared to the corresponding bonds in unstrained systems. Indeed, small-ring heterocycles are the foremost chemically reactive among the class of small-ring compounds, making these molecules intriguing for preparation and study. In view of the above, it is no wonder that the parent compounds of three-membered ring systems containing two heteroatoms, at least one of which is sulfur, are not known thus far. The isolation and characterization of the first stable, substituted dithiirane (i.e. **16**) and its oxidized derivatives (e.g., **17**) have been just recently reported.^[18,26] (Eq. 2).



On the other hand, hypervalent three-membered thiaheterocycles of type **18** not only are not known to date, but even their possible intermediacy has been only recently invoked.^[27]



The parent compound of the four-membered 1,2-dithietane system **19** has until now remained unknown. The parent compound of the 1,3-dithietane system **20** was first prepared in 1976^[28] whereas that of the 1,2-dithiete system **21** is thermally stable only within low temperature matrix conditions.^[29]

**19****20****21**

Mono- and dihetero analogues of cyclopropane for which geometry is available have, characteristically, high strain energies.^[30] The perturbation of heteroatom-containing three-membered rings has been analyzed in terms of interaction of the heteroatom (or group) with ethylene.^[31] Regardless of whether electron donation from a suitable heteroatom orbital into the ethylene π^* -orbital, or donation from the ethylenic π -orbital into the heteroatom orbitals including d-orbitals (if available) is the operative mechanism, the ultimate result is the destabilization of the σ -framework.

Extensive research since 1980 has established that theory, in particular molecular orbital *ab initio* calculations, is an extremely useful and reliable source of fundamental chemical information (such as molecular structure, thermodynamic data, and electronic structure) for a wide variety of molecules.^[32] On the other hand, gas-phase ion-molecule investigations have been demonstrated to be very useful for probing intrinsic reactivities even for reactive intermediates such as small strained rings and heterocycles (both neutral and ionic), which are difficult to examine in solution. Since the experimental results of gas-phase studies are directly comparable to *ab initio* quantum molecular orbital calculations, these two complementing strategies appear to be the combined methods of choice for the future study

of three- and four-membered rings containing two sulfur atoms. Indeed, by adding a second set of both d- and f-type polarization functions, *ab initio* quantum mechanical calculations at the MP2/6-31G (2d2f) level of theory predicted the parent compound of the 1,2-dithiete heterocyclic system **21** to have higher thermodynamical stability than its ring-opened isomer (1,2-dithioglyoxal), in full agreement with experimental results.^[33]

Thus, the combination of these two methodologies with the development of synthetic methodologies for the preparation of thermodynamically and kinetically stable, strained three- and four-membered ring systems via appropriate (bulky) substitution and/or their inclusion within appropriate stabilizing systems, will facilitate answers to the still open questions related to these classes of intriguing compounds.

In view of the great distortion from the optimal (normal) bond lengths and, particularly, angles in the small-ring members of the sulfur heterocycles (a) the predictions, based on theoretical calculations, of their experimental accessibility; (b) the actual synthesis of particularly strained (but, relatively, thermodynamically stable) and/or uniquely substituted molecules of this class of compounds; (c) the use of specially designed systems within these series, e.g. as synthons in organic synthesis; and (d) the in-depth understanding of their special nature, characteristics, and observed chemistry, have still remained as intriguing challenges and, therefore, ‘organizers’ and ‘directives’ of contemporary and future research in this area.

The following account of our work constitutes a walk on the exciting trail of the intriguing and interesting class of compounds within the framework of our continuous longitudinal effort in pursuit of these—some as yet elusive—three- and four-membered thiaheterocycles.

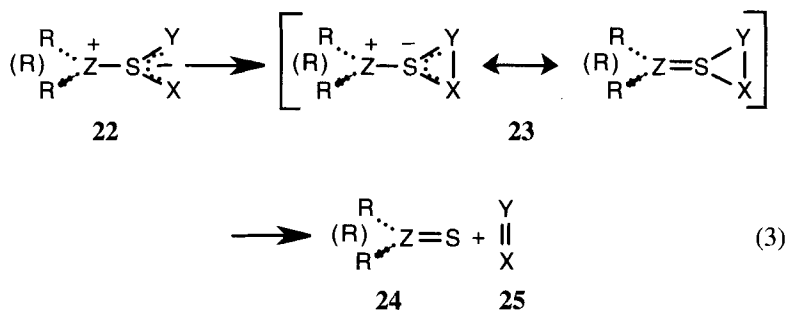
2. SO₂ ADDITION AND “SO”, “S₂” AND S TRANSFER IN THE SYNTHESIS OF SMALL-RING SULFUR HETEROCYCLES

2.1. Introduction

While both three-membered sulfur heterocycles^[2,6,15-17] and hypervalent sulfuranes^[34-37] are well-known classes of compounds the chemistry of which is well-established, thiadioxiranes, thiaoxiranes and thiaoxaziridines (**18**, X = Y = O; X = C, Y = O; X = NR, Y = O, respectively) are as yet elusive.

We reasoned^[27] that an energetically low-lying unoccupied molecular orbital (LUMO) of the π -type attached to sulfur will stabilize a tricoordinate

hypervalent sulfurane bonding array **23**, provided the latter is potentially capable of being formed from an appropriate precursor. Furthermore, the unique geometric and electronic constraints of such systems should eventually, under mild thermolytic conditions, induce a cheletropic-type fragmentation of the three-membered ring sulfurane with the concomitant formation of the corresponding thiones and unsaturated systems (i.e. **24** and **25**, respectively) as illustrated in Eq. 3.

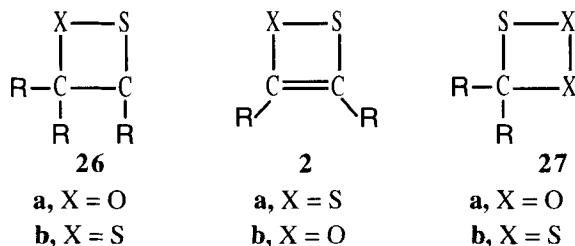


The above expected reverse $[n + 1]$ cycloaddition reaction^[38] in which the hypervalent three-membered thiaheterocycle **23** is destroyed, is of special interest in that the geometric factors require it to take place in a disrotatory or suprafacial manner.^[39] Consequently, this fragmentation must occur by the non-linear cheletropic path (the cyclic transition state contains 4 MO's) similar to the non-linear cheletropic extrusion of sulfur dioxide from thiirane dioxides which is a *symmetry-allowed* ($\sigma 2_s + \sigma 2_a$) reaction.

Thus, the provision of solid experimental evidence, for (a) the synthetic accessibility of three-membered hypervalent thiaheterocycles; (b) their relative thermodynamic stability (σ aromaticity^[38]?); and (c) their non-linear cheletropic mode of fragmentation, was the guiding purpose of this portion of our work.

The few known examples of four-membered 1,2-oxathietanes **26a**,^[40] 1,2-dithietanes **26b**,^[41] 1,2-dithietes **2a**,^[42] and the hitherto unknown 1,2,3-thiadioxetanes **27**^[43] and oxathiete **2b** are of chemical^[3] and practical significance, fundamental theoretical interest, and biological as well as medicinal importance.

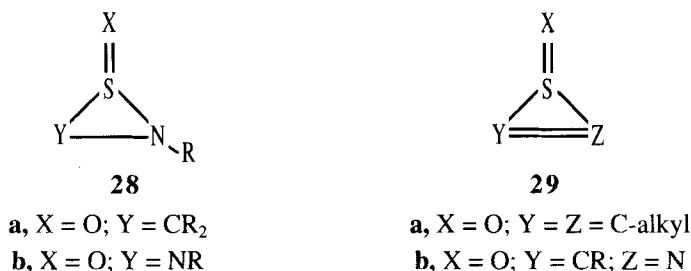
The practical importance is associated with both the analogy of these systems to the extensively studied 1,2-dioxetanes which are of importance in bioluminescence and chemiluminescence reactions^[44] and their being poten-



tial reactive intermediates in chemical reactions,^[45-47] photochemical in particular.^[46-47] From a theoretical point of view, the interest in these heterocycles stems from their being potential 6π aromatic systems (e.g., **2**)^[48] and the effects of the sulfur atom on the direction, rates, energetics, and energy distribution in their anticipated pericyclic reactions of the formal $[\sigma 2s + \sigma 2a]$ type^[39] (applicable in **26**, **2** and **27**). The biological interest is related to the anticancer activity of some of the 1,2-oxathietanes^[40] and their ability (i.e. **26a**) to induce pyrimidine dimers in DNA^[49] as well as the biological activity associated with cyclic disulfides^[50] (i.e., **26b** and, possibly, **27b**).

Saturated and unsaturated three-membered heterocycles continue to be a subject of considerable interest among chemists. Systems of type **28** and **29** are no exception^[6,15,16] so that the preparation and isolation of the thus far elusive thiaziridine oxides **28a**, thiadiaziridine oxides **28b**, thiirene oxides **28a**, and thiazirine oxides **29b** constitute an intriguing synthetic challenge.^[17]

The presence of one or more heteroatoms in these strained systems potentially alters their reactivity and stability, increases their content of strain energy^[51] and substantially decreases the availability of methods for their synthesis.



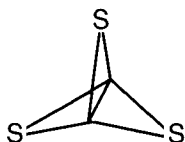
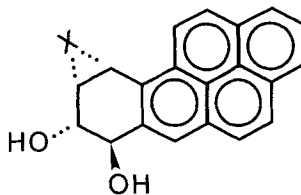
Both theoretical and experimental studies on the structure, energies, strain energies, bonding, and charge distribution in small-ring propellanes

have been important in the development of modern organic chemistry.^[51] The smallest conceivable member of this series of hydrocarbons is [1.1.1]propellane which was synthesized some years ago and found to be remarkably stable.^[52]

Since the “normal” bond angles at sulfur are considerably smaller than those at the corresponding (tetrahedral) carbon, one might expect that small sulfur-containing rings might be less strained than their hydrocarbon analog (e.g. S.E.₄ < S.E.₃).^[2] Accordingly, the sulfur analog **30** of [1.1.1]propellane should be less strained than the latter and, therefore, an attractive synthetic target.

High-level *ab initio* molecular orbital calculations of the structure and vibrational frequencies for 2,4,5-trithia[1.1.1]propellane **30** have been carried out at the MP2/6-31G* level, together with a parallel set of calculations for [1.1.1]propellane, cyclopropane, and thiirane.^[53] This was done as a preliminary to the possible synthesis of **30**.

Finally, the chemical and biological consequences of the replacement of the oxygen atom in the polycyclic aromatic hydrocarbon (PAH) epoxides^[54] and the ultimate carcinogen PAH *trans*-7,8-diol 9,10-epoxide (DE-2)^[55] **31a** by the “bulkier”, more polarizable and more nucleophilic sulfur atom, would provide a unique opportunity for study and in-depth understanding of the nature of bonding, thermostability and stereospecific structure-chemical/ biochemical reactivity relationships in the diol episulfides (DeS’s) (e.g. **31b**) once accessible.

**30****31**

a, X = O

b, X = S

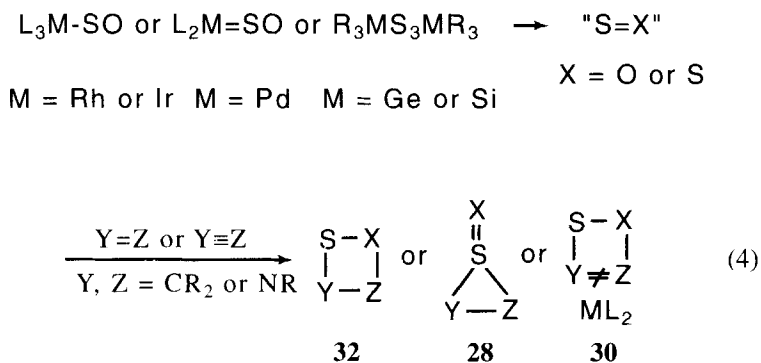
Clearly, the synthesis of the four- and three-membered systems **2** and **26–31**, followed by the study of their structure, chemistry, medicinal and carcino-toxicological potential^[56–57] are of considerable interest and significance. All of the above heterocycles contain either the “S=X” moiety

regiospecifically added to multiple bonds (e.g. alkenes, acetylenes or heteroalkenes) or a transferred "S" unit to bridge between two adjacent carbon atoms. Such a synthetic methodology should provide, if successful, a straightforward direct entry into these systems. The realization of both, the efficient and convenient generation of "S=X" and the successful synthesis of the above unique four- and three-membered rings, by means of appropriate methodology/ies, will not only open the door for the study of the chemistry of these unique systems, several of which are not known thus far, but also would facilitate the synthesis of many interesting S-X, "S=X" and S-containing larger-size heterocycles as well as other sulfur-containing organic compounds via their initial trapping, followed by a multitude of possible transformations.

2.2. Synthesis Strategies

With respect to the targeted hypervalent thiaheterocycles **23**, the *in-situ* generated lithio-*N,N*-dimethylimidazolium salts which readily undergo sulfonylation with sulfur dioxide and analogues^[27] were used as promising precursors. We expected that the generated zwitterionic species **22** should, eventually, rearrange to give the hypervalent thiaheterocycle **23**, since the latter would be stabilized by the energetically low-lying, unoccupied molecular orbital (LUMO) of the π -type of the imidazolium electron acceptor system adjacent to the hypervalent sulfur.

Similarly, based on the reported trapping of diatomic sulfur "S₂" and "SO"^[59,60] by dienes with little to moderate success, the trapping of these species by alkenes and alkynes was attempted, via their thermal or ligand exchange generation from transition metal complexes.



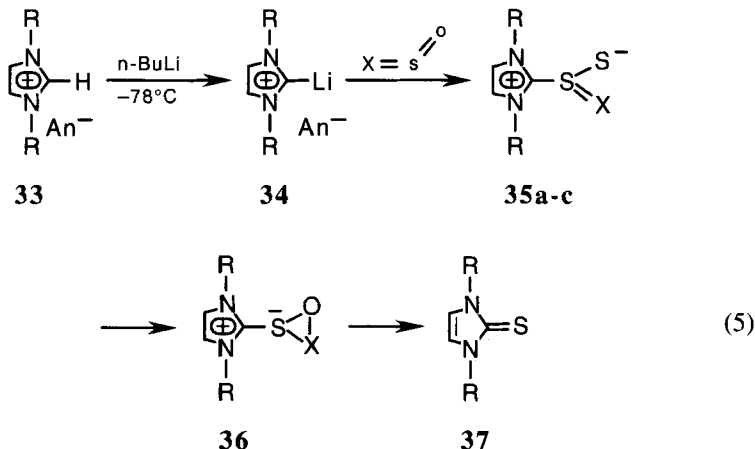
In the case of the alkynes, the expected labile unsaturated products were hoped to be insoluble as stabilized organometallic complexes such as **30**. Since metal carbonyl moieties are known to stabilize antiaromatic systems,^[61] the use of $M_n(\text{CO})_m$ [e.g., $\text{Fe}_2(\text{O})_9$] for both the transfer and complexation-stabilization of thermodynamically unstable products was attempted, too.

Although the acid-catalyzed synthesis of the bay region tetrahydrobenzo[*a*]pyrene (*THBaP*) was recently reported,^[62] the well-established extreme susceptibility of the bay region DE's to protic acids,^[63] prompted us to investigate the transition metal complex $\text{Ti}(\text{OPr-i})_4$ as a Lewis acid substitute for the synthesis of **31b** from its corresponding epoxide using nucleophilic S-transfer agents. Selected results of our recent synthetic work are presented and briefly discussed below.

2.3. Results and Discussion

The general scheme for obtaining the hypervalent ring system **36** (expected to be relatively, thermodynamically stable) is shown below:

Treatment of the lithiated species **34** with the electrophilic sulfur dioxide as well as with its C- and N-analogues (i.e. sulfines and *N*-sulfinylamines,



a, $\text{An} = \text{Br}$

b, $\text{An} = \text{CF}_3\text{SO}_3$

c, $\text{An} = \text{I}$

d, $\text{An} = \text{BF}_4$

e, $\text{An} = \text{ClO}_4$

a, $\text{X} = \text{O}$

b, $\text{X} = \text{CR}_2$

c, $\text{X} = \text{NR}$

respectively) led smoothly to **35a–c** which, in turn, gave **37** via the intermediacy of the hypervalent three-membered ring sulfuranes **36a–c**.^[27]

SCF-MO calculations revealed that the lowest energy mode of decomposition of species of type **35** is dissociation into the singlet carbene-sulfur dioxide complex lying only a few kcal above the bound sulfur dioxide.^[27] Consequently, the equilibrium of **34** and sulfur dioxide (or sulfine, or *N*-sulfinylamine) with **35** accounts for the isolation of substantial amounts of the starting imidazolium salts **33** after the work-up at the end of the long-time duration sulfonylation-thionation reactions (e.g. **34** → → → **37**).

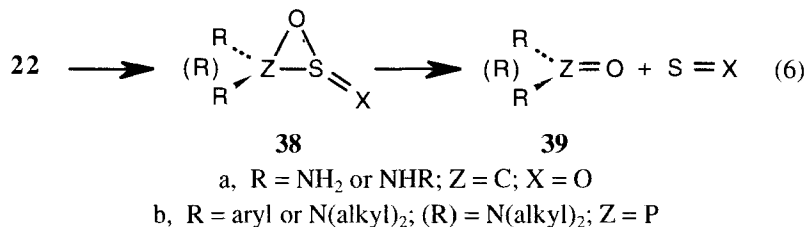
The fact that thione **37** and the recovered starting imidazolium salt **33** appear to be the only products originated in **33** in the transformation **33** → **34** → **4** → [**36**] → **37**, strongly suggests that.^[34]

- a) *the yield of 37 is actually the ultimate conversion percentage of both 33 and 36 to 37 under the reaction conditions employed;*
- b) *the hypervalent three-membered thiaheterocycle 35 is indeed the intermediate connecting 35 and 37 on the reaction surface;*
- c) *the stabilizing effect of the LUMO of the imidazolium π-system on the adjacent incipient hypervalent sulfur is sufficient to facilitate the rearrangement of 35 to 36;*
- d) *once formed, the three-membered ring sulfurane 36 has a life-time sufficient (before collapsing back to the highly resonance-stabilized acyclic zwitterionic isomer 35) for undergoing a cheletropic fragmentation leading to 37; and*
- e) *the thermally allowed cheletropic fragmentation of 36 to give 37 is energetically the most favored one available to this intermediate in its ground state.*

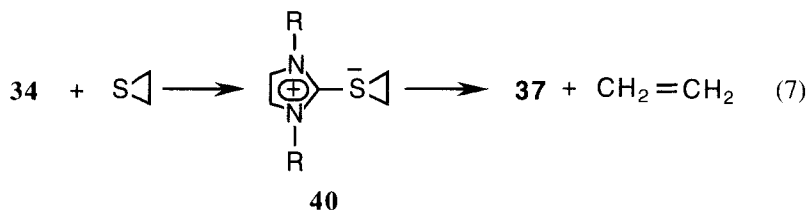
The kinetics of the fragmentation of species of type **36** (e.g., **36d**: R = NH₂, Z = C, X = Y = O; and **36e**: R = *n*-butyl, Z = C, X = Y = O) is of the first order with composites of $k_1 = 1.0 \times 10^{-4}$ ^[10] (in CD₃CN; 45 °C) and $k_1 = 1.2 \times 10^{-4}$ (in DMSO-*d*₆; 85 °C) for **36d** and **36e**, respectively.

These results indicate that the hypervalent three-membered thiaheterocycles **36** enjoy considerable thermodynamic stability which can be accounted for in terms of the δ aromaticity,^[38] largely confined to molecules with three-membered rings including three-membered heterocycles (e.g. thiranes, oxiranes, aziridines which resemble cyclopropane in exhibiting unexpected stability combined with unusual chemical behaviour).^[38]

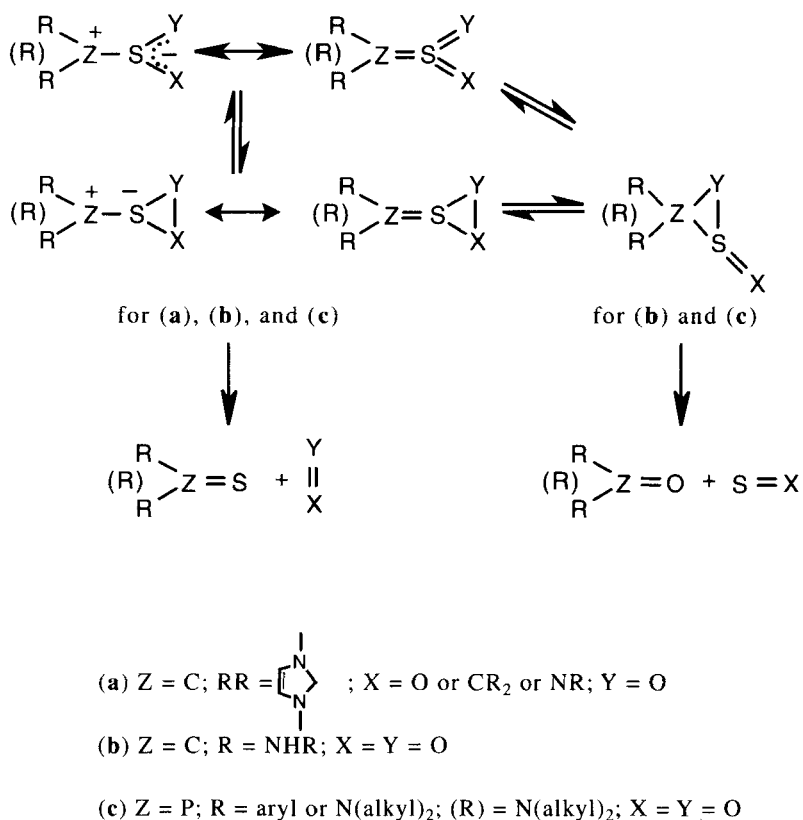
As we previously reported,^[27] thiourea dioxides (i.e., **22**: R = NR₂; Z = C, X = Y = O) and phosphine sulfide, S,S-dioxides (i.e., **22**: R = aryl and N-(alkyl)₂; Z = P; X = Y = O) yield on thermolysis the corresponding ureas and thioureas and the phosphine oxides and phosphine sulfides, respectively. The intermediacy of a three-membered sultine **38** was proposed^[27] to account for the formation of both ureas **39a** and phosphine oxides **39b** in these transformations.



The fact that thiirane, too, like sulfur dioxide and its C- and N-analogues, reacts with lithiated salts to give thione **37** (albeit in small yields) under the same reaction conditions, is strong support for the sequence **34** → **35** → **36** → **37** depicted above. The hypervalent thiirane **40**, formed directly by the nucleophilic attack of the lithiocarbenium ion **34** on the sulfur atom of the thiirane, fragments cheletropically to yield the observed thione **37** and ethylene.

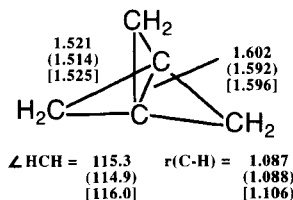
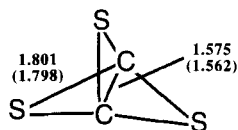


In this reaction, as in the cheletropic loss of carbon monoxide from cyclopropanones^[65] and the cheletropic fragmentations of **23a-c**, stereochemical information on the extrusion process is lacking. However, for the related reverse process, the stereospecific combination of singlet carbenes with olefins to give cyclopropanes, semiempirical calculations yield results in concordance with the analysis of a non-linear cheletropic process.^[66]

Scheme 1^[64]

In taking all the experimental evidence and theoretical considerations into account, the following general mechanism is suggested^[64] for the thermolytic cheletropic fragmentation of imidazolium sulfates **35a–c**, thiourea *S,S*-dioxides, phosphine sulfide *S,S*-dioxides, and hypervalent imidazolium thiiranes **40**.

The existence of hypervalent three-membered thiaheterocycles **23** as relatively stable intermediates on the reaction surface connecting species of type **22** with thiones **24** has been thus established. Geometries for **41** and **30** as optimized at the MP2/6-31G* (in parentheses) and MP2/6-311G(MC)* levels are compared below with available experimental data.^[67]

**41** (D_{3h})**30** (D_{3h})

The calculated heats of formation for these two and the related cyclopropane and thiirane from the MP2/6-311G(MC)* energies of bond separation reactions together with experimental heats of reference molecules^[68] are given in Table I.^[53]

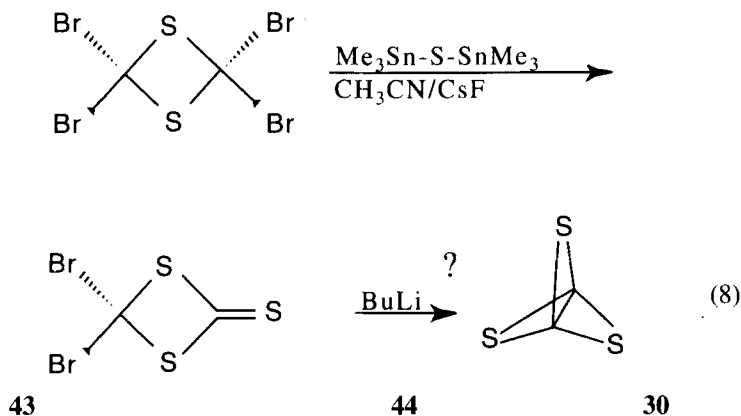
The vibrational frequencies and the infrared and Raman intensities for **41**, **30**, **42**, and **1** have been also calculated at the MP2/6-31G* level^[53] and compared with available experimental data.

The excellent agreement between our theoretical calculations and experiment for the known molecules lends confidence to our predictions for 2,4,5-trithia[1.1.1]propellane **30**. The C-C intrabridgehead bond length is predicted to decrease from 1.602 Å in **1** to 1.575 Å in **24**, making it closer to the range of lengths of normal C-C single bonds and the value of only 11 kJ mol⁻¹ (at 298 K) obtained for the difference in strain energy (S.E.) between **30** and **41**, should make the former tightly bound molecule (i.e., **30**) experimentally accessible.^[53] The synthesis of a possible key precursor (2,4-dichloro-1,3,5-trithiabicyclopentane) to the targeted trithia[1.1.1]propellane was, unsuccessfully, attempted at time.^[67] We, therefore, treated the readily accessible tetrabromo-1,3-dithietane^[69] with hexamethyldisilathiane (or its Sn analog), expecting to obtain the bridgehead dibromotrithia[1.1.1]propellane. Rather, we obtained the 1,3-dithietane-2-thione **44** (meaning double displacement of bromine, by sulfur, on the same carbon atom) via which we are currently

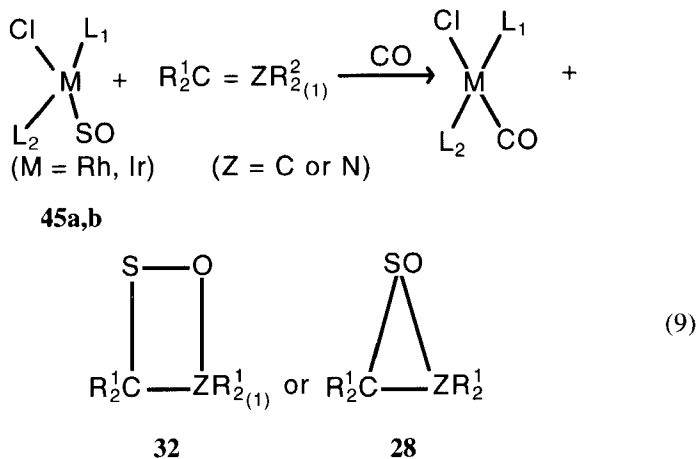
TABLE I Calculated and experimental heats of formation (Δ_f° , kJ mol⁻¹)

Molecule		calculated	experimental
[1.1.1]propellane	41	352	351
2,4,5-trithia[1.1.1]propellane	30	542	—
cyclopropane	42	58	53.3
thiirane	1	71	82.1

trying to get to the target compound **30**, using organometallics (e.g. BuLi) to induce this transformation (Eq. 8)



Our initial working scheme in using organometallic aided “SO”, “S₂” and S transfer in the synthesis of small-ring sulfur heterocycles followed the procedure depicted in Eq. 9,¹⁷⁰ expecting **32** or **28** to be formed.

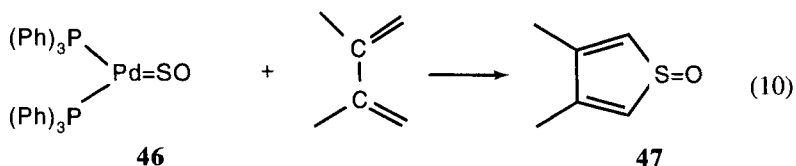


In our hands, in the reaction of either the Rh or the Ir complex **45a,b** with the nucleophilic ethyl or trimethylsilyl ether, PhCH=NPh, norbornene, diphenylacetylene, the dienes tetraphenylcyclopentadienone, 2,5-dimethyl-tetrahydrofuran, 2,3-dimethylbutadiene, and 3,5-di-*tert*-butyl-*o*-benzoquinone, no trace of any of the expected cycloadducts was detected. No

insoluble products other than $i\text{-Pr}_3\text{PO}$ and/or $i\text{-Pr}_3\text{PS}$ were present in the filtrate after the removal of the organometallics by filtration.

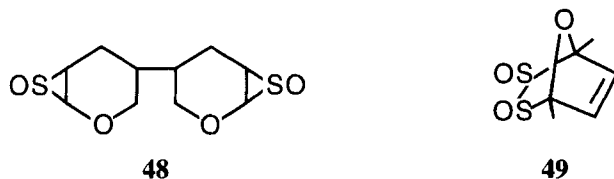
Based on the experimental results reported above, our conclusion is that the use of the rhodium-SO and the iridium-SO complexes for the generation of "SO"—to be trapped by alkenes, alkynes and/or conjugated dienic systems to form the corresponding [2 + 1], [2 + 2] or [2 + 4] cycloadducts—is very problematic, to say the least. Most probably, the cycloaddition does not occur to any noticeable extent, or does not take place at all, at least under the conditions employed by us. In fact, even the very modest "positive" results reported by Schenk *et al.*,^[59] for the case of selected conjugated dienes^[70–72] could not be reproduced by us.^[73]

A recent paper^[60] reported the preparation of the palladium complex **46** and its SO ligand undergoing a cycloaddition reaction with dienes; e.g. dimethylbutadiene, to give the thiophen **47** (Eq. 10):



We have extensively explored this route in an attempt to extend its scope, by treating the palladium complex **46** with alkenes, alkynes and heteroalkenes as well as with various conjugated dienes and heterodienes, including those multibond-containing compounds which were used with the rhodium and iridium complexes **45a,b**. However, except for recovering the unreacted starting materials, some $(\text{C}_6\text{H}_5)_3\text{PO}$ and $(\text{C}_6\text{H}_5)_3\text{PS}$, in the case of the norbornene, and the corresponding hydroquinone in the case of the 3,5-di-*tert*-butyl-*o*-benzoquinone, no reaction was detected between the complex **46** (the potential source for in-situ SO generation) and either of the following: 3,5-di-*tert*-butyl-*o*-benzoquinone, acetylene, ethyl vinyl ether, benzalaniline, tetraphenylcyclopentadienone, and norbornene.^[73] These negative results are remarkably similar to those observed for the Rh- and Ir-SO complexes. The palladium complex **46** did react, however, with 3,4-dihydro-2*H*-pyran and 2,5-dimethylfuran. The tentative structures of the products **48** and **49** (both symmetric) are based on spectroscopic data (MS, ^1H and ^{13}C nmr) of the purified adducts (column chromatography and crystallization).^[73]

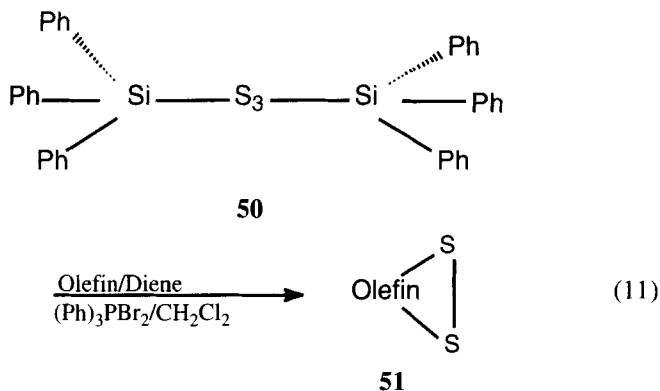
In both cases, the chelotropic mode of cycloaddition of the SO moiety across the multibond system (1,2 or 1,4) is clearly preferred. This is in con-



trast with the exclusive (2 + 2 or 2 + 4) mode of addition in the case of the analogous diatomic sulfur "S₂". Whereas the mechanism for the formation of the α -disulfoxide ring system appears to be straightforward, the elucidation of that for the formation of the oxidative dimerization requires further study and "hard" experimental evidence. Compound **49** is of particular interest (if the tentatively assigned structure is correct), since very few α -disulfoxides are known to be formed, or to be stable enough to survive isolation.^[74]

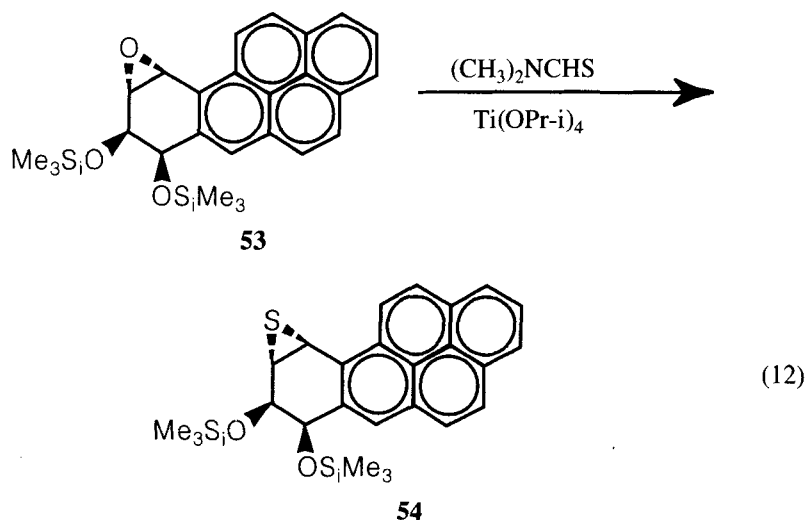
The rather low yields of both **48** and **49** via the procedure depicted in Eq. 10,^[60] require optimization of the reaction conditions in order to make this route synthetically practical.

In applying organometallics-involved synthetic methodologies within our pursuit of stable strained three- and four-membered sulfur-containing heterocycles, we have extensively used the diatomic singlet "S₂"-generating agents (e.g. **50**) of the type developed by Steliou *et al.*^[75] (Eq. 11), and the monoatomic sulfur transfer agents [(CH₃)₃Si]₂S and (CH₃)₂NCHS for four- (Eq. 11) and three-membered rings,^[76,77] respectively.

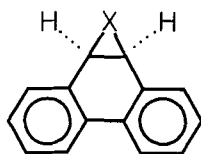


Finally, with respect to the PAH series, the treatment of bis(trimethylsilyl)-DE-2^[78] **53** with excess of the sulfur transfer agent *N,N*-dimethyl-

thioformamide, in the presence of titanium tetraisopropoxide, afforded the target DeS compound **54** in 81% yield as colorless crystals^[79] (Eq. 12).



Since the reaction of the sulfur transfer agent bis(trimethylsilyl) sulfide with bromine both in and without the presence of phenanthrene afforded elemental sulfur, the targeted phenanthrene episulfide **55b** was, apparently, not formed in this case. On the other hand, nmr monitoring of the reaction of the epoxide **55a** with the sulfur transfer agent 3-methylbenzothiazole-2-thione, under acidic conditions, revealed the following spectrum: δ 7.21–8.73 (m, arom.), 6.37 (d), 5.50 (d), and 3.93 (s). The latter singlet was, tentatively, assigned to the targeted episulfide **55b**.^[54]

**55****a**, X = O**b**, X = S

We have ultimately developed a facile synthesis of the hitherto unknown benzo[*a*]pyrenediol episulfide **31b**, the first stereoselectively prepared sul-

fur analogue of the ultimate carcinogen DE-2 **31a**.^[79] Our methodology—Lewis acid-catalyzed epoxide ring-opening and oxygen substitution by sulfur—is applicable for the preparation of benzylic thiiranes, including those of the substituted and unsubstituted PAHs.

In conclusion, “SO” appears not to be reactive towards multiple single bonds and, therefore not very useful, synthetically, in this respect. When it cycloadds, the cheletropic mode appears to be preferred (exclusively?). At any rate, the chemistry of the thermally generated “SO” is different from that of the analogous “S₂” species. Sulfur transfer agents, on the other hand, are very useful for providing the sulfur atom for the construction of stable, strained small-ring sulfur heterocycles.

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