over as the reaction proceeds. The reaction mixture is warmed gently by means of a heating mantle to ca. 35 °C. If rapid bubbling is seen in the exit bubbler, then the reaction is too vigorous and should be cooled until only occasional bubbles pass through the mercury exit tube. As the reaction proceeds the amount of liquid in the reaction flask diminishes and the reaction is considered complete when only a thick slurry remains in the reaction vessel; reaction time takes about 4 h in all. Roughly 70 g of DCFM is produced during this time. A yield of 80% is typical for this procedure, though yields as high as 87% have been obtained: $^1$H NMR (neat) $\delta$ 7.47 (d, $J_{H-F}$ = 50 Hz); $^{13}$C NMR (neat) $\delta$ 104.2 (dt, $J_{C-F}$ = 292 Hz, $J_{C-D}$ = 34 Hz).

**Acknowledgment.** We thank J. Wright and P. Neill for technical assistance and UCSD-Ac.Sen.Grant (RL208-G) for partial support of this work.

**Registry No.** DCFM, 558-19-0; CDFM, 1495-14-3; chloroform-*d*, 865-49-6.

## Synthesis and Diels–Alder Reactions of 5-Alkenyl-1,3-oxathiole 3-Oxides. A New Class of Diheterosubstituted 1,3-Dienes

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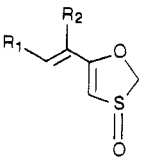
The Diels–Alder reaction remains one of the cornerstones of synthetic organic chemistry.[1] Recent years have witnessed an almost explosive development of heterosubstituted dienes as components for Diels–Alder syntheses.[2,3] The heteroatom substituent not only can control the regiochemical and stereochemical outcome of the cycloaddition but also can endow the newly formed cyclohexene with useful functionality for subsequent elaboration of the cycloadduct.[1,2]

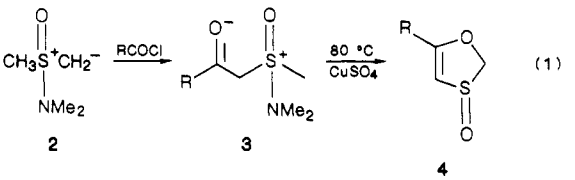
For ongoing studies of factors which control face selectivity in Diels–Alder reactions of chiral dienes,[4] we required a series of sulfinyl dienes that incorporated an additional oxygen substituent. Although the preparation and cycloaddition chemistry of dienes containing alkoxy and sulfide substituents have been examined in some detail,[5] dienes containing sulfinyl and alkoxy substituents have not, to the best of our knowledge, received significant study.[6] In this paper, we report that one class of dienes of this general type, specifically 5-alkenyl-1,3-oxathiole 3-oxides (**1**), can be prepared by the general method of Johnson.[7] We also



**1**

report[4] that the sulfinyl substituent exerts complete control of the face selectivity of Diels–Alder reactions of these dienes and surprisingly that the ring oxygen substituent has a net *deactivating* effect on cycloadditions of dienes **1** with electron-deficient dienophiles.

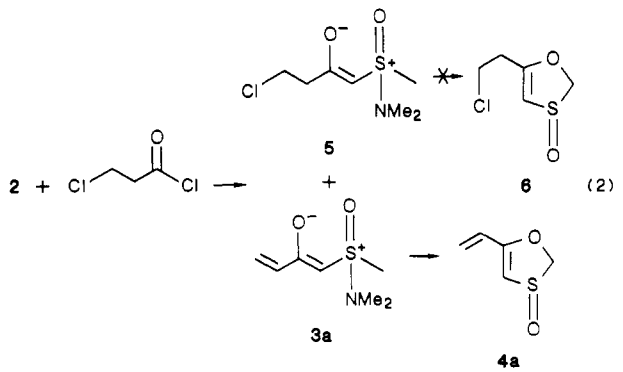
Johnson had previously demonstrated[7] that ylides **3** derived from acylation of (dimethylamino)methyloxosulfonium methylide (**2**) with acid chlorides cyclize in the presence of anhydrous $CuSO_4$ to yield 5-substituted 1,3-oxathiole-3-oxides **4** in good yield (eq 1). Although 5-



**2** **3** **4** (1)

alkenyl-substituted 1,3-oxathiole 3-oxides were not included in this original report,[7] we have found that the Johnson synthesis can be employed to provide ready access to this class of heterosubstituted 1,3-dienes. Our results are summarized in Table I. The reaction of **2** with $\alpha,\beta$-unsaturated acid chlorides was instantaneous at −78 °C and yielded unsaturated ylides **3a–i** as hygroscopic oils, which, in most cases, were impossible to obtain in anhydrous form. The oxygen-substituted ylides **3e**, **3f**, and **3i** were particularly prone to decomposition during isolation, thus necessitating rapid chromatographic purification. Cyclization of the unsaturated ylides at 80 °C in the presence of anhydrous $CuSO_4$ proceeded without incident to give, after quick filtration of the crude material through alumina, the corresponding dienes **4a–i** in good yields.

Attempts to prepare the parent ylide of this class, **3a**, from acryloyl chloride and oxosulfonium methylide **2** were not successful, since reaction of these components afforded only traces of **3a** and copious amounts of polymer. Alternatively, 3-chloropropionyl chloride was found to react smoothly with **2**, giving the chloro-substituted ylide **5** in 68% yield. Initial attempts to cyclize **5** gave intractable mixtures with no trace of the expected oxathiole 3-oxide **6**. However, analysis of the reaction mixture at short



**5** **6** **3a** **4a** (2)

reaction times did reveal the presence of **3a**, suggesting that **5** was decomposing, presumably by loss of HCl, under the reaction conditions. The known acid lability[7] of oxa-

(1) See, e.g.: Desimoni, G.; Tacconi, G.; Bario, A.; Pollini, G. P. *Natural Product Syntheses Through Pericyclic Reactions*; ACS Monograph 180; American Chemical Society: Washington, DC, 1984; Chapter 5.

(2) For reviews, see: Petrazilka, M.; Grayson, J. I. *Synthesis* **1981**, 753. Danishefsky, S. *Acc. Chem. Res.* **1981**, *14*, 400.

(3) Recent leading references as well as a discussion of models for predicting regioselectivity in cycloadditions of heterosubstituted dienes can be found in Kahn, S. D.; Pau, C. F.; Overman, L. E.; Hehre, W. J. *J. Am. Chem. Soc.* **1986**, *108*, 7381.

(4) See: Fisher, M. J.; Kahn, S. D.; Hehre, W. J.; Overman, L. E. *J. Am. Chem. Soc.*, in press.

(5) Cohen, T.; Mura, A. J.; Shull, D. W.; Fogel, E. R.; Ruffner, R. J.; Falck, J. R. *J. Org. Chem.* **1976**, *41*, 3218. Trost, B. M.; Ippen, J.; Vladuchick, W. C. *J. Am. Chem. Soc.* **1977**, *99*, 8116. Trost, B. M.; Vladuchick, W. C.; Briges, A. G. *Ibid.* **1980**, *102*, 3554. Cohen, T.; Kosarych, Z. *J. Org. Chem.* **1982**, *47*, 4008.

(6) Dienes containing acylamino and sulfinyl substituents have received some attention: Overman, L. E.; Petty, C. B.; Ban, T.; Huang, G. *J. Am. Chem. Soc.* **1983**, *105*, 6335.

(7) Johnson, C. R.; Rogers, P. E. *J. Org. Chem.* **1973**, *38*, 1793, 1798.

0022-3263/88/1953-2630$01.50/0 

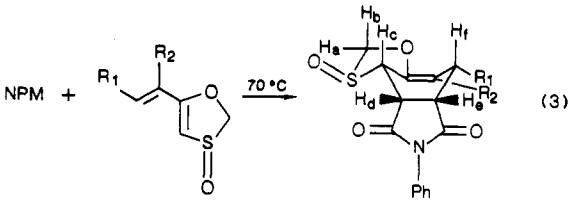
**Table I. Preparation of Ylides 3 and 5-Alkenyl-1,3-oxathiole 3-Oxides 4**

| | compd R | ylide 3 yield, % | diene 4 yield, % | diene 4 mp, °C |
|---|---|---|---|---|
| a | $CH_2$=CH | 30[a] | 69 | [b] |
| b | (*E*)-PhCH=CH | 85 | 69 | 108–109.5 |
| c | (*E*)-$CH_3$CH=CH | 60 | 85 | 85.5–87 |
| d | $CH_2$=CMe | 87 | 77 | [b] |
| e | (*E*)-EtOCH=CH | 51 | 93 | [b] |
| f | (*E*)-MeOCH=CMe | 42 | 74 | 86–88 |
| g |  | 74 | 84 | 118–120 |
| h | $CH_2$=C(OMe) | 50 | 76 | 77–78 |
| i |  | 49 | 73 | 112–113 |

[a] From 2 and 3-chloropropionyl chloride. [b] An oil.

thiole 3-oxides would rationalize our inability to form 6 in this way. It was subsequently found that the desired ylide **3a** could be prepared in low yield (30%) by slow addition of 3-chloropropionyl chloride to a solution containing 3 equiv of 2 at 0 °C (see eq 2). Diagnostic[7] $^1$H and $^{13}$C NMR characterization data for the ylides 3 and dienes 4 prepared in this study are summarized in Tables II–IV.

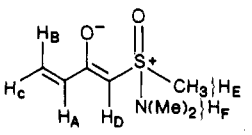
The Diels–Alder reactivity of the alkenyloxathiole 3-oxides 4 proved somewhat disappointing. For example, diene **4c** failed to give a cycloadduct when heated with neat acrolein at 80 °C or when heated at 100 °C with the pyrrolidine enamine of cyclopentanone or the imine derived from benzaldehyde and *n*-butylamine. With the more reactive electron-deficient dienophile *N*-phenylmaleimide (NPM), **4a–g** reacted smoothly at 70–80 °C to give, in each case, a single cycloadduct in good yield (see eq 3 and Table V). The stereostructure of **7c** was unambiguously established by single-crystal X-ray analysis, the details of which have been published elsewhere.[4] That the other adducts also resulted from endo cycloaddition from




(3)

7

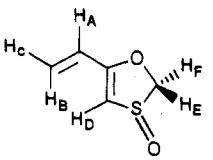
**Table II. $^1$H NMR Data for Ylides 3**



| compd | $^1$H NMR data[a,b] $H_A$ | $H_B$ | $H_C$ | $H_D$ | $H_E$ | $H_F$ | other |
|---|---|---|---|---|---|---|---|
| 3a | 6.25 [m] | 6.05 [m] | 5.4 [m] | 4.34 [s] | 3.49 [s] | 2.91 [s] | |
| 3b | 6.58 [d (15.3)] | 7.5–7.4 [m] | | 4.48 [s] | 3.51 [s] | 2.92 [s] | Ph, 7.3 [m] |
| 3c | 5.98 [d (15.3)] | 6.84 [dq (15.5, 6.9)] | | 4.22 [s] | 3.47 [s] | 2.89 [s] | Me, 1.82 [dd (6.86, 1.89)] |
| 3d | | 5.2 [m] | 5.69 [s] | 4.50 [s] | 3.46 [s] | 2.73 [s] | Me, 1.91 [m] |
| 3e | 5.41 [d (12.4)] | 7.39 [d (12.4)] | | 4.10 [s] | 3.46 [s] | 2.90 [s] | OEt, 3.89 [q (7.06)], 1.32 [t (7.06)] |
| 3f | | 7.07 [d (1.18)] | | 4.30 [s] | 3.46 [s] | 2.90 [s] | OMe, 3.76 [s] Me, 1.75 [s] |
| 3g | | 6.45 [m] | | 4.42 [s] | 3.47 [s] | 2.91 [s] | $CH_2CH_2CH_2$, 2.56–2.41 [m], 2.0–1.9 [m] |
| 3h | | 4.87 [s] | 5.25 [d (2.0)] | 4.23 [s] | 3.47 [s] | 2.91 [s] | OMe, 3.63 [s] |
| 3i | | 7.4 [s] | | 4.26 [s] | 3.49 [s] | 2.98 [s] | $OCH_2CH_2CH_2$, 4.0 [t (5.27)], 2.29 [m], 1.90 [m] |

[a] Chemical shift in δ; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet (*J* in Hz). [b] In $CDCl_3$. Spectra recorded at 250 or 300 MHz.

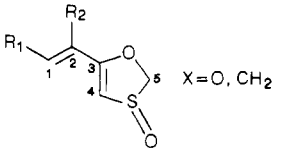
**Table III. $^1$H NMR Data for Dienes 4**



| compd | $^1$H NMR Data[a,b] $H_A$ | $H_B$ | $H_C$ | $H_D$ | $H_E$ | $H_F$ | other |
|---|---|---|---|---|---|---|---|
| 4a | 6.38 [dd (17.4, 10.8)] | 6.05 [dd (17.4, 0.7)] | 5.69 [d (11, 0.7)] | 6.24 [s] | 4.89 [d (11.4)] | 5.40 [d (11.4)] | |
| 4b | 6.59 [d (16.0)] | 7.20 [m] | | 6.19 [s] | 4.86 [d (11.2)] | 5.35 [d (11.2)] | Ph, 7.41–7.20 [m] |
| 4c | 6.08 [dd (15.6, 1.4)] | 6.59 [dq (15.6, 6.95)] | | 6.08 [s] | 4.86 [d (11.3)] | 5.35 [d (11.3)] | Me, 1.91 [dd (6.9, 1.4)] |
| 4d | | 5.44[c] [m] | 5.84[c] [m] | 6.27 [s] | 4.89 [d (11.2)] | 5.40 [d (11.2)] | Me, 2.01 [m] |
| 4e | 5.4 [d (12.5)] | 7.28 [d (12.5)] | | 5.96 [s] | 3.96 [d (11.2)] | 4.87 [d (11.2)] | OEt, 3.94 [q (7.1)], 1.35 [t (7.1)] |
| 4f | | 6.97 [d (1.43)] | | 6.01 [s] | 4.84 [d (11.2)] | 5.33 [d (11.1)] | OMe, 3.81 [s], Me, 1.80 [s] |
| 4g | | 6.50 [m] | | 6.12 [s] | 4.89 [d (11.2)] | 5.38 [d (11.2)] | $CH_2CH_2CH_2$, 2.58 [m], 2.00 [m] |
| 4h | | 4.57 [d (3.0)] | 5.01 [d (3.0)] | 6.53 [s] | 4.88 [d (11.8)] | 5.40 [d (11.2)] | OMe, 3.68 [s] |
| 4i | | | 7.33 [s] | 5.98 [s] | 4.87 [d (11.4)] | 5.36 [d (11.4)] | $OCH_2CH_2CH_2$, 4.11 [m], 2.00 [m], 2.2 [m] |

[a] Chemical shift in δ; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet (*J* in Hz). [b] In $CDCl_3$. Spectra recorded at 250 or 300 MHz. [c] Assignments may be reversed.

Table IV. $^{13}C$ NMR Data for Dienes 4 and 9

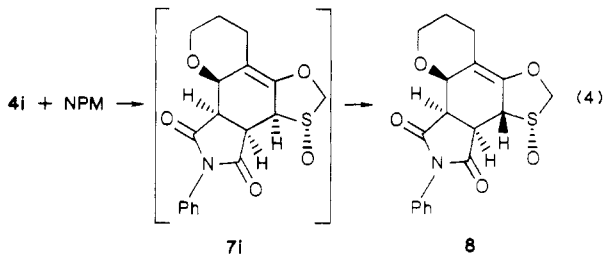



| | $^{13}C$ chemical shift[a] | | | | |
|---|---|---|---|---|---|
| compd | C-1 | C-2 | C-3 | C-4 | C-5 |
| **4a** | 125.3 | 124.5 | 164.9 | 105.9 | 90.7 |
| **4b** | 139.3 | 114.8 | 165.5 | 105.5 | 90.8 |
| **4c** | 138.3 | 118.9 | 165.4 | 103.4 | 90.6 |
| **4d** | 122.1 | 132.0 | 167.3 | 103.9 | 90.5 |
| **4e** | 157.0 | 94.0 | 166.2 | 100.7 | 90.7 |
| **4f** | 153.9 | 103.5 | 169.0 | 99.7 | 90.6 |
| **4g** | 139.4 | 132.0 | 164.4 | 103.2 | 90.6 |
| **4h** | 90.8 | 151.1 | 162.9 | 104.1 | 90.4 |
| **4i** | 150.9 | 103.1 | 168.1 | 98.7 | 90.6 |
| **9** | 131.3[b] | 131.4[b] | 152.8 | 122.9 | |

[a] In $CDCl_3$; ppm from TMS. [b] Assignments may be reversed.

the face anti to the sulfinyl oxygen was readily established by virtue of the characteristic long-range coupling observed between the bridgehead hydrogen $H_c$ and the cis hydrogen of the methylene group of the oxathiole 3-oxide ring. The signal at lower field ($\delta$ 5.11–5.44, see Table V), which can confidently[7,8] be assigned to the hydrogen cis to the sulfoxide oxygen ($H_b$), showed a coupling of 0.9–1.2 Hz to $H_c$. This long-range coupling between $H_b$ and $H_c$ is consistent *W* coupling[9] between these hydrogens and establishes the cis relationship between $H_b$, $H_c$, and the oxygen of the sulfinyl group.

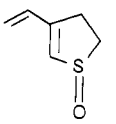
Diene **4i** also reacted with NPM at 70 °C to give initially the cycloadduct arising from endo addition anti to the sulfoxide oxygen, since the $^1H$ NMR (500 MHz) spectrum of the crude product displayed a diagnostic dd at $\delta$ 5.10 ($J$ = 1.5, 9.5 Hz) for $H_b$ of adduct **7i**. This initial adduct isomerized upon standing in the reaction medium at 70 °C, or upon chromatography, to give **8** (see eq 4). The




**7i** **8**

stereostructure for **8** followed directly from $^1H$ NMR homonuclear decoupling and chemical shift data. Signals at $\delta$ 5.14 and 4.90 are characteristic for the diastereotopic methylene hydrogens of the oxathiole 3-oxide ring of **8**. The signal at higher field appeared as a dd with coupling constants of 9.5 and 0.65 Hz. The methine hydrogen $\alpha$ to the sulfoxide ($H_c$) was observed at $\delta$ 2.93, almost 0.8 ppm upfield from its characteristic position in adducts **7**. This unusual upfield shift coupled with the fact that the long range *W* coupling now appears in the methylene proton anti to the sulfoxide oxygen suggests that **8** is the product of epimerization at the methine hydrogen $\alpha$ to the sulfinyl group. Of the adducts prepared in this study, **8** was the only one for which this epimerization was rapid. The origin of the high anti face selectivity in cycloadditions of dienes **4** with NPM is discussed in detail elsewhere[4] and likely derives from destabilizing electrostatic repulsions between the sulfinyl oxygen and the carbonyl oxygen of the imide dienophile.

To pursue in a more quantitative fashion the effect on Diels–Alder reactivity of the oxygen substituent[10] of the oxathiole ring, a competition experiment was conducted with **4a** and sulfinyl diene **9**. This experiment demonstrated that, with respect to NPM, **4a** was less reactive by a factor of 16 than **9**, indicating that the oxygen substituent of the heterocyclic ring was, somewhat surprisingly, *decreasing cycloaddition reactivity*. The $^{13}C$ NMR data for dienes **4a** and **9** (see Table V) confirm[11] the expectation that **4a** is more electron-rich than diene **9**, which lacks the oxygen substituent. For example, the terminal carbons of **4a** are observed at 106 and 125 ppm, while these carbons of **9** are observed at 123 and 131 ppm from TMS. The difference in reactivity of **4a** and **9** is, therefore, not predicted by simple FMO analysis[12] of cycloaddition reactivity. One possible rationalization for the low cycloaddition reactivity of the 5-alkenyl-1,3-oxathiole 3-oxides **4** would focus on the conjugation of the oxygen and sulfinyl groups (the vinylogous sulfinic ester grouping)[13] which is lost upon cycloaddition of **4**.




**9**

It also merits note that we were unsuccessful in accomplishing the cycloaddition of NPM with diene **4h**, which contains a second oxygen substitution on the diene framework. For example, attempted reaction of **4h** with NPM at 70 °C for 30 h gave only traces of cycloadduct ($^1H$ NMR analysis), while longer reaction times (up to 3 weeks at 70 °C) or higher temperatures (100 °C for 5 days) led only to the decomposition of the diene. The initially puzzling lack of reactivity of **4h** has some precedent. For example, McDonald and co-workers[14] have reported that 2,3-dimethoxy-1,3-butadiene and 3,4-dimethoxyfuran are considerably less reactive than 1-acetoxy-1,3-butadiene in cycloaddition reactions with electron-deficient olefins. To our knowledge, the low reactivity of electron-rich dienes of this type is not rationalized by any current analysis of Diels–Alder reactivity.[15]

## Conclusion

5-Alkenyl-1,3-oxathiole 3-oxides are available in two steps and in useful yields from $\alpha,\beta$-unsaturated acid chlorides. These heterocycles represent the first examples of heterosubstituted dienes endowed with both oxygen and sulfoxide substitution. These diheterosubstituted dienes react with high anti face selectivity with the reactive dienophile *N*-phenylmaleimide to provide cycloadducts

(8) Cooper, R. G. D.; DeMarco, P. V.; Cheng, J. C.; Jones, N. D. *J. Am. Chem. Soc.* **1969**, *91*, 1408.

(9) Jackman, L. M.; Sternhell, S. *Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry*; Pergamon: New York, 1978; pp 334–341.

(10) Oxygen substituents directly attached to the diene framework typically[2] enhance Diels–Alder reactivity.

(11) See, e.g.: Kajimoto, O.; Fueno, T. *Tetrahedron Lett.* **1972**, 3329.

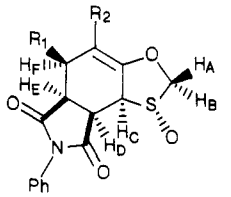
(12) See, e.g.: Fleming, I. *Frontier Orbitals and Organic Chemical Reactions*; Wiley: New York, 1976; pp 110–114.

(13) We are unaware of experimental or theoretical estimates of the delocalization energy of sulfinate esters.

(14) McDonald, E.; Suksamrarn, A.; Wylie, R. D. *J. Chem. Soc. Perkin Trans 1* **1979**, 1893.

(15) A possible explanation is that dipole interactions (i.e., of the vicinal C–O bonds) favor an s-trans conformation for **4h**. As pointed out by McDonald,[14] this explanation would not rationalize the low reactivity of 3,4-dimethoxyfuran.

**Table V. Preparation and Diagnostic $^1H$ NMR Characterization Data for Cycloadducts 7 and 8**




| cycloadduct | | | | time, | yield, | $^1H$ NMR data[b,c] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| compd | $R^1$ | $R^2$ | mp, °C | h[a] | % | $H_A$ | $H_B$ | $H_C$ | $H_D$ | $H_E$ | $H_F$ |
| **7a** | H | H | 178–180 | 168 | 89 | 4.62 [d (9.6)] | 5.14 [dd (9.6, 1.3)] | 3.63 [m] | 4.18 [dd (8.8, 5.5)] | 3.28 [m] | 2.45 [m] |
| **7b** | Ph | H | 222.5–223 | 168 | 87 | 4.90 [d (9.5)] | 5.2 [dd (9.5, 1.0)] | 3.77 [m] | 4.24 [dd (8.9, 5.9)] | 3.54 [t (8.4)] | 3.95 [ddd (8.2, 2.64, 2.63)] |
| **7c** | $CH_3$ | H | 209.5–210 | 168 | 75 | 4.74 [d (9.5)] | 5.13 [dd (9.5, 1.0)] | 3.60 [m] | 4.16 [dd (8.6, 5.2)] | 3.24 [t (8.0)] | 2.7 [m] |
| **7d** | H | $CH_3$ | 194–196 | 168 | 95 | 4.52 [d (9.6)] | 5.11 [dd (9.6, 1.3)] | 3.60 [m] | 4.11 [dd (8.9, 5.5)] | 3.86 [m] | 2.66 [m] |
| **7e** | OEt | H | 202.5–203.5 | 12 | 48 | 4.87 [d (9.5)] | 5.15 [dd (9.5, 1.0)] | 3.50 [m] | 4.15 [dd (8.4, 4.9)] | 4.00 [t (8.3)] | 4.39 [ddd (8.3, 2.07, 2.06)] |
| **7f** | OMe | $CH_3$ | 196–198 | 12 | 75 | 4.75 [d (9.5)] | 5.11 [dd (9.5, 1.0)] | 3.50 [s] | 4.09 [dd (8.7, 4.0)] | 3.74 [t (8.2)] | 4.15 [m] |
| **7g** | $CH_2CH_2CH_2$ | | 211.5–212 | 36 | 82 | 4.75 [d (9.4)] | 5.11 [dd (9.4, 1.8)] | 3.61 [m] | 4.16 [dd (8.9, 4.8)] | 3.74 [t (8.2)] | 2.9 [m] |
| **8** | | | | 72 | 69 | 4.93 [dd (11.5, 0.6)] | 5.44 [d (11.5)] | 2.94 [s] | 4.15 [dd (8.6, 2.2)] | 3.36 [dd (8.6, 3.5)] | 4.33 [dd (3.2, 2.7)] |

[a] 70 °C in toluene. [b] Chemical shift in δ; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet (*J* in Hz). [c] In $CDCl_3$. Spectra recorded at 500 MHz.

which contain potentially useful enol ether and sulfoxide functionality.

## Experimental Section[16]

**(Dimethylamino)methyloxosulfonium [1-Oxo-2-propenyl]methylide (3a).** (Dimethylamino)dimethyloxosulfonium fluoroborate (0.497 g, 2.38 mmol)[7] was placed in a flame-dried flask and dried by azeotroping with benzene (2 × 10 mL). The resulting dry salt was suspended in THF (10 mL), degassed (3×), cooled to −78 °C, and deprotonated with *n*-BuLi (1.00 mL of a 2.30 M solution in hexanes, 2.30 mmol). This mixture was stirred at −78 °C for 0.25 h and then allowed to warm to 0 °C. 3-Chloropropionyl chloride (0.097 g, in 0.75 mL of THF, 0.768 mmol) was then added slowly over a period of 5 min, and the resulting mixture was allowed to warm to room temperature. After 1 h at room temperature, the crude mixture was concentrated, dissolved in $CH_2Cl_2$ (50 mL), filtered, and reconcentrated. The crude material was purified by chromatography (silica gel 200–400 mesh, 50:1 $CH_2Cl_2$/EtOH) to give 50.0 mg (38%) of **3a** as a pure clear oil: $^1H$ NMR (250 MHz, $CDCl_3$) 6.25 (m, C*H*=$CH_2$), 6.05 (m, =C*H*H), 5.40 (m, =CH*H*), 4.34 (s, =CHSO), 3.49 (s, $CH_3SO$), 2.91 (s, $(CH_3)_2N$); IR (film) 1636, 1552, 1409, 1207, 1057, 683 $cm^{-1}$; MS (CI), *m/e* 176 ($MH^+$); MS (EI), *m/e* (relative intensity) 175.0666 (66, 175.0666 calcd for $C_7H_{13}NO_2S$), 148 (16), 133 (100), 132 (47).

**(Dimethylamino)methyloxosulfonium [(*E*)-1-Oxo-3-phenyl-2-propenyl]methylide (3b). Representative Procedure for Preparing Ylides 3.**[17] (Dimethylamino)dimethyloxosulfonium fluoroborate (~0.9 g) was placed in a flame-dried tared flask and dried by azeotroping with benzene (2 × 10 mL). The resulting dry salt (0.834 g, 3.99 mmol) was suspended in THF (15 mL), degasses (3×), cooled to −78 °C, and deprotonated with *n*-BuLi (2.10 mL of a 2.30 M solution in hexane, 3.90 mmol). This solution was maintained at −78 °C for 1 h, and then cinnamoyl chloride (0.316 g, in 2.60 mL of THF, 1.89 mmol) was added via syringe. The resulting solution was maintained at −78 °C for 0.5 h and then at room temperature for 1 h. The crude reaction mixture was concentrated, dissolved in $CH_2Cl_2$ (50 mL), filtered, and reconcentrated. The crude material was chromatographed (silica gel 240–400 mesh, 40:1 $CH_2Cl_2$–EtOH) to give 0.406 g (85%) of **3b** as a pale yellow oil: $^1H$ NMR (300 MHz, $CDCl_3$) 7.48–7.26 (m, 6 H), 6.58 (d, *J* = 15.7 Hz, C=CH), 4.48 (s, C=CHSO), 3.51 (s, $CH_3SO$), 2.92 (s, $(CH_3)_2N$); IR (film) 1638, 1553, 1203, 1105, 950, 933, 895, 763 $cm^{-1}$; MS (CI), *m/e* 252 ($MH^+$); MS (EI), *m/e* (relative intensity) 251.0966 (9, 251.0979 calcd for $C_{13}H_{17}NO_2S$), 193 (63), 131 (100), 115 (99).

**5-(2-Phenylethenyl)-1,3-oxathiole 3-Oxide (4b). Representative Procedure for Preparing Dienes 4.**[18] Anhydrous $CuSO_4$ (0.160 g, 0.992 mmol) was added to a solution of **3b** (0.124 g, 0.496 mmol) and toluene (20 mL). This mixture was maintained at 80 °C for 24 h and then allowed to cool to room temperature. The crude reaction mixture was filtered, and the collected copper salts were washed with $CH_2Cl_2$ (25 mL). The combined filtrate was concentrated, and the resulting crude product was chromatographed (alumina 70–230 mesh, activity II–III, $CHCl_3$), giving 70.0 mg (69%) of **4b** as a chromatographically pure pale yellow solid. An analytical sample was prepared by recrystallization from ether/pentane (mp 108–109.5 °C): $^1H$ NMR (250 MHz, $CDCl_3$) 7.41–7.27 (m, 5 H), 7.18 (d, *J* = 14.7 Hz, =C*H*Ph), 6.59 (d, *J* = 10.0 Hz, C=CH), 6.19 (s, =CHS), 5.35 (d, *J* = 11.2 Hz, OC*H*HS), 4.85 (d, *J* = 11.2 Hz, OCH*H*S); $^{13}C$ NMR (75 MHz, $CDCl_3$) 90.8, 105.5, 114.8, 127.6, 129.0, 129.9, 134.9, 139.3, 165.5 ppm; IR (KBr) 1578, 1557, 1447, 1203, 1040, 1019, 759, $cm^{-1}$; MS (CI), *m/e* 207 ($MH^+$); MS (EI), *m/e* (relative intensity) 206.0405 (20, 206.0401

(16) General experimental details: Tetrahydrofuran (THF) and $Et_2O$ were distilled from Na and benzophenone. Dimethylformamide (DMF) was distilled from $CaH_2$ at 20 mm, while $CH_2Cl_2$, benzene, toluene, and diisopropylamine were distilled from $CaH_2$ at atmospheric pressure. The molarities indicated for organolithium reagents were established by titration with 2,5-dimethoxybenzyl alcohol.[20] $^1H$ NMR and $^{13}C$ NMR were measured at 250 and 63, 300 and 75, and 500 and 125 MHz, respectively, with a Bruker WM-250 spectrometer, Nicolet QE-300 spectrometer, or a Nicolet GN-500 spectrometer. $^1H$ NMR chemical shifts are reported as δ values in ppm relative to TMS. $^1H$ NMR coupling constants are reported in Hz and refer to apparent multiplicities and not true coupling constants. Multiplicity is indicated as follows: s (singlet); d (doublet); t (triplet); q (quartet); m (multiplet); app d (apparent doublet); app t (apparent triplet); dd (doublet of doublets); etc. High-resolution mass spectra were measured on a VG Analytical 7070E spectrometer. Low-resolution mass spectra were measured on a Finnigan 4000 GC/MS/DS spectrometer. Infrared spectra were recorded with a Perkin-Elmer 283 spectrometer or a Nicolet 5DBX FTIR spectrometer. Microanalyses were performed by Atlantic Microlabs, Atlanta, GA. TLC and column chromatography were done with E. Merck silica gel. Radial chromatography was done with a Harrison Research Chromatotron. All reactions were run under an argon atmophere and concentrations were performed under reduced pressure with a Büchi rotary evaporator.

(17) Ylides **3c–i** were prepared following this general procedure.

(18) Dienes **4a–i** were prepared following this general procedure.

calcd for $C_{11}H_{10}O_2S$), 128 (100), 115 (43) 77 (20).

**(1*R**,5*S**,5a*S**,8a*R**,8b*S**)-5,5a,6,8,8a,8b-Hexahydro-6,8-dioxo-5,7-diphenyl-2*H*,7*H*-3-oxa-1-thia-7-aza-*as*-indacene *S*-Oxide (7b). Representative Procedure for Preparing Cycloadducts 7.**[19] A solution of NPM (23.0 mg, 0.131 mmol), **4b** (27.0 mg, 0.131 mmol), and toluene (0.13 mL) was maintained at 70 °C for 7 days. The reaction mixture was allowed to cool to room temperature, concentrated, and the resulting crude material was chromatographed (silica gel 240-400 mesh, 30:1 $CH_2Cl_2$/EtOH) to give 43.0 mg (87%) of **7b** as a pale yellow solid. An analytical sample was prepared by recrystallization from *i*-PrOH, giving **7b** as a fine yellow powder (mp 222.5-223.0 °C): $^1$H NMR (500 MHz, $CDCl_3$) 7.5-7.1 (m, PhH), 5.64 (dd, $J$ = 2.9, 5.8 Hz, =CH), 5.20 (dd, $J$ = 1.0, 9.5 Hz, OC*H*HSO), 4.90 (d, $J$ = 9.5 Hz, OCH*H*SO), 4.24 (dd, $J$ = 5.1, 8.9 Hz, OCCHCSO), 3.95 (ddd, $J$ = 8.2, 2.64, 2.63 Hz, C*H*Ph), 3.77 (m, CHSO), 3,54 (t, $J$ = 8.4 Hz, OCC*H*CHPh); $^{13}$C NMR (125 MHz, $CDCl_3$) 42.4, 43.4, 45.6, 67.5, 91.6, 99.7, 125.8, 127.8, 128.5, 128.7, 128.9, 129.2, 131.0, 137.9, 154.9, 173.3, 176.3 ppm; IR (KBr) 1704, 1498, 1389, 1207, 1166, 1151, 1047, 1003 cm$^{-1}$; MS (CI), $m/e$ 380 ($MH^+$); MS (EI), $m/e$ (relative intensity) 379.0879 (1, 379.0878 calcd for $C_{21}H_{17}NO_4S$), 160 (54), 148 (100), 115 (47). Anal. Calcd for $C_{21}H_{17}NO_4S$: C, 66.48; H, 4.52; N, 3.69. Found: C, 66.21; H, 4.60; N, 3.69.

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(19) All cycloadducts were prepared following this general procedure.
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## The Regiospecific Pummerer-Like Introduction of Chlorine Atoms into Pyrrol-3-yl and Indol-3-yl Sulfoxides†

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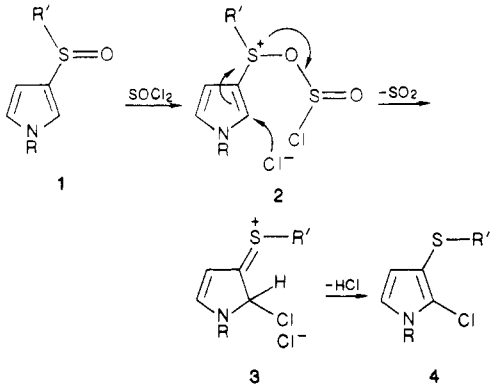
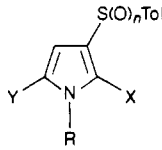
Recent work from this laboratory made available for the first time a general synthesis of pyrrol-3-yl sulfoxides from the corresponding 2-isomers by acid-catalyzed isomerization.[1] In subsequent studies of the chemistry of this novel class of compounds, we sought to exploit the known reactions of sulfoxides to introduce a substituent regiospecifically into the 2-position (e.g., chloro) and thus prepare 2,3-disubstituted pyrroles from pyrrole itself.

From the outset, we expected that in a Pummerer-like reaction[2] with thionyl chloride and the sulfoxide **1**, a sulfoxonium chloride **2** would be formed. With such an intermediate, *the only reasonable point of attack by Cl⁻ on the ring to enable the elimination of $SO_2$ would be the 2-position.* The sulfonium salt **3** upon loss of a proton would give the chloro sulfide **4**. In fact 3-(*p*-tolylsulfinyl)pyrrole (**5a**)[1] reacted virtually instantaneously at 0 °C with thionyl chloride to give a less polar compound, which, although reasonably stable in solution protected from oxygen, decomposed to tar upon attempted isolation. When the reaction was carried out in the presence of suspended sodium bicarbonate followed by excess *m*-chloroperoxybenzoic acid, the products were obtained as




the stable sulfones. Thus formed were 2-chloro-3-(*p*-tolylsulfonyl)pyrrole (**6a**) in 38% yield and 2,5-dichloro-3-(*p*-tolylsulfonyl)pyrrole (**7a**) in 10% yield. Likewise *N*-methyl-3-(*p*-tolylsulfinyl)pyrrole (**5b**) afforded similar yields of **6b** and **7b**. When the acid chloride was changed to oxalyl chloride and the reaction carried out at −78 °C, only traces of dichloropyrroles were observed and the monochlorosulfones were obtained in substantially higher yields (see Table I). Moreover, by limiting the quantity of oxidizing agent to 1.1 equiv, the corresponding 2-chloro-3-(*p*-tolylsulfinyl)pyrroles (**8**) were obtained as stable crystalline solids in good yields.




**5a**, R=H, X=Y=H, $n$=1
**b**, R=$CH_3$, X=Y=H, $n$=1
**c**, R=$CH_2Ph$, X=Y=H, $n$=1
**6a**, R=H, X=Cl, Y=H, $n$=2
**b**, R=$CH_3$, X=Cl, Y=H, $n$=2
**c**, R=$CH_2Ph$, X=Cl, Y=H, $n$=2
**7a**, R=H, X=Y=Cl, $n$=2
**b**, R=$CH_3$, X=Y=Cl, $n$=2
**8a**, R=H, X=Cl, Y=H, $n$=1
**b**, R=$CH_3$, X=Cl, Y=H, $n$=1
**c**, R=$CH_2Ph$, X=Cl, Y=H, $n$=1
**9a**, R=H, X=Cl, Y=H, $n$=0
**b**, R=$CH_3$, X=Cl, Y=H, $n$=0
**c**, R=$CH_2Ph$, X=Cl, Y=H, $n$=0

Though mechanistically reasonable, the structures of the chlorinated pyrroles **6** and **8** were easily confirmed by their NMR spectra (Table II), which all show the expected value for $J_{4,5}$ of 3.2 to 3.4 Hz. Entry of the chlorine atom at either of the other available positions would give instead a coupling constant of 1.35-1.80 Hz for $J_{2,4}$ or 1.95-2.30 Hz for $J_{2,4}$, which are well established values in the pyrrole series.[3] The origin of dichloropyrroles **7a** and **7b** is mechanistically less clear, but having suppressed their formation, we did not investigate them further.

The reaction was extended to indol-3-yl sulfoxides with analogous results in higher yields. Furthermore, due to their greater inherent stability, the indolyl sulfides **11** could be isolated and characterized as such, thus supporting the presumed identity of the initially formed products **9** in the pyrrole series. Some of the indole products were then

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