Reagent Design and Study of 1,4-Dithiins as a Promising Class of Reagents (Synthons) for Cycloaddition. Diels–Alder Reactions with Anthracene Derivatives via Charge-Transfer Complexes

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Abstract: Contrary to previous notions, 1,4-dithiin and derivatives are suggested to readily take on a planar structure based on MO calculations and on cyclic conjugation theory. Cycloaddition reactions of 1,4-dithiintetracarboxylic *N,N'*-dimethyldiimide (**5**) and dianhydride (**6**) with various anthracene derivatives have been investigated. These derivatives react smoothly with electron-rich anthracenes via charge-transfer complexes to give Diels–Alder adducts in high yields. In contrast, **5** reacts slowly with electron-deficient 9-anthraldehyde to afford an adduct without passing through a charge-transfer complex. The reaction of **5** with acridine gives a stable 1:1 complex, which does not change further to give an adduct. Kinetic study of these reactions clarified the remarkable effects of substituents, reagent concentration, and solvents. The mechanisms of these reactions are discussed on the basis of kinetic observations and in terms of the frontier molecular orbital theory.

A new concept of cyclic conjugation reported recently by Inagaki and Hirabayashi[2] as a modification of the Hückel rule[3] has proven useful as a general method of predicting thermal stabilities and electronic properties of unsaturated cyclic organic molecules. According to this theory, the degree of cyclic electron delocalization of unsaturated ring systems, which are composed of donor (D) and acceptor (A) units, depends on the mode of D–A arrangements as well as on orbital phase continuity requirements.[4,5] Thus, cyclic conjugation is first classified into *continuous* and *discontinuous* according to whether D's and A's are connected together along the conjugation chain like **2** and **3** or whether D's and A's alternate like **1** and **4** (Chart I). The continuous conjugation is further classified as *electron delocalizing* and *electron localizing* depending on whether orbital phase continuity is retained (**1a**) or interrupted (**1b**; interruption is shown by an arrow). Therefore, the degree of electron delocalization decreases in the order continuous with electron delocalizing (aromatic) > discontinuous (nonaromatic and nonantiaromatic) > continuous with electron localizing (antiaromatic).[2]

We have been applying this concept to the design of reagents in pericyclic reactions on the assumption that the molecules belonging to the discontinuous or continuous with an electron-localizing system can be potential dienophiles. For example, *p*-benzoquinone (**1**, Chart I) has a discontinuous cyclic conjugation, and hence it can be a potential dienophile if the energy of the LUMO can be lowered (Figure 1). When this is done by introducing electron-withdrawing substituents as in *p*-benzoquinone-2,3-dicarboxylic anhydride (**2**, X = O)[6] and *N*-phenylimide (**2**, X = NPh)[6] and naphthodiquinone (**3**),[7] their reactivities in cycloaddition are remarkably improved.[6,7]

As a part of our systematic study of reagent design by frontier molecular orbital (FMO) control, 1,4-dithiin (**4**)[8] was chosen as a target structure for elaboration to a potential dienophile. In **4**, cyclic conjugation is again discontinuous.[2] The studies on the

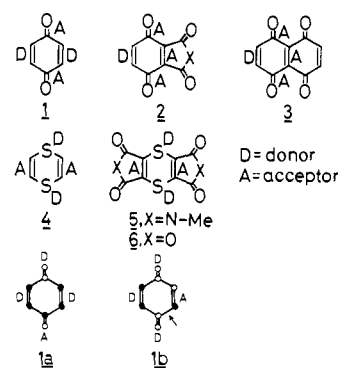## Chart I

D = donor
A = acceptor

5, X = N–Me
6, X = O

Table I. Calculations of 1,4-Dithiin (4) in Boat Conformation: Pucker Angle (θ) and Energy Relative to Planar Conformation

computation method	θ, deg[a]	$E_{boat} - E_{planar}$, kcal/mol	ref
HMO	132	−6.4	19
EHT[b]	140	−2.16	20
STO-3G[b]	131	−14.6	21
STO-3G/gradient[c]	153.0	0.02	this work[d]
MNDO/FP[c,e]	162.7	0.38	this work[f]

[a] X-ray analysis[17,18] gave 137 ± 2°. [b] Geometry obtained by partial optimization. [c] Complete geometry optimization. [d] See note 22b. [e] Fletcher–Powell energy minimization algorism. [f] See note 23h.

cycloaddition reaction have been hampered by the low thermal stability of **4**.[9,10] Dithiin (**4**) and its derivatives generally undergo thermal extrusion of sulfur to give corresponding thiophene derivatives.[11-15] Nevertheless, Draber[16] observed that 1,4-dithi-

(1) (a) Kyushu University. (b) Hokkaido University.
(2) Inagaki, S.; Hirabayashi, Y. *J. Am. Chem. Soc.* **1977**, *99*, 7418.
(3) Hückel, E. *Z. Phys.* **1931**, *70*, 204; **1932**, *76*, 628.
(4) Fukui, K.; Inagaki, S. *J. Am. Chem. Soc.* **1975**, *97*, 4445.
(5) Inagaki, S.; Fujimoto, H.; Fukui, K. *J. Am. Chem. Soc.* **1976**, *98*, 4693.
(6) Kanematsu, K.; Morita, S.; Fukushima, S.; Ōsawa, E. *J. Am. Chem. Soc.* **1981**, *103*, 5211.
(7) Yoshino, S.; Hayakawa, K.; Kanematsu, K. *J. Org. Chem.* **1981**, *46*, 3841.
(8) Parham, W. E.; Wynberg, H.; Ramp, F. L. *J. Am. Chem. Soc.* **1953**, *75*, 2065.

(9) Kobayashi, K.; Mutai, K. *Chem. Lett.* **1977**, 1149.
(10) Fanghänel, E.; Poleschner, H. *J. Prakt. Chem.* **1981**, *323*, 1.
(11) Simmons, H. E.; Vest, R. D.; Blomstrom, D. C.; Roland, J. R.; Carins, T. L. *J. Am. Chem. Soc.* **1962**, *84*, 4746.
(12) Parham, W. E.; Mayo, G. L. O.; Gadsby, B. *J. Am. Chem. Soc.* **1959**, *81*, 5993.
(13) Scherer, O.; Kluge, F. *Chem. Ber.* **1966**, *99*, 1973.
(14) Kobayashi, K.; Mutai, K. *Tetrahedron Lett.* **1979**, 5003; **1981**, 5201.
(15) Simmons, H. E.; Vest, R. D.; Vladuchick, S. A.; Webster, O. W. *J. Org. Chem.* **1980**, *45*, 5113.
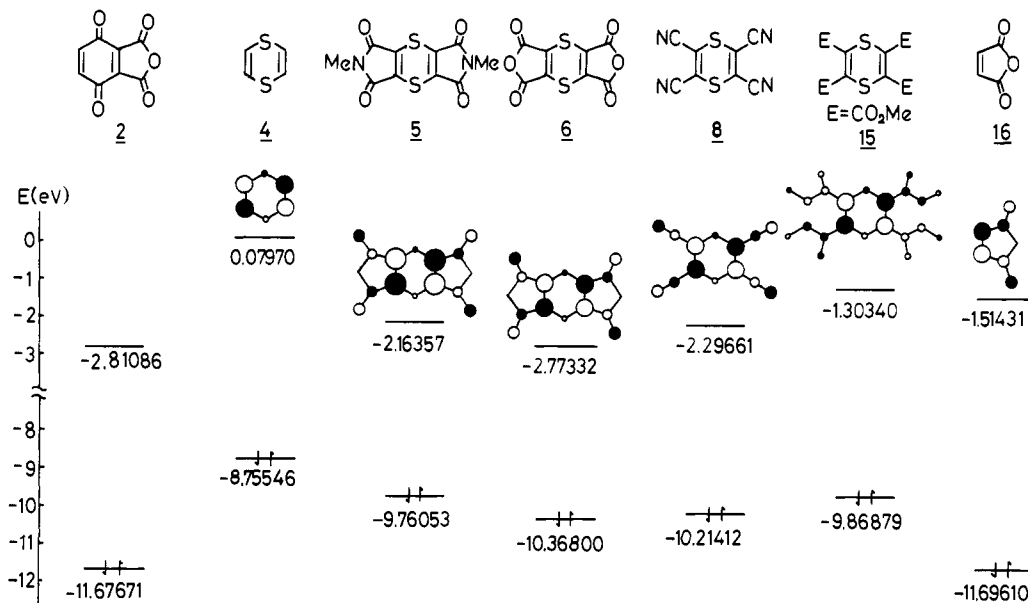(16) Draber, W. *Chem. Ber.* **1967**, *100*, 1559.

Figure 1. FMO energy levels by MNDO calculations.

intetracarboxylic N,N'-dimethyldiimide (**5**) and dianhydride (**6**) were thermally stable and formed adducts with anthracene. We have now analyzed the frontier molecular orbitals of **4**, **5**, **6**, and related molecules and have thoroughly investigated cycloaddition reactions of **5** and **6** with anthracene derivatives.

Results

Theoretical Expectations. We start by considering the molecular conformation of the 1,4-dithiin ring system, since there appears to have been some confusion on this problem that directly pertains to the nature of cyclic conjugation in the ring. An X-ray analysis of **4** has revealed a boat structure with a dihedral angle (θ) between the two SCCS planes of 137 ± 2°.[17,18] Previous
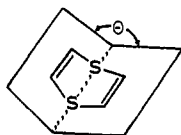
theoretical calculations by HMO[19] and EHT[20] claimed to have agreed with the X-ray results, finding the boat structure as an energy minimum, although the energy separations from the planar structure obtained in these calculations are insignificantly low (Table I). Recent ab initio calculations at the STO-3G level reported the highest energy separation (−14.6 kcal/mol) between the two conformations.[21] However, our recalculations of **4** with STO-3G basis set including gradient geometry optimization[22] and with Dewar's MNDO including Fletcher–Powell minimization[23]

Chart II
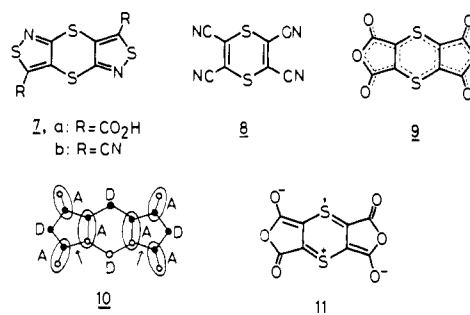
indicate that the boat and planar conformations have virtually identical energies (Table I).[24,51]

Recent experimental evidence does not support the predominance of boat structure: both determinations of ^{1}H NMR coupling constants in nematic phase[25,26] and ultraviolet photoelectron spectroscopy[27] failed to choose between a boat and planar structure in **4**. Attempts to observe diastereomeric pairs of optically active alcohol esters of a tricyclic derivative of **4** (**7a**) (Chart II) by NMR and crystallization were unsuccessful.[28] Finally **7a** was found to exist in a planar conformation,[29] whereas **7b** was observed to be in a puckered (boat) structure[30] by recent X-ray analyses. All these facts clearly point to a nearly flat energy surface of the 1,4-dithiin ring. In the solid state, the ring should readily adapt to either structure, depending on the packing force. In solution and in the vapor phase, it is most likely that the ring rapidly oscillates between these structures.[31]

Vladuchick et al.[28] expressed a view similar to the above, but they regard **7** as antiaromatic and assert the origin of the high thermal stability of **7** to the large HOMO–LUMO separation. The 1,4-dithiin ring itself has long been believed to represent an

(17) Howell, P. A.; Curtis, R. M. Lipscomb, W. N. *Acta Crystallogr.* **1954**, *7*, 498.

(18) Parham, W. E.; Wynberg, H.; Hasek, W. R.; Howell, P. A.; Curtis, R. M.; Lipscomb, W. N. *J. Am. Chem. Soc.* **1954**, *76*, 4957.

(19) Kreevoy, M. M. *J. Am. Chem. Soc.* **1958**, *80*, 5543.

(20) Ray, N. K.; Narashimhan, P. T. *J. Mol. Struct.* **1967–1968**, *1*, 489.

(21) Galasso, V. *J. Mol. Struct.* **1981**, *85*, 159.

(22) (a) Komornicki, A.; Ishida, K.; Morokuma, K.; Ditchfield, R.; Conrad, M. *Chem. Phys. Lett.* **1977**, *45*, 595. (b) A program package IMSPAK by Morokuma et al. (Morokuma, K.; Kato, S.; Kitaura, K.; Ōmine, I.; Sakai, S.; Obara, S.) was used.

(23) (a) Dewar, M. J. S.; Thiel, W. *J. Am. Chem. Soc.* **1977**, *99*, 4899, 4907. (b) Thiel, W. *QCPE* **1978**, *12*, 353. (c) Parameters for sulfur atom: Dewar, M. J. S.; Mckee, M. L.; Rzepa, H. S. *J. Am. Chem. Soc.* **1978**, *100*, 3607. (d) Dewar, M. J. S.; Ford, G. P. *Ibid.* **1979**, *101*, 5558. (e) Davis, L. P.; Guidry, R. M.; Williams, J. R.; Dewar, M. J. S. *J. Comput. Chem.* **1981**, *2*, 433. (f) Thiel, W. *J. Am. Chem. Soc.* **1981**, *103*, 1413. (g) Engelke, R. *Chem. Phys. Lett.* **1981**, *83*, 151. (h) In our MNDO calculations, d orbitals of sulfur atom were not included.[23c] Recent ab initio gradient calculations of thiophene with 4-21 basis set augmented with polarization functions revealed little effects of the addition of d functions, except for C–S bond lengths: Cordell, F. R.; Boggs, J. E. *J. Mol. Struct.* **1981**, *85*, 163.

(24) Galsso[21] states that MIND/3 full geometry optimization of **4** gave a flattened structure.

(25) Long, R. C., Jr.; Goldstein, J. H. *J. Mol. Spectros.* **1971**, *40*, 632.

(26) Russell, J. *Org. Magn. Reson.* **1972**, *4*, 433.

(27) Colonna, F. P.; Distefano, G.; Galasso, V. *J. Electron Spectrosc. Relat. Phenom.* **1980**, *18*, 75.

(28) Vladuchick, S. A.; Fukunaga, T.; Simmons, H. E.; Webster, O. W. *J. Org. Chem.* **1980**, *45*, 5122.

(29) Teufer, G.; Gilmour, P.; Guggenberger, L. J., manuscript in preparation for *Acta Crystallogr.*

(30) Guggenberger, L. J.; Vladuchick, S. A. *Acta Crystallogr.*, in press.

(31) Radical anions of **4** and related molecules are suggested to take puckered forms: Eargle, D. H., Jr.; Ramos de Carvahlo, M. C. *J. Phys. Chem.* **1973**, *77*, 1716.

Table III. Yield and Spectral Data for Diels-Alder Adducts

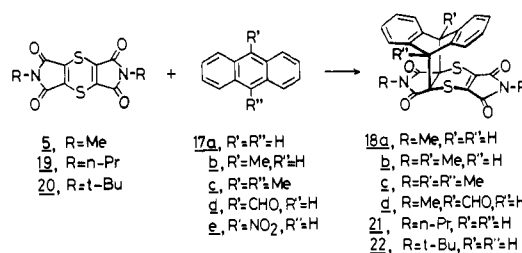| adduct	% yield[a]	mp, °C	IR,[b] cm⁻¹	UV,[c] λmax, nm (ε)	¹H NMR,[d] δ (J, Hz)	MS, m/e
18a	quant	285–288	1780, 1710, 1570	289 sh (4370), 412.5 (788)	7.38–7.06 (m, 8 H), 4.73 (s, 2 H), 2.82 (s, 3 H), 2.62 (s, 3 H)	460 (M⁺), 282, 178
18b	quant	266–271	1775, 1710, 1575	290 sh (4680), 415 (926)	7.38–7.07 (m, 8 H), 4.69 (s, 1 H), 2.84 (s, 3 H), 2.64 (s, 3 H), 2.36 (s, 3 H)	282, 192
18c	quant	269–272	1775, 1705, 1575	292 sh (4320), 417 (892)	7.38–7.08 (m, 8 H), 2.83 (s, 3 H), 2.62 (s, 3 H), 2.38 (s, 6 H)	282, 206
18d	97	216–219	1780, 1710, 1575	290 sh (4840), 407 (977)	11.0 (s, 1 H), 7.25–7.07 (m, 8 H), 4.72 (s, 1 H), 2.85 (s, 3 H), 2.71 (s, 3 H)	282, 206
21	90	270–272	1760, 1690, 1570	282 sh (5300), 412 (982)	7.42–7.04 (m, 8 H), 4.74 (s, 2 H), 3.40–3.02 (m, 4 H), 1.75–1.35 (m, 4 H), 1.10–0.40 (m, 6 H)	516 (M⁺), 338, 178
22	71	255–259	1770, 1703, 1595	284 sh (4590), 408 (942)	7.38–7.07 (m, 8 H), 4.72 (s, 2 H), 1.49 (s, 9 H), 1.21 (s, 9 H)	544 (M⁺), 366, 178
23a	91	260.5–261	1850, 1790, 1775, 1590		7.52–7.23 (m, 8 H), 4.80 (s, 2 H)	256, 178
23c	85	260–261	1850, 1785, 1775, 1595		7.52–7.25 (m, 8 H), 2.40 (s, 6 H)	256, 206

[a] All isolated yields.   [b] KBr plates.   [c] CHCl₃; sh = shoulder.   [d] CDCl₃.

antiaromatic 8π-electron system with a negative resonance energy,[32] and hence it was thought natural that **4** prefers a nonplanar conformation in order to avoid the destabilization present in the planar form. However, according to Inagaki's third-order perturbation theory,[2] the cyclic electron delocalization in **4** is discontinuous since the lone pairs of electrons on the sulfur atoms behave as donors and C=C bonds as acceptors which are alternately arranged. It is therefore not entirely surprising for **4** and derivatives to favor a planar conformation since the cyclic conjugation in this ring is "insignificant".[2]

The same theory probably applies to explain the observed, unexpectedly high thermal stabilities of 1,4-dithiin derivatives **5–7** and also **8**.[15] Stabilization due to tricyclic conjugation for **5–7**, as shown in **9**, wherein the 1,4-dithiin ring is incorporated in a polycondensed system, is excluded, since the phase continuity[5] is interrupted, as shown by an arrow in **10**. The local electron delocalization due to D–A interaction between a neighboring sulfur lone electron pair and a C=C bond will increase as the acceptor strength of the C=C bond is enhanced by the attachment of an electron-withdrawing substituent such as a carbonyl or cyano group without suffering from the Hückel rule or the phase continuity requirement. In other words, while the D–A interacting including its immediate substituent must be limted only between the neighboring pair as in **11** (one can draw several similar structures), the stabilization gained by such interactions should be considerably larger than one would have expected from the notion of short conjugation.[33–35]

Because of the extensive D–A interactions within the molecule and also because of the expected absence of antiaromaticity in

(32) Hess, B. A., Jr.; Schaad, L. J. *J. Am. Chem. Soc.* **1973**, *95*, 3907.
(33) In contrast, 1,2-dithiin (**12**)[34] is continuous with regards to cyclic

12

13, X = O
14, X = NR

electron delocalization,[2] and for this reason its antiaromatic instability will not be much affected by an electron-withdrawing substituent like **13** and **14**. These predictions regarding 1,2- and 1,4-dithiin derivatives will be an interesting challenge to experimental as well as theoretical verification.

(34) (a) Schroth, W.; Langguth, H.; Billig, F. *Z. Chem.* **1965**, *5*, 353. (b) Schroth, W.; Billig, F.; Reinhold, G. *Angew. Chem.* **1967**, *79*, 685.
(35) The effect of substituents on thermal stability was not apparent in the *p*-benzoquinone series (1–3) that we studied previously,[6] for two reasons: the C=C bond in this series is expected to act not as an acceptor but as a donor in the cyclic conjugation mode, and the *p*-benzoquinone ring is much more stable than 1,4-dithiin ring. This line of reasoning leads us to predict that oxides of 1,4-dithiin (mono- and disulfoxides and sulfones) will not acquire thermal stability by electronegative substituents, since SO and SO₂ groups are acceptors.

Scheme I

5, R=Me
19, R=n-Pr
20, R=t-Bu

17a, R'=R''=H
   b, R'=Me,R''=H
   c, R'=R''=Me
   d, R'=CHO, R''=H
   e, R'=NO₂, R''=H

18a, R=Me, R'=R''=H
   b, R=R'=Me, R''=H
   c, R=R'=R''=Me
   d, R=Me, R'=CHO, R''=H
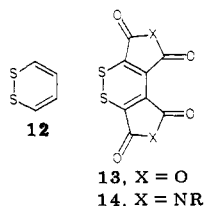**21**, R=n-Pr, R'=R''=H
22, R=t-Bu, R'=R''=H

4, electronegatively substituted derivatives, **5**, **6**, **8**, and tetracarboxylic acid tetramethyl ester (**15**), are expected to favor a planar conformation like **7a**. Draber[16] has suggested the planarity for **5** and **6** based on strong ultraviolet absorptions at long wavelength, thermal stability, and ability to form charge-transfer (CT) complexes. Our MNDO calculations of these derivatives starting from puckered structures with an initial θ angle of about 140° gave equilibrium geometries having the following θ values: **5**, 175.0°; **6**, 179.0°; **8**, 159.4°; **15**, 148.3°. All of these more or less flattened upon energy minimization. **5** and **6** are predicted to be nearly planar. The only exception is **15**, which still shows considerable puckering in the equilibrium geometry. Inspection of the structure indicates that the planes of ester groups (COOCH₃) are almost perpendicular to the SCCS planes, probably as the result of steric congestion between oxygen atoms of vicinal ester groups. The final molecular structure approximates a C_s point group as shown. The lack of conjugation between the dithiin ring and substituents in **15** leaves the inductive electron-withdrawing effect of carbonyl as the only driving force for flattening of the ring.


15   **16**

An additional merit of attaching electronegative substituents to **4** is the enhancement in dienophilic reactivity as a result of a lowered LUMO energy level.[36] Figure 1 illustrates the frontier molecular orbital levels and atomic coefficient schemes as obtained by MNDO calculations.[23h,37] LUMO's of **5**, **6**, **8**, and **15** are considerably lower than those of **4** and even of a typical dienophile, maleic anhydride (**16**). The lowest LUMO level is achieved by dianhydride **6** and is comparable to that of **2**, a highly reactive dienophile discovered in our previous study.[6] Methoxycarbonyl

(36) Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley: New York, 1976.
(37) See the Supplementary Material.

Chart III

23, a: R = H
c: R = CH₃

24

25
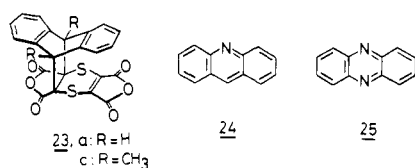
groups in **15** are not as effective as one would have expected apparently because of the noncoplanarity mentioned above. Like in **2** and **3**, the LUMO's of these dithiin derivatives have the largest coefficients at C_2 and C_3, the site of reaction in cycloaddition. Furthermore, the magnitude of LUMO coefficients at the carbonyl carbons are larger than at the sulfur atoms, and therefore exo-addition with respect to the dithiin ring due to the existence of secondary orbital interactions[36] is predicted in the reaction with dienes.

Thus, 1,4-dithiin derivatives **5**, **6**, and **8** seem to act as strong acceptors in CT complex formation and to possess high pericyclic reactivity with planar electron-rich dienes. These expectations are fully substantiated for **5** and **6** as described below.

Cycloaddition Reactions. When diimide **5** was allowed to react with anthracene (**17a**), 9-methylanthracene (**17b**), 9,10-di-methylanthracene (**17c**), and 9-anthraldehyde (**17d**) in refluxing benzene, the characteristic deep purple color[38] of **5** disappeared and corresponding 1:1 Diels–Alder adducts **18a–d** were obtained in quantitative yields (Scheme I). Structures of these crystalline adducts were determined on the basis of the elemental analysis and spectroscopic data which are summarized in Table III.

Mass spectra of these adducts hardly showed a molecular ion peak, and the prominent peaks correspond to the retro-Diels–Alder products, namely **5** (m/e 282) and anthracenes (base peak). IR spectra exhibited characteristic imide bands at 1770 and 1710 cm⁻¹, while ¹H NMR spectra clearly showed two N-methyl signals, one of them being shifted upfield as the result of shielding effect of the aromatic ring. N-n-Propylimide **19** and N-$tert$-butylimide **20**[38] similarly added to anthracene **17a** to give 1:1 Diels–Alder adducts **21** and **22** in 90% and 71% yields (Scheme I), respectively, although much longer reaction time was needed than in the reaction of **5**, probably because of increased steric demand in these higher analogues.

In accordance with the preliminary observation by Draber,[16] the reactions of 1,4-dithiins (**5**, **19**, **20**) with the electron-rich anthracenes (**17a–c**) proceed via CT complexes, as evidenced by remarkable color change in the course of reaction. Immediately after the start of reaction, a new absorption band appeared at 500–550 nm, and this CT band gradually disappeared as the reaction proceeded. Stable 1:1 complex could be isolated as a brown solid by brief treatment of **5** with **17a** in refluxing THF. The complex changed quantitatively into Diels–Alder adduct **18a** upon heating in benzene. In sharp contrast, the reaction of **5** with an electron-deficient anthracene (**17d**) proceeded without CT complex formation, since neither the remarkable color change nor the new absorption band was observed. These observations agree with kinetic data (vide infra). Highly electron-deficient 9-nitroanthracene (**17e**) did not react with **5** even under drastic conditions (150 °C, 48 h in a sealed tube), and the starting materials were recovered unchanged.

Dianhydride **6** behaved similarly to **5** in the reaction with anthracene derivatives. Thus, treatment of **6** with **17a** and **17c** in benzene at room temperature led to rapid formation of CT complexes with new UV absorption at 570–620 nm. These complexes could be isolated as brown solids having limited stabilities. On heating in benzene at 80 °C, these complexes gradually turned into corresponding Diels–Alder adducts **23a** and **23c** (Chart III) in 91% and 85% yields, respectively. Structures of these adducts, which are acid labile, were assigned on the basis of spectroscopic data (Table III).

Table IV. Second-Order Rate Constants for Cycloaddition of Diimide (**5**, 0.001 M) with Substituted Anthracenes (**17a–d**, ArH, 0.050 M) at 25.0 °C

ArH	solvent	k_2 M⁻¹ s⁻¹	k_{rel}
17a	CHCl₃	1.88 × 10⁻⁴ (0.337 × 10⁻⁴)ᵃ	1 (0.2)ᵃ
17b	CHCl₃	1.31 × 10⁻²	70
17b	C₆H₅Cl	4.76 × 10⁻³	25
17c	CHCl₃	6.19 × 10⁻² (0.0695 × 10⁻²)ᵃ	329 (3.7)ᵃ
17c	C₆H₅Cl	2.64 × 10⁻²	140
17dᵇ	C₆H₅Cl	2.96 × 10⁻⁶	0.037

ᵃ Maleic anhydride (**16**) as excess dienophile, 25.2 °C; ref 41.
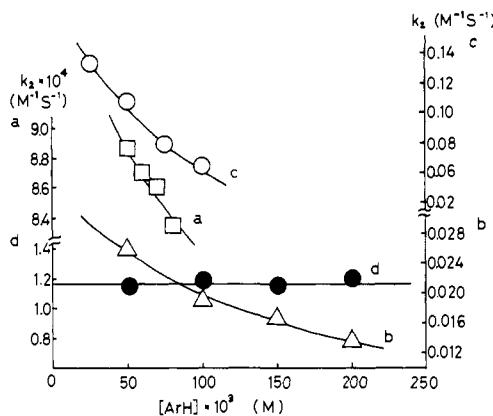ᵇ [**5**] = 0.014 M; [ArH] = 0.150 M.

Figure 2. Concentration dependence of the second-order rate constants k_2 (M⁻¹ S⁻¹) for the cycloaddition reactions of dithiin **5** with anthracene derivatives (ArH): (a) ArH = **17a**; 49.3 °C, CHCl₃ (upper left-hand ordinates, □), (b) ArH = **17b**; 33.9 °C, CHCl₃ (lower right-hand ordinates, Δ), (c) ArH = **17c**; 33.8 °C, CHCl₃ (upper right-hand ordinates, O), and (d) ArH = **17d**; 65.8 °C, C₆H₅Cl (lower left-hand ordinates, ●). The concentration of dithiin [D] is 0.001 M for a–c and 0.0143 M for concentration of dithiin [D] is 0.001 M for a–c and 0.0143 M for (d).

Reactions of **5** with the nitrogen-containing anthracene analogues acridine (**24**) and phenazine (**25**) have also been investigated. With an equimolar amount of **24** in chloroform at room temperature, **5** gave a highly colored complex as precipitate. Upon recrystallization from benzene, green prisms, mp 249 °C (dec), were obtained in 93% yield. Even when a large excess (5–10 molar equiv) of **24** was used, the same complex was obtained in 70–90% yield. Surprisingly high thermal stability of the complex was shown by the complete recovery of unchanged material from prolonged heating in toluene at 150 °C (sealed tube). The 1:1 nature of this complex is apparent from elemental analysis and ¹H NMR spectrum. The latter shows signals all attributable to **5** and **24** and hence clearly indicates that this product is not the Diels–Alder adduct. The UV spectrum contains only composite absorptions of the two components but no CT band. Therefore, the new complex was concluded to be a 1:1 compound with no significant charge transfer.[39] In contrast, attempted reaction of **5** with **25** under various conditions invariably resulted in the recovery of unchanged starting materials.

Kinetics. Rate measurements were conducted for the cyclo-addition reactions between **5** and **17a–c** always under large excess of dienes over dienophile. The reaction was followed by UV spectrometry, which showed continuous spectral change with isosbestic points. The pseudo-first-order rate constants were obtained by following the disappearance of the CT bands at 500–550 nm. The second-order rate constants (k_2) were calculated according to the usual method are are summarized in Table IV. In the case of reaction of **5** with **17d** which did not show CT band, the second-order rate constant was directly obtained by measuring

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(38) Diimides **5**, **19**, and **20** are dark green crystals, but their solutions in various solvents are colored deep purple.

Table V. First-Order Rate Constants (k_1') and Equilibrium
Constants (K)

ArH	solvent	t, °C	k_1', s^{-1}	K, M^{-1}
17a	CHCl$_3$	49.3	4.44 × 10^{-4}	2.22
17b	CHCl$_3$	33.9	4.36 × 10^{-3}	8.36
17b	C$_6$H$_5$Cl	33.9	2.52 × 10^{-3}	4.19
17c	CHCl$_3$	33.8	9.65 × 10^{-3}	20.8
17c	C$_6$H$_5$Cl	33.9	7.31 × 10^{-3}	8.44

Table VI. Activation Parameters for Cycloaddition Reactions of
Diimide (5, 0.001 M) with Substituted Anthracenes (17a-d,
ArH, 0.050 M)

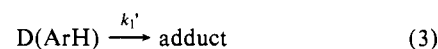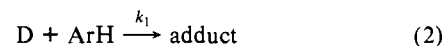| ArH	solvent	log A^a	E_a, kcal M^{-1}	$-\Delta S^{\ddagger}$, eu^b
17a	CHCl$_3$	5.2 (5.2)^c	12.2 (13.1)	38.5 (37)^c
17b	CHCl$_3$	8.0	13.5	25.9
17b	C$_6$H$_5$Cl	7.0	12.7	30.4
17c	CHCl$_3$	5.7 (4.7)^c	9.4 (8.0)	36.5 (39)^c
17c	C$_6$H$_5$Cl	6.0	10.3	35.2
17d^d	C$_6$H$_5$Cl	5.1	13.9	39.3

^{a} Unit: s^{-1} M^{-1}. ^{b} 25.0 °C. ^{c} Obtained with maleic anhydride
(16) as excess dienophile; ref 41. ^{d} [D] = 0.014 M; [ArH] =
0.150 M.

the decrease in the longest absorption band of **5** at 600–630 nm.
As Table IV shows, **5** reacts 5–90 times more rapidly than maleic
anhydride **16**, as can be expected from the lower LUMO level
of **5** than **16** (Figure 1). The rate enhancement of methyl group
in anthracene is more pronounced with **5** than with **16**. Elec-
tron-withdrawing formyl group retards the reaction with **5**.

It is interesting to note that these reactions show marked
variation in k_2, depending on the diene concentration [ArH] as
shown in Figure 2. While k_2 of **17d** stays constant over the entire
diene concentration range studied, those of **17a–c** decrease as the
diene concentration increases. This concentration dependence
suggests that the adducts are formed from **17a–c** not only through
the CT complex (see eq 3 in Scheme II) but also by the direct
cycloaddition of the free dienophile to diene (eq 2). If this is the
case and eq 3 is assumed to be rate-determining,[40] the plot of $1/k_2$
vs. [ArH] should give a straight line with a slope of $1/k_1'$ and
an intercept of $1/(k_1'K)$ (eq 4) according to Andrews and Keefer.[41]
Figure 3 presents such a graphical interpretation, from which the
first-order rate constant k_1' and the equilibrium constant K could
be calculated[41] (see Table V). Both k_1' and K increase as an-
thracene is substituted by one and two methyl groups. This result
indicates that the electron-donating substituent facilitates both
the formation of CT complexes (K) and their conversion into
Diels–Alder adducts (k_1'). The values of equilibrium constants
K are considerably larger than that reported previously for the
anthracene–maleic anhydride complex ($K = 0.296$ M^{-1})[41] but
smaller than that for cyclooctatetraene–phencyclone complex (K
= 48.1 M^{-1}).[42]

Activation parameters for these reactions were also calculated
by fitting second-order rate constants (k_2) at various temperatures
into the Arrhenius equation (Table VI). The entropies of ac-
tivation were found to lie within the range reported for typical
concerted Diels–Alder reactions[43] and suggest a highly ordered
transition state. Effects of solvents were examined for the two
representative combinations, **5** with **17b** and **17d**, for which the
mechanisms are typically different. The second-order rate con-
stants thus obtained[37] are plotted in Figure 4 against Dimroth's
E_T values of solvents,[44] which are believed to reflect the ionizing
power of the medium. The small slopes of the least-squares

Scheme II

$$D + ArH \underset{}{\overset{K}{\rightleftharpoons}} D(ArH) \qquad (1)$$

$$D + ArH \xrightarrow{k_1} adduct \qquad (2)$$

$$D(ArH) \xrightarrow{k_1'} adduct \qquad (3)$$

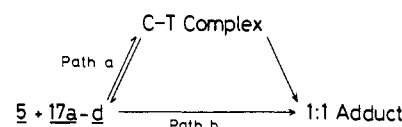$$\frac{1}{k_{obsd}} = \frac{1}{k_1'K} + \frac{[ArH]}{k_1'} \qquad (4)$$

$$K, \text{equilibrium constant} \left(= \frac{[D(ArH)]}{[D][ArH]} \right)$$

D, dienophile (diimide **5**)

ArH, diene (anthracenes **17a–c**)

k_{obsd}, experimental rate constant ($= k_2$)

Scheme III

straight lines for both combinations of reactants indicate that these
reactions occur through a nonpolar transition state.

Discussion

The above experimental results clearly indicate that there are
two independent paths for the formation of the Diels–Alder ad-
ducts of diimide **5** and anthracene derivatives **17a–d**. This is
illustrated in Scheme III: path a, the cycloaddition via a CT
complex, and path b the direct cycloaddition. The choice between
these reaction pathways merely depends upon the electronic
properties of the addends. In the reaction of electron-rich an-
thracene, path a becomes increasingly important as the elec-
tron-donating abilities of diene increases (**17a** to **17c**). In contrast,
only path b is available for the reaction of modestly electron-
deficient diene **17d**. The change in reaction mechanism is ac-
companied by dramatic decrease in the reaction rate in the order
of decreasing donor ability of diene (see Table IV), and no reaction
occurs to the strongly electron-deficient diene **17e**. These results
qualitatively agree with theoretical predictions made by Epiotis[45]
based on the donor–acceptor interaction treatment. In terms of
FMO theory, the rate trend within methyl derivatives parallels
well with the HOMO energy level calcualted by MNDO method:
the rate increases as the HOMO level increases (Table VIII). On
the other hand, the importance of CT complex formation in the
[4 + 2] cycloaddition has been well documented[45–48] on the basis
of the fact that the same sandwich structure is proposed for the
transition state of the diene addition and for the CT complex
formation. Interestingly enough, the limiing separation between
HOMO of diene and LUMO of dienophile differs among these
two processes; namely, the lowest possible HOMO level for the
CT complex formation with **5** can be laid between those of an-
thracene (**17a**) and 9-anthraldehyde (**17d**), or between −8.1 and
−8.3 eV. Whereas the cycloaddition occurs at HOMO levels as
low as −8.3 eV, Table VIII shows that dienes that do not react
with **5** (**17e**, **24**, **25**) have HOMO's lower than this limit. It may
be added that there is one more aspect which agreed with Epiotis's
prediction: the rate of Diels–Alder reaction of **5** with **17b** which

(40) This assumption is based on the observation of the typical change in
the color of the reaction mixture: the color of the CT complex and the strong
CT band (in the UV spectrum) appears instantaneously but disappears slowly
as the formation of adduct proceeds.

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95. (c) Reichardt, C. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 29.

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1973, *95*, 7301.

Table VIII. FMO Energy Levels (eV) of Anthracene and Derivatives (17a–e), Acridine (24), and Phenazine (25) by MNDO

	17a	17b	17c	17d	17e	24	25
LUMO	−0.84340	−0.89608	−0.97036	−1.14202	−1.58094	−1.03073	−1.24886
HOMO	−8.04643	−8.02918	−7.98803	−8.30343	−8.72939	−8.50988	−8.91483
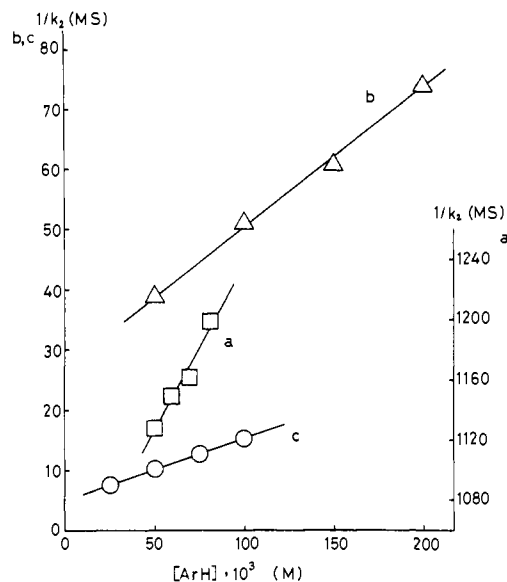
Figure 3. Plots of $1/k_2$ vs. [ArH] for the reaction of dithiin with (a) **17a** at 49.3 °C (right-hand ordinates, □), (b) **17b** at 33.9 °C (left-hand ordinates, △), and (c) **17c** at 33.8 °C (left-hand ordinates, ○), respectively.
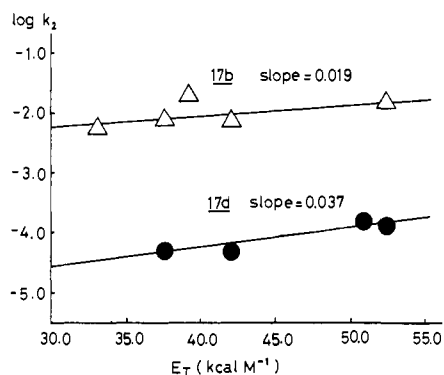
Figure 4. Plots of log k_2 vs. E_T for the cycloadditions dithiin **5** with **17b** (△, 33.9 °C) and **17d** (●, 52.2 °C).

is preceeded by CT complex formation hardly changed in various solvents.[45]

In conclusion, the cyclic conjugation theory proved highly powerful in predicting and understanding the enhancement of the reactivity in cycloaddition of 1,4-dithiin derivatives carrying cis-locked electron-withdrawing substituents. These substituents cause not only the lowering of the LUMO energy level but also the increase in the thermal stability and hence the planarity of 1,4-dithiin ring. The latter effect is especially favorable for the formation of CT complexes with planar anthracene derivatives and for the subsequent adduct formation to take place.[49]

Experimental Section

The melting points were measured with a Yanagimoto micro melting point apparatus and are uncorrected. The UV spectra were determined with a Hitachi EPS-3T spectrophotometer. The ¹H NMR spectra were taken with a JEOL PS-100 spectrometer and a Hitachi R-600 spectrometer with tetramethylsilane as an internal standard, and the chemical

shifts are expressed in δ values. The ¹³C NMR spectra were recorded on a JEOL FX-100 with tetramethylsilane as an internal standard. The IR spectra were taken with a JASCO IR A-1 infrared spectrometer. Mass spectra were obtained with a JEOL-01SG double-focusing spectrometer operating at an ionization potential of 75 eV. The solid samples were ionized by electron bombardment after sublimation directly into the electron beam at 150–200 °C.

1,4-Dithiintetracarboxylic N,N′-Dimethyldiimide (5). Compound **5** was prepared by the method of Michailidis et al.,[50] who reported no experimental details. To a solution of N-methylsuccinamic acid (9.40 g, 0.072 mol), prepared from succinic anhydride and methylamine, in dry dioxane (20 mL) was added dropwise a solution of thionyl chloride (17.3 g, 0.144 mol) in dry dioxane (10 mL) at room temperature with stirring. The solution was heated at 50 °C for 4 h. After cooling, the contents were poured into ice water (200 mL) and the precipitates were filtered off (6.9 g) and then recrystallized from 1,2-dimethoxyethane (280 mL) to give **5** (2.2 g, 22%) as dark green needles, mp 269–272 °C (sealed tube) (lit.[16] mp 263–265 °C); UV (CHCl₃) λ$_{max}$ 305 nm (ε 3020), 383 (1995), 595 (54); IR (KBr) 1780, 1700, 1570 cm⁻¹; ¹H NMR (Me₂SO-d_6) δ 2.85 (s); mass spectrum, m/e 282 (M⁺). Anal. Calcd for $C_{10}H_6N_2O_4S_2$: C, 42.55; H, 2.14; N, 9.92. Found: C, 42.54; H, 2.17; N, 9.90.

1,4-Dithiintetracarboxylic N,N′-Di-n-propyldiimide (19) and N,N′-Di-tert-butyldiimide (20). Compounds **19** and **20** were prepared as above from N-n-propylsuccinamic acid and N-tert-butylsuccinamic acid, respectively.

19: yield 44%, dark green glossy plates, mp 243.5–246.5 °C dec (sealed tube); IR (Nujol) 1715, 1695, 1580 cm⁻¹; ¹H NMR (CDCl₃) δ 0.88 (t, J = 7.5 Hz, 6 H), 1.40–1.78 (m, 4 H), 3.45 (t, J = 7.5 Hz, 4 H); ¹³C NMR (CDCl₃) δ 11.1 (s), 21.6 (s), 42.6 (s), 131.2 (s), 163.8 (s). Anal. Calcd for $C_{14}H_{14}N_2O_4S_2$: C, 49.69; H, 4.17; N, 8.28. Found: C, 49.61; H, 4.18; N, 8.38.

20: yield 52%, reddish brown needles, mp 273–276 °C dec (sealed tube); IR (Nujol) 1770, 1710, 1590 cm⁻¹; ¹H NMR (CDCl₃) δ 1.55 (s); ¹³C NMR (CDCl₃) δ 28.7 (s), 59.1 (s), 131.1 (s), 164.9 (s); mass spectrum (m/e) 366 (M⁺). Anal. Calcd for $C_{16}H_{18}N_2O_4S_2$: C, 52.44; H, 4.95; N, 7.64. Found: C, 52.43; H, 5.00; N, 7.62.

1,4-Dithiintetracarboxylic dianhydride (6) was prepared by the method of Draber:[16] mp 221–222 °C dec (sealed tube) (lit.[16] mp 221–222 °C); IR (KBr) 1870, 1840, 1810, 1765, 1570 cm⁻¹; ¹³C NMR (acetone-d_6) δ 134.8 (s), 158.8 (s).

General Procedure for Cycloadditions. To a solution of a slight excess amount of anthracene derivatives (**17a–d**) in benzene was added powdered 1,4-dithiintetracarboxylic N,N′-diimide (**5, 19, 20**), and the reaction mixture was refluxed until the blue color faded away. The solution was concentrated, chromatographed on silica gel with benzene as an eluent, and recrystallized from benzene to give the corresponding 1:1 adducts as yellow prisms. In the case of reaction of dianhydride **6**, the acid-sensitive products were purified only by recrystallization from benzene. The physical properties and spectral data of these cycloadducts are summarized in Table III.

Reaction of 5 with Acridine (24). A mixture of **5** (141 mg, 0.50 mmol) and **24** (90 mg, 0.50 mmol) in chloroform (10 mL) was stirred for 2 days at room temperature. The reaction mixture was concentrated in vacuo, and the residue was recrystallized from benzene to give the complex (164 mg, 71%) as bright green prisms, mp 237–239 °C (sealed tube): IR (KBr) 1790, 1710, 1620, 1610, 1570 cm⁻¹; ¹H NMR (CDCl₃) δ 8.75 (s, 1 H), 8.21 (dm, J = 8.5 Hz, 2 H), 7.98 (dm, J = 8.5 Hz, 2 H), 7.76 (ddd, J = 8.5, 6.7, 1.4 Hz, 2 H), 7.50 (ddd, J = 8.5, 6.7, 1.4 Hz, 2 H), 3.00 (s, 6 H), 1.68 (s, 2 H); mass spectrum (m/e) 282, 179. Anal. Calcd for $C_{23}H_{15}N_3O_4S_2$: C, 59.89; H, 3.28; N, 9.10. Found: C, 59.97; H, 3.50; N, 8.81.

The same reaction was conducted with **5** (141 mg, 0.50 mmol) and **24** (90 mg, 0.50 mmol) in toluene (30 mL) in a sealed tube for 48 h at 150 °C. After the mixture was cooled to room temperature, the precipitated crystals (141 mg, 61%) were collected by filtration and iden-

(49) While **5** showed poor reactivity toward nonplanar cyclohepta-1,3,5-triene, the 1:1 adducts were obtained in high yields with planar dienes such as 1,4-diphenyl-2,3-benzofuran and 2,5-dimethyl-3,4-diphenylcyclopentadienone.

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(51) **Note Added in Proof.** Recently, 1,4-dihydrobenzene (hydrocarbon analogue of **4**) was also shown to prefer planar conformation by theoretical calculations: Lipkowitz, K. B.; Rabideau, P. W.; Raber, D. J.; Hardee, L. E.; Schleyer, P. V. R.; Kos, A. J. Kahn, R. A. *J. Org. Chem.* **1982**, *47*, 1002.

tified with the above 1:1 complex by IR and ^{1}H NMR spectra. Reaction of **5** (141 mg, 0.50 mmol) and **24** (448 mg, 2.5 mmol) in chloroform (10 mL) at room temperature for 3 days also gave the same complex (225 mg, 97%).

Kinetics. The kinetic run was initiated by mixing 1–2 mL of diene (**17a–d**) stock solution and 1–2 mL of dienophile (**5**) solution into a 10 × 10 mm quartz cell, which was thermostated with flowing water at a given temperature. In the case of the reaction of **5** and **17a–c**, the diene concentration was in large excess over that of dienophile and the rates were measured by following the disappearance of the CT bands at 500–550 nm. The pseudo-first-order rate constants were calculated from a plot of $\ln[(A_t - A_\infty)/(A_0 - A_\infty)]$ vs. time by a least-squares method, where A_t is the absorbance at time t and A_∞ is the absorbance after 10 half-lives. The second-order rate constants (k_2) were obtained in the usual manner. The treatment of Andrews and Keefer[41] was followed in the calculation of the equilibrium constants.

The rates of the reaction of **5** with **17d** which showed no CT bands were measured by following the disappearance of the dienophile **5** at 600–630 nm. The initial concentrations of **5** and **17d** used were 0.0143 M and 0.15 M, respectively, because of the low solubility of **5**. The second-order rate constants (k_2) were calculated from a plot of $(\ln[(A_0 - A_\infty)(b - a)/(A_t - A_\infty) + a] - \ln b)/(b - a)$ vs. time by a least-squares method, where A_0 and A_∞ are the same as above and a and b are the initial concentrations of **5** and **17d**, respectively. The kinetic data are listed in Tables IV–VII.[37]

Single and Double Ring-Closure Reactions of Dianions of Bis(diphenyl thioacetals). A New, Synthetically Useful Principle of Carbene Generation and Intramolecular Capture

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Abstract: A mechanistic study described herein leads to the new, potentially useful general principle that normally stable anions of diphenyl thioacetals decompose to carbenes when they are generated in a molecule with a second anionic site nearby; it also appears that the second anionic site may be influential in determining the selectivity of the carbene. Strong evidence is presented that dianions are intermediates in the alkyllithium-induced conversions of 1,1,4,4-tetrakis(phenylthio)butane (**1A**) and 1,1,6,6-tetrakis(phenylthio)hexane (**1C**) to 1,2-bis(phenylthio)cyclobutene (**2A**) and 6,6-bis(phenylthio)bicyclo[3.1.0]hexane (**4**), respectively. The use of *p*-*tert*-butyl groups as aryl labels leads to the conclusion that the carbenic carbon atom of the assumed anion carbene intermediate **6**, formed by ejection of thiophenoxide ion from the dianion (**5**) of **1A**, bonds with sulfur to produce a 5-membered ring anion ylide (**8**), which rearranges to **2A**. Similar labeling experiments are interpreted as indicating that the carbenic carbon atom of the corresponding anion carbene (**14**), derived from **1C**, inserts into the weak CH bond adjacent to the negatively charged carbon atom to produce a cyclopentyl thioacetal anion (**15**), which ejects a thiophenoxide ion to yield the bicyclic product **4**. The new principle has been dramatically demonstrated by treating 5,5-bis(phenylthio)-1-pentanol (**21**) with *sec*-butyllithium whereby the geometric isomers of 2-(phenylthio)cyclopentanol (**24**) are produced, presumably via insertion of the carbenic carbon atom of the anion carbene **23** into the reactive CH bond of the carbinol anion.

A remarkable ring closure reaction (1A → 2A and 1B → 2B)
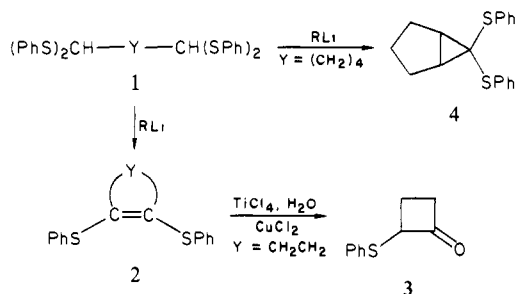
A, Y = CH$_2$CH$_2$; B, Y = CH$_2$CH(CH$_3$)CH$_2$; C, Y = (CH$_2$)$_4$

has been reported recently from this laboratory.[1] This type of ring closure is of interest not only because of its novelty but because **3**, the hydrolysis product of **2A**,[2] is synthetically useful as a

surrogate for cyclobutanone[2] and as a precursor of 2-methoxy-3-(phenylthio)-1,3-butadiene.[3] We now report a still more remarkable ring closure of a bis(dithioacetal), we present a mechanistic study of these highly unusual ring closures, and, most importantly, we enunciate a new principle of carbene generation and use, which should have wide applicability in synthetic organic chemistry; the principle is dramatically illustrated by the cyclization of a straight-chain primary alcohol terminated by a thioacetal group, such cyclization involving unprecedented CC bond formation between carbinol and thioacetal carbon atoms.

Results and Discussion

When **1C**, prepared by the reaction of 1,4-diiodobutane with bis(phenylthio)methyllithium, was treated with 2–4 equiv of methyllithium in THF containing 2–4 equiv of tetramethyl-

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