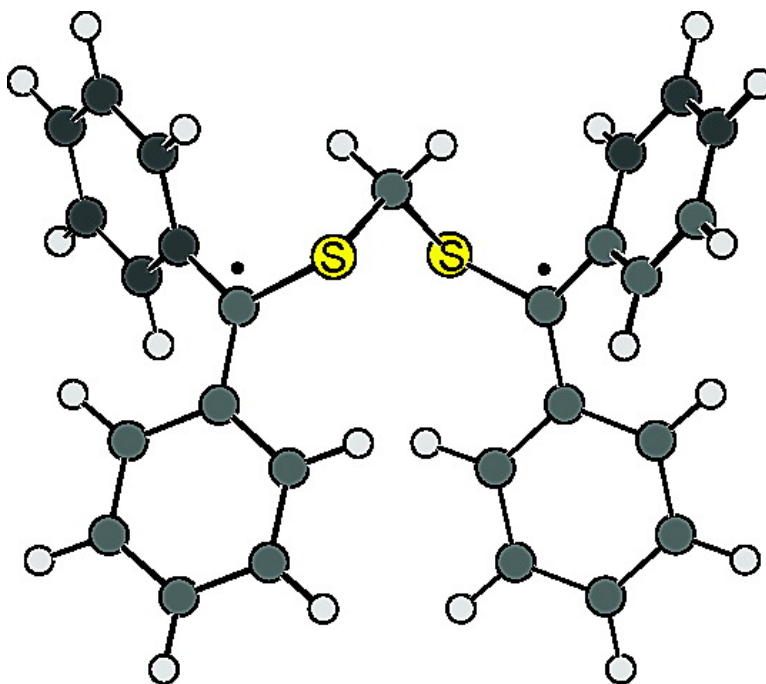


A Computational Study of the Cycloaddition of Thiobenzophenone S-Methylide to Thiobenzophenone

Reiner Sustmann, Willi Sicking, and Rolf Huisgen

J. Am. Chem. Soc., **2003**, 125 (47), 14425-14434 • DOI: 10.1021/ja0377551 • Publication Date (Web): 01 November 2003

Downloaded from <http://pubs.acs.org> on March 30, 2009



More About This Article

Additional resources and features associated with this article are available within the HTML version:

- Supporting Information
- Links to the 5 articles that cite this article, as of the time of this article download
- Access to high resolution figures
- Links to articles and content related to this article
- Copyright permission to reproduce figures and/or text from this article

[View the Full Text HTML](#)



ACS Publications
High quality. High impact.

A Computational Study of the Cycloaddition of Thiobenzophenone *S*-Methylide to Thiobenzophenone

Reiner Sustmann,^{*,†} Willi Sicking,[†] and Rolf Huisgen[‡]

Contribution from the Institut für Organische Chemie der Universität Duisburg-Essen, 45117 Essen, Germany, and Department Chemie, Ludwig Maximilians Universität, Butenandtstrasse 5-13, Haus F, 81377 München, Germany

Received August 5, 2003; E-mail: reiner.sustmann@uni-essen.de

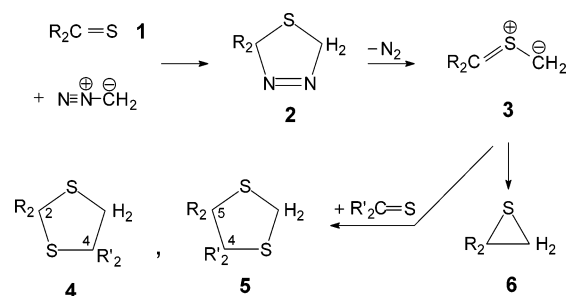
Abstract: The cycloaddition of thiobenzophenone *S*-methylide to thiobenzophenone, an experimentally well-known reaction, was studied, using (U)HF/3-21G* for finding stationary points and (U)B3LYP/6-31G**/(U)HF/3-21G* single-point calculations for energies. Some optimizations were performed by (U)B3LYP/6-31G* to check the reliability of the calculations. The comparison of the concerted pathways and stepwise reactions via *C,C*-biradicals and *C,S*-zwitterions showed that the formation of a tetraphenyl-substituted *C,C*-biradical and its ring closure to 4,4,5,5-tetraphenyl-1,3-dithiolane constitutes the energetically most probable pathway of product formation, despite the fact that the regioisomeric 2,2,4,4-tetraphenyl-substituted product is more favorable by 17 kcal mol⁻¹. Model calculations on bond dissociation energies showed that (U)B3LYP with various basis sets overestimates radical stabilization, whereas CBS-QB3 closely reproduced experimental values. Results with the BLYP functional are similar to those with B3LYP. The consequences of the overestimation of radical stability for the cycloaddition mechanism involving biradicals are discussed. Thiobenzophenone *S*-methylide, if not captured by a dipolarophile, dimerizes to 2,2,3,3-tetraphenyl-1,4-dithiane. Calculation disclosed likewise a tetraphenyl-substituted *C,C*-biradical as intermediate.

Introduction

The chemistry of thiocarbonyl ylides has been well reviewed,^{1–4} but their 1,3-dipolar cycloadditions have not (yet) reached the same synthetic importance as those of, e.g., nitrones (azomethine oxides) or azomethine ylides. Thioketone *S*-methylides **3** are prepared by the two-step sequence from thioketones **1** and diazomethane via 2,5-dihydro-1,3,4-thiadiazoles **2**. The nucleophilic 1,3-dipoles **3** undergo irreversible electrocyclicization to give thiiranes **6** but are easily intercepted in situ by electrophilic C=C bonds producing thiolanes.

The C=S bond of thiones is a “superdipolarophile”⁵ and accepts thiocarbonyl ylides with formation of 1,3-dithiolanes **4** and **5**. The regiochemistry is striking: sterically hindered cycloalkanethione *S*-methylides and dialkylthioketone *S*-methylides react with alicyclic or aliphatic thiones to give exclusively the 2,2,4,4-tetrasubstituted 1,3-dithiolanes **4**.⁶ Aryl groups in one or both reactants lead to a preference or even complete formation of the 4,4,5,5-tetrasubstituted isomers **5** (Scheme 1).

Scheme 1



Obviously, several mechanisms are involved in 1,3-dithiolane formation. As a consequence of the scarcity of experimental criteria, we resorted to quantum chemical calculations. In a previous contribution, concerted and stepwise mechanisms for the cycloadditions of thioformaldehyde *S*-methylide and thioacetone *S*-methylide with thioformaldehyde and thioacetone were analyzed by ab initio and DFT methods.⁷

The parent system, **3** + **1** with R = R' = H, undergoes concerted cycloaddition without passing a transition structure (TS), i.e., product formation occurs without activation energy. For the concerted cycloaddition of **3** + **1**, R = R' = Me, small barriers of activation were found for the formation of both regioisomeric 1,3-dithiolanes, a lower barrier for **4** than for **5**. The evaluation of the potential energy surface for both the unsubstituted and dimethyl-substituted reaction partners brought

(7) Sustmann, R.; Sicking, W.; Huisgen, R. *Chem. Eur. J.* **2003**, *9*, 2245–2255.

[†] Institut für Organische Chemie der Universität Duisburg-Essen.

[‡] Department Chemie, Ludwig Maximilians Universität.

- (1) Kellogg, R. M. *Tetrahedron* **1976**, *32*, 2165–2184.
- (2) Huisgen, R.; Fulka, C.; Kalwisch, I.; Li, X.; Mloston, G.; Moran, J. R.; Pröbstl, A. *Bull. Soc. Chim. Belg.* **1984**, *993*, 511–532.
- (3) Mloston, G.; Heimgartner, H. *Pol. J. Chem.* **2000**, *74*, 1503–1532.
- (4) Mloston, G.; Heimgartner, H. In *The Chemistry of Heterocyclic Compounds*; Padwa, A., Pearson, W. H., Eds.; John Wiley: New York, 2002; Vol. 59, pp 315–360.
- (5) Fisera, L.; Huisgen, R.; Kalwisch, I.; Langhals, E.; Li, X.; Mloston, G.; Polborn, K.; Sicking, W.; Sustmann, R. *Pure Appl. Chem.* **1996**, *68*, 789–796.
- (6) Huisgen, R.; Mloston, G.; Polborn, K.; Sustmann, R. *Chem. Eur. J.* **2003**, *9*, 2256–2263.

to light cycloaddition pathways via *C,C*- and *C,S*-biradicals, the formation of which required somewhat higher activation energies than the concerted processes. However, the modest differences in barrier heights suggested that suitable radical-stabilizing substituents R might change the mechanistic preference from the concerted to the stepwise pathway of cycloaddition. A case of particular interest is **3** + **1**, R = R' = phenyl, which would provide intermediate biradicals with diphenylmethyl stabilization. The calculation of the hypersurface of this reaction is the subject of this contribution.

The reaction of thiobenzophenone *S*-methylide (**3**, R = Ph) with thiobenzophenone (**1**, R = Ph) has an amusing history which deserves brief recounting. In 1930 Bergmann et al. ascribed biradical character to thiobenzophenone and regarded, besides the deep blue color, the reaction with diazomethane as evidence.⁸ The formation of 4,4,5,5-tetraphenyl-1,3-dithiolane (**5**, R = R' = Ph) as 2:1 product showed a formal analogy to the reaction of triphenylmethyl with diazomethane which gives rise to hexaphenylpropane.⁹

Bergmann et al.⁸ as well as Schönberg et al.,¹⁰ who described in 1931 the same reaction, abstained from proposing a detailed pathway for the quantitative formation of dithiolane **5**, R = Ph. In a broad variation of diazoalkane and thione, Schönberg's group observed that each reactant pair furnished either 1,3-dithiolane or thiirane, without allowing mechanistic conclusions.¹¹

The mechanistic elucidation of the "Schönberg reaction", i.e., the formation of **5**, R = R' = Ph, from thiobenzophenone and diazomethane at 0 °C, was achieved in the Munich laboratory,^{12,13} 50 years after its discovery. When the reaction was carried out in THF at -78 °C, the isolable thiadiazoline **2**, R = R' = Ph, was quantitatively formed; it lost N₂ (a 1,3-dipolar cycloreversion) at -45 °C in THF with a half-life of 56 min. When thiobenzophenone *S*-methylide (**3**, R = R' = Ph) was liberated in the presence of thiobenzophenone, 4,4,5,5-tetraphenyl-1,3-dithiolane (**5**, R = R' = Ph) was isolated in 95% yield; searching of the mother liquor for the regioisomer **4**, R = R' = Ph, was in vain. Replacement of the second equivalent of thiobenzophenone by other dipolarophiles with C=C, C≡C, C=S, or N=N bonds made a wealth of five-membered cycloadducts accessible.^{14,15}

The corresponding thiadiazoline from adamantanethione and diazomethane (**2**, R₂ = C₉H₁₄) loses N₂ with a half-life of 88 min at +40 °C in THF.¹⁶ The enormous rate increase for the N₂ extrusion from **2**, R = Ph, (56 min at -45 °C) demonstrates how much the formation of thiobenzophenone *S*-methylide (**3**, R = Ph) profits from the incipient phenyl conjugation.

Computational Methods

Semiempirical calculations on the PM3 level were initially performed.¹⁷ However, the reliability of semiempirical methods for

biradical structures is low and the results are, therefore, not reported here. Ab initio and DFT calculations were carried out with the Gaussian98 suite of programs.¹⁸ Due to the size of the systems, geometry optimizations were carried out mostly on the (U)HF level with the 3-21G* basis set which includes polarization functions for second row elements. Single point calculations of the stationary points obtained by these calculations were done with (U)B3LYP/6-31G*. Some optimization calculations of ground states, intermediates (I), and transition structures (TS), although very time-consuming, were done by (U)B3LYP/6-31G*.

Molecules with obviously closed shell character were evaluated by DFT theory using the B3LYP functional. In cases where biradical character was assumed, UB3LYP was applied including the key words guess = alter or guess = mix in Gaussian. When B3LYP and UB3LYP gave identical results, the key word stable = opt was additionally applied in order to look for an improved UB3LYP wave function with a lower total energy. Biradical character (BRC)¹⁹ was determined by CAS(2,2)/3-21G* calculations, if not indicated otherwise in the Tables. CAS(2,2) is the minimum configuration interaction to calculate BRC. This approach does not, however, take proper account of the dynamic electron correlation, which may lead to an overestimation of the true biradical character.²⁰ As a check on the quality of the CAS(2,2) determined BRC, the total energies calculated by RHF and UHF methods are compared. If this difference is small, 2–3 kcal mol⁻¹, the biradical contribution to the total wave function must be small. This must also be the case when B3LYP and UB3LYP both indicate a closed shell configuration.²¹ In general B3LYP and UB3LYP yielded identical results when the CAS(2,2) calculated biradical character did not exceed 30% appreciably. The BRC should parallel the magnitude of the energy difference between a RHF and a UHF, in our case RB3LYP and UB3LYP calculation. High BRC should be present when this difference exceeds 10 kcal mol⁻¹ (see below). The energies of singlet and triplet biradical wave function can be taken as further proof of a high BRC. When their energies are close or identical, the structure should be a true biradical.

Stationary points were checked by frequency calculations to see whether they constituted minima or maxima on the potential energy surface. All transition structures are characterized by only one imaginary frequency. TSs were tested whether they connected properly the ground state of reactant(s) and product. The results were corrected, if possible, by ZPVE. Determinations of TSs by UB3LYP/6-31G* were done by reaction coordinate calculations, and ΔZPVE corrections for these structures were estimated from related, properly evaluated TSs.

Apparently, density functional evaluations do not provide reliable energies in cases of high biradical character. More advanced procedures such as the CASPT2 scheme available in MOLCAS,²² which was

- (8) Bergmann, E.; Magat, M.; Wagenberg, D. *Ber. Dtsch. Chem. Ges.* **1930**, *63*, 2576–2584.
 (9) Schlenk, W.; Bornhardt, C. *Liebigs Ann. Chem.* **1912**, *394*, 178–185.
 (10) Schönberg, A.; Cernik, D.; Urban, W. *Ber. Dtsch. Chem. Ges.* **1931**, *64*, 2577–2581.
 (11) Schönberg, A.; König, B.; Singer, E. *Chem. Ber.* **1967**, *100*, 767–777.
 (12) Kalwisch, I.; Li, X.; Gottstein, J.; Huisgen, R. *J. Am. Chem. Soc.* **1981**, *103*, 7032–7033.
 (13) Huisgen, R.; Kalwisch, I.; Li, X.; Mloston, G. *Eur. J. Org. Chem.* **2000**, 1685–1694.
 (14) Li, X.; Huisgen, R. *Tetrahedron Lett.* **1983**, *24*, 4181–4184.
 (15) Huisgen, R.; Li, X.; Giera, H.; Langhals, E. *Helv. Chim. Acta* **2001**, *84*, 981–999.
 (16) Huisgen, R.; Mloston, G. *Pol. J. Chem.* **1999**, *73*, 635–644.

- (17) Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 109, 221.
 (18) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Rega, N.; Salvador, P.; Dannenberg, J. J.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Baboul, A. G.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, Revision A. 11.3; Gaussian, Inc.: Pittsburgh, PA, 2002.
 (19) Houk, K. N.; Yamaguchi, Y. In *1,3-Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984; Vol. 2, pp 407–450.
 (20) Jensen, F. *Introduction to Computational Chemistry*; John Wiley & Sons: New York, 1999; pp 117–122.
 (21) Isobe, H.; Takano, Y.; Kitagawa, Y.; Kawakami, T.; Yamanaka, S.; Yamaguchi, K.; Houk, K. N. *Mol. Phys.* **2002**, *100*, 717–727.
 (22) Anderson, K.; Barysz, M.; Bernhardsson, A.; Blomberg, M. R. A.; Cooper, D. L.; Fülscher, M. P.; de Graaf, C.; Hess, B. A.; Karlström, G.; Lindh, R.; Malmqvist, P.-Å.; Nakajima, T.; Neogrády, P.; Olsen, J.; Roos, B. O.; Schimmelpfennig, B.; Schütz, M.; Seijo, L.; Serrano-Andrés, L.; Siegbahn, P. E. M.; Stålring, J.; Thorsteinsson, T.; Veryazov, V.; Widmark, P. O. MOLCAS, Version 5.4; Lund University: Sweden; 2002.

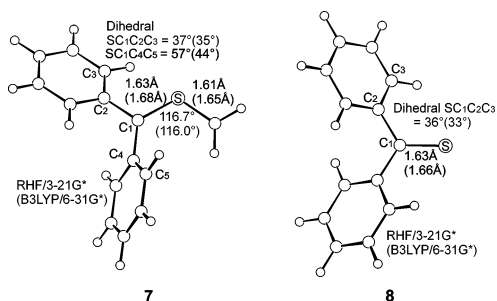
Table 1. B3LYP/6-31G*/RHF/3-21G* Calculations on Thiobenzophenone *S*-methylide (**7**), Thiobenzophenone (**8**), Cycloadducts (**9** and **10**), and TSs (**11** and **12**); Energies Relative to **7** + **8** in kcal mol⁻¹

	structure	$\Delta ZPVE$ RHF/ 3-21G*	E_{rel}	%BRC CAS(<i>m,n</i>)/ 3-21G*	<i>m,n</i>	$E_{rel} + \Delta ZPVE$
thiobenzophenone- <i>S</i> -methylide	7			18.6	4,3	
thiobenzophenone	8			9.9	2,2	
	7+8	0.0	0.0			0.0
2,2,4,4,-tetraphenyl-1,3-dithiolane	9 (Prod)	4.0	-45.2			-41.2
4,4,5,5,-tetraphenyl-1,3-dithiolane	10 (Prod)	4.3	-28.7			-24.4
TS for 2,2,4,4,-tetraphenyl-1,3-dithiolane	11 (TS)	0.7	5.7	16.6	6,5	6.4
TS for 4,4,5,5,-tetraphenyl-1,3-dithiolane	12 (TS)	1.1	10.0	35.4	6,5	11.1

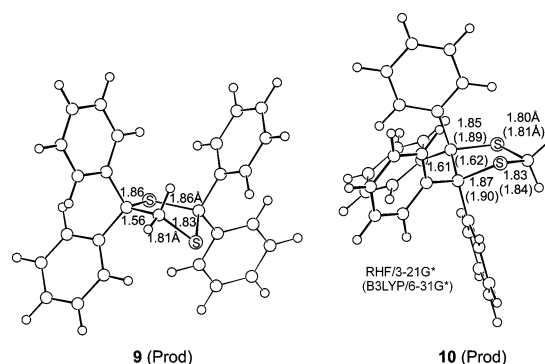
applied in our previous study,⁷ cannot be used here due to the size of the systems. To obtain an estimate of the DFT “error”, bond dissociation energies were determined with CBS-QB3 for small molecules, and compared with DFT results using various basis sets and experimental values.

Results and Discussion

Structures of reactants and products. The structures of thiobenzophenone *S*-methylide (**7**) and thiobenzophenone (**8**) were determined on the RHF/3-21G* and the B3LYP/6-31G* levels of theory (Tables 1 and 3). The C–S bond lengths of **7** are slightly different, being 1.63 Å (1.68 Å) at the substituted side and 1.61 Å (1.65 Å) at the other side (B3LYP/6-31G* values in brackets). The CSC bond angle amounts to 117° (116°). Due to steric interaction, the phenyl groups cannot be coplanar with the CSC plane for optimal conjugation. One dihedral angle SC–CC is 37° (35°), *exo* phenyl group, the other is 57° (44°). In particular the *exo* phenyl group can interact favorably with the allylanionic π system of **7**; on the basis of the $[\cos^2 \alpha]$ function, $\alpha = 36^\circ$ corresponds to 65% of full conjugation energy. A similar situation arises for thiobenzophenone (**8**). The C=S double bond length of 1.63 Å (1.66 Å) compares well with that of thioformaldehyde (1.64 Å),⁷ and the dihedral angle SC–CC of the C₂ symmetric molecule is 36° (33°). The percent BRC of **7** and **8** amounts to 19 and 10%, respectively. The C–S bond of **7** is nearly as short as the C=S bond of **8**. The resonance energy of the parent 1,3-dipole **3**, R = R' = H, was 19.3 kcal mol⁻¹, as determined from the rotational barrier with UB3LYP/6-31G*.⁷



Due to the one-sided phenyl substitution of the 1,3-dipole, two regioisomeric cycloadducts can be formed (**9** and **10**). In 4,4,5,5-tetraphenyl-1,3-dithiolane (**10**) the four phenyl groups reside on neighboring atoms, thus causing strong steric interactions, while in 2,2,4,4-tetraphenyl-1,3-dithiolane (**9**) these groups are at maximal distance from each other. Both five-membered rings are not planar. In **9** an envelope structure is realized with one sulfur atom out of the quasi-plane of the four other atoms.



In **10** it is the methylene group that is out of the plane, which, however, is not as well defined as in **9**. The steric encumbrance in **10** finds its expression in the reaction energy. Relative to starting molecules these are -41.2 kcal mol⁻¹ for **9** and -24.4 kcal mol⁻¹ for **10**; thus, the interaction of two neighboring phenyl pairs produces an extra destabilization of 16.8 kcal mol⁻¹ (Table 1). An elongated C–C-bond length of 1.61 Å in **10** is the consequence of strain; the C–C bond length in isomer **9** is 1.56 Å. The cycloadditions of thioacetone *S*-methylide to thioacetone, where two methyl pairs are present instead of the phenyl groups in **7** and **8**, displayed reaction energies of -61.1 (**4**, R = R' = CH₃) and -56.1 (**5**, R = R' = CH₃) kcal mol⁻¹, respectively. For the cycloaddition of thioformaldehyde *S*-methylide to thioformaldehyde the corresponding value is -76.1 kcal mol⁻¹.⁷ Both alkyl and aryl substitution lead to a destabilization of the 1,3-thiolane ring system, with phenyl exerting a much more pronounced effect.

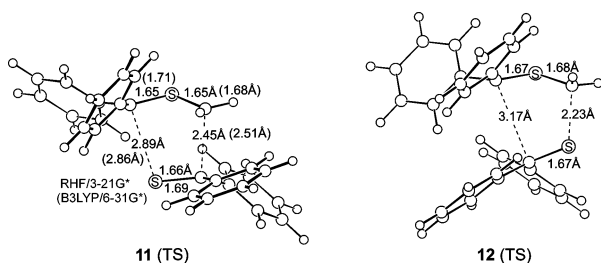
The steric repulsion of the two phenyl pairs in **10** may be compared to that in hexasubstituted ethanes. On the basis of thermochemical measurements,²³ Rüdhardt and Beckhaus ascribed a strain energy $H_s = 6.5$ kcal mol⁻¹ to 2,2,3,3-tetramethylbutane. For 2,2,3,3-tetraphenylbutane, force field MM2 calculation provided $H_s = 26.1$ kcal mol⁻¹, whereas $H_s = 18.2$ kcal mol⁻¹, resulting from thermochemical data, was regarded as less reliable.²⁴ The cyclic 1,3-dithiolanes are not strictly comparable with the open-chain structures, but 5.0 kcal mol⁻¹ for the steric interaction of two pairs of methyl groups and 16.8 kcal mol⁻¹ for two phenyl pairs appear reasonable. Of course, the energy levels of the products reflect not only their steric destabilization, but also the loss of conjugation energy of the reactants.

A cycloaddition enthalpy of -24.4 kcal mol⁻¹ is in accordance with the cycloreversion of **10** at elevated temperature;

(23) Rüdhardt, C.; Beckhaus, H.-D. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 529–538.

(24) Schätzer, J. Ph.D. Thesis, University of Freiburg 1980.

the electrocyclicization $3 \rightarrow 6$, $R = R' = \text{Ph}$, and the head–head dimerization to tetraphenyl-1,4-dithiane renders the splitting irreversible. Schönberg et al.¹⁰ described the thermolysis of **10** at 220 °C. When **10** was heated in CDCl_3 at 135 °C for 35 h in a sealed tube, 66% of 1,1-diphenylethylene (desulfurization of thiirane **6**, $R = \text{Ph}$) and 100% thiobenzophenone were analyzed.¹³



Concerted Cycloaddition of Thiobenzophenone *S*-Methylide to Thiobenzophenone. The four-center approach of the reactants **7** and **8** should be hindered by four phenyl groups. Are concerted pathways to dithiolanes **9** and **10** possible at reasonable barrier heights? A search of the potential energy surface (RHF/3-21G*) revealed TSs **11** and **12** which correspond to the two addition directions (Table 1). Activation energies of 6.4 and 11.1 kcal mol⁻¹ (B3LYP/6-31G*/RHF/3-21G*) for the formation of **9** and **10**, respectively, are surprisingly moderate. The two TSs differ by 4.7 kcal mol⁻¹ compared with a difference in product stability of 16.8 kcal mol⁻¹. Thus, the TSs must occur early on the reaction coordinate; indeed, early TSs are a general characteristic of concerted cycloadditions.^{25a} The C–S bonds of the reactants **7** and **8** are only slightly elongated in **11** and **12**. In TS **11** both incipient bonds are about 1.0 Å longer than in dithiolane **9**. However, the two new σ -bonds in TS **12** greatly deviate from a synchronous cycloaddition: 2.23 Å for the C–S bond and 3.17 Å for the C–C bond. Thus, C–S bond making is fairly progressed, whereas the formation of the C–C bond, which is flanked by four phenyl groups, has barely started. BRC, determined by CAS(6,5)/3-21G* calculations, is significantly greater for TS **12** (35%) than for TS **11** (17%).

According to the activation energies, the concerted cycloaddition of **7** with **8** should furnish the 2,2,4,4-tetraphenyl-1,3-dithiolane (**9**), in contrast to the experimental observation. In 1987 Achiwa et al. generated thiobenzophenone *S*-methylide (**7**) from a silylated precursor and reacted it with thiobenzophenone; dithiolane **10** was isolated in 54% yield.²⁶ The Japanese authors derived the regiochemical preference for **10** in a concerted cycloaddition from a FMO correlation diagram with MNDO calculated HO–LU energies and atomic orbital coefficients. The result is at variance with our TS calculation—the present “state of art”—and illustrates the fallacies of regiochemical assignments on the basis of the second-order term of the perturbation equation; steric effects are neglected.

FMO Energies and Reactivity. The π -FMO energies of thiocarbonyl ylide **3**, $R = \text{H}$, as well as those of ethylene, formaldehyde, and thioformaldehyde were calculated with B3LYP/6-31G* and reveal in Figure 1 that the energy separation of $\text{HO}_{(\text{CH}_2\text{SCH}_2)}$ and $\text{LU}_{(\text{CH}_2\text{S})}$ is the smallest by far. A simple

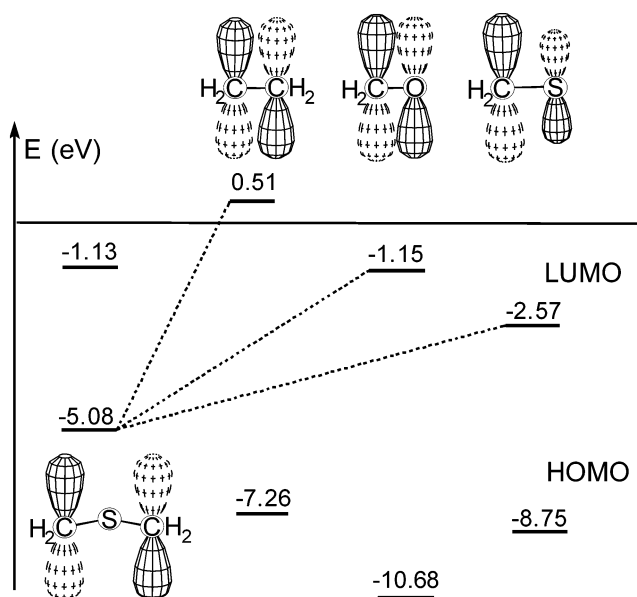


Figure 1. Frontier molecular orbitals for thioformaldehyde *S*-methylide, ethylene, formaldehyde, and thioformaldehyde according to B3LYP/6-31G* calculations.

nucleophile–electrophile addition appears possible and would establish *one* bond between the reactants, giving rise to a biradical or zwitterion which subsequently closes the five-membered ring. DFT and ab initio methods showed that biradical formation in the interaction of **3** + **1** ($R = R' = \text{H}$ or Me) is feasible but still requires higher activation energies than the concerted cycloadditions.⁷

One large and one small π -HO–LU interaction likewise increases the rate of the concerted cycloaddition, compared with two equidistant interactions, as shown in the Essen laboratory in the early 1970s²⁷ and widely confirmed in the meantime.^{25b} The term “superdipolarophile”⁵ pertains to concerted and two-step pathways and ultimately is a consequence of the low π HO–LU separation of the C=S double bond in comparison with C=C, C=N, and C=O. For example, the unusually fast cycloadditions of nitrones to thiones²⁸ are concerted according to ab initio calculation.²⁹

Cycloaddition Pathway to **10 via C,C-Biradical **14**.** TS **12** for the concerted process leading to the experimentally observed dithiolane **10** attracted attention, due to the inequality of the two incipient σ bonds. The long C–C bond (3.17 Å) and a BRC of 35% suggest that the omission of CC bonding might open a more favorable pathway via a biradical with double diphenylmethyl stabilization.

We probed the potential energy surface by UHF/3-21G* and concentrated on two extended biradical conformations **14a** and **14b** which are energy minima. On the way from the reactants to these intermediates, we arbitrarily chose points **13a** and **13b** on the reaction coordinates in which the incipient C–S bond has a length of 2.70 Å. There was no restriction on other degrees of freedom in the calculation of **13a,b**. Since the C–S bond length in the calculated TS for the formation of the corresponding methyl-substituted biradical is 2.28 Å,⁷ the structures **13a**

(27) Sustmann, R. *Pure Appl. Chem.* **1974**, *40*, 569–593.

(28) Huisgen, R.; Fisera, L.; Giera, H.; Sustmann, R. *J. Am. Chem. Soc.* **1995**, *117*, 9671–9678.

(29) Sustmann, R.; Sicking, W.; Huisgen, R. *J. Am. Chem. Soc.* **1995**, *117*, 9679–9685.

(25) Huisgen, R. In *1,3-Dipolar Cycloaddition Chemistry*, 1st ed.; Padwa, A., Ed.; Wiley-Interscience, 1984; Vol. 1, (a) pp 35–47; (b) pp 99–128; (c) pp 40–42.

(26) Aono, M.; Terao, Y.; Achiwa, K. *Chem. Lett.* **1987**, 1851–1852.

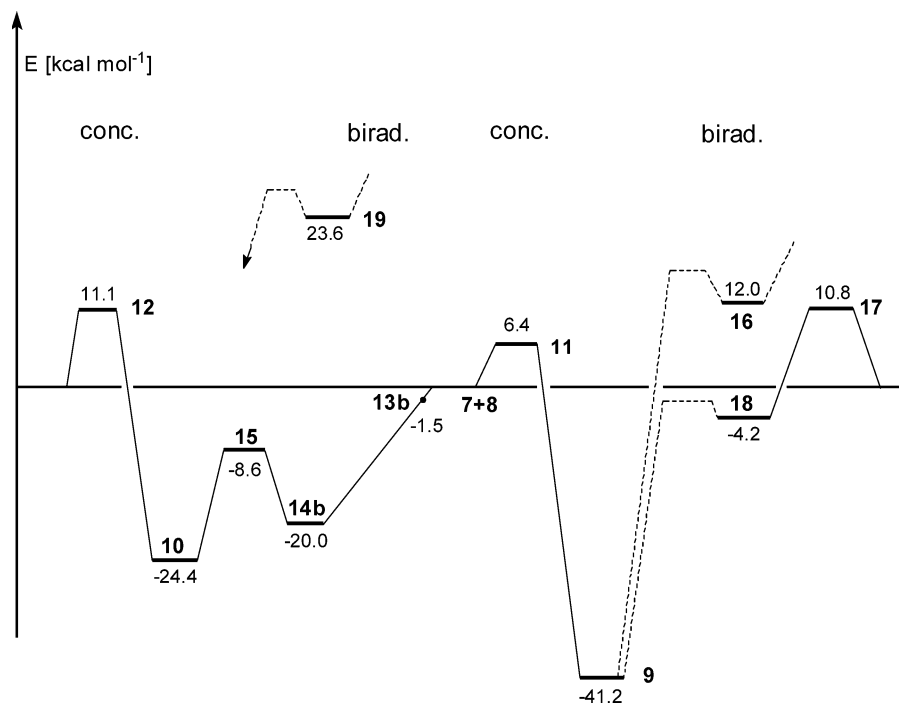


Figure 2. (U)B3LYP/6-31G**/(U)HF/3-21G* energy diagram for the concerted and stepwise cycloaddition of thiobenzophenone *S*-methylide to thioacetone in kcal mol⁻¹.

Table 2. C,C-Biradical Pathways to **10** (UB3LYP/6-31G**/UHF/3-21G*); Energies Relative to Reactants in kcal mol⁻¹

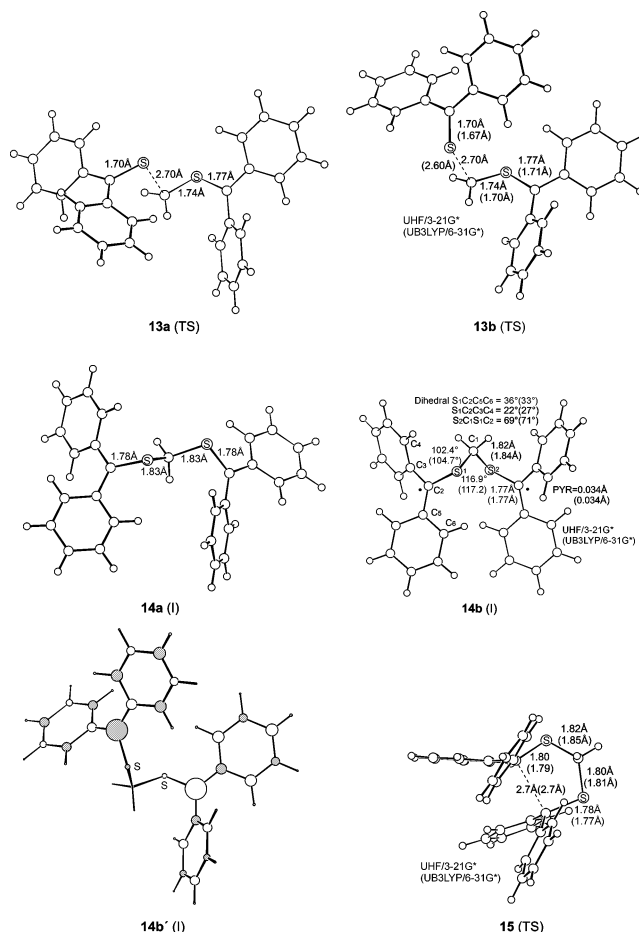
structure	$\Delta ZPVE^a$	$\Delta ZPVE$		%BRC		$E_{rel} + \Delta ZPVE$
		UB3LYP/6-31G*	E_{rel}	CAS(<i>m,n</i>)/3-21G*	<i>m,n</i>	
13a (TS) ^b	0.4		-1.2	47.0	6,5	-0.8
13b (TS) ^b	0.4		-1.9	44.3	6,5	-1.5
14a (I)	1.2		-18.4	89.6	2,2	-17.2
14b (I)	1.2	1.4	-21.4	98.0	2,2	-20.2 ^a / -20.0 ^c
15 (TS) ^b	1.5		-10.1	28.1	2,2	-8.6

^a $\Delta ZPVE$ from ref 7, cycloaddition of thioacetone *S*-methylide to thioacetone; ^b See text; ^c $\Delta ZPVE$ from an UB3LYP/6-31G* optimization; ^d Triplet energy (UB3LYP/6-31G**/UHF/3-21G*); ^e Closed shell energy (RB3LYP/6-31G**/UHF/3-21G*).

and **13b** assumed here should be located *before* the proper TS. The energies of these “snapshots” on the way to real TSs should be positive relative to the reactants level. However, evaluation of their energies by single-point UB3LYP/6-31G**/UHF/3-21G* calculations furnished -0.8 kcal mol⁻¹ for **13a** and -1.5 kcal mol⁻¹ for **13b** (Table 2). Using this level of theory, there seem to be no barriers on the way to biradical conformations **14a** and **14b**. The same single-point method provided the energies of the biradicals, -17.2 kcal mol⁻¹ for **14a** and -20.2 kcal mol⁻¹ for **14b**, when ZPVE corrections for methyl-substituted biradicals⁷ were used. The biradical energies are only 7.2 and 4.2 kcal mol⁻¹, respectively, above the energy of dithiolane **10**. A pictorial representation of the potential energy surface is given in Figure 2.

ZPVE calculations for structures of the size of **14** require a high amount of computation time. This effort was undertaken for biradical **14b**, and the resulting $\Delta ZPVE$ amounts to 1.4 kcal mol⁻¹, i.e. only little different from the value (Table 2) obtained for the corresponding structures of methyl-substituted biradicals.⁷ Therefore, we used for the other structures of Table 2 the

$\Delta ZPVE$ values which come from the study of the system thioacetone *S*-methylide + thioacetone.⁷



Not the barrier of ring closure, **14** → **10**, but rather that of ring opening was calculated. The C–C bond of **10** was

Table 3. (U)B3LYP/6-31G* Calculations on Thiobenzophenone *S*-methylide (**7**), Thiobenzophenone (**8**), Cycloadduct **10**, TSs **11**, **13b**, and **15**, and Biradical **14b**; Energies Relative to **7** + **8** in kcal mol⁻¹

structure	$\Delta ZPVE$	E_{rel}	%BRC CAS(<i>m,n</i>) 3-21G*	<i>m,n</i>	$E_{rel} + \Delta ZPVE$
7			24.2	4,3	
8			10.5	2,2	
7+8	0.0	0.0			0.0
10 (Prod)	3.8	-26.6			-22.8
11 (TS)	0.6	6.3			6.9
13b (TS) ^b	0.4 ^a	+0.4	30.4	6,5	+0.8
14b (I)	1.4	-16.8	95.1	2,2	-15.4
15 (TS) ^b	1.5 ^a	-6.5	27.1	2,2	-5.0

^a $\Delta ZPVE$ from ref 7, cycloaddition of thioacetone *S*-methylide to thioacetone. ^b See text.

successively elongated by UHF/3-21G* calculations until the apparent TS **15** was reached at a distance of 2.7 Å, and a relative energy of -8.6 kcal mol⁻¹ (single-point UB3LYP/6-31G*//UHF/3-21G*) resulted. On further elongation, the reaction coordinate leads to biradical conformation **14b** which has C₂ symmetry. Structure **14b'** displays a different view of **14b** and presents the spin density distribution. Most of the density is accumulated at the two central C atoms, and the amount of delocalization into the phenyl rings depends on the differing SC-CC dihedral angles. CAS(2,2)/3-21G* calculations attribute 90 and 98% BRC to **14a** and **14b**, respectively. According to the energy criteria (see Computational Methods and Table 2) **14** constitutes a true singlet biradical: The difference between the RB3LYP/6-31G* and UB3LYP/6-31G* energies on the UHF/3-21G* structure is -15.2 kcal mol⁻¹, and there is no energetic difference between the singlet and triplet biradical. The TS **15** is on the way to a closed shell molecule, as the decrease of BRC to 28% reveals. Similarly, the structures **13a** and **13b** (no local maxima) show partial BRC (47 and 44%).

Thus, the exclusive formation of the thermodynamically less favored dithiolane **10** from **7** + **8** is kinetically controlled by the intermediacy of *C,C*-biradical **14b**. However, the calculated stability of **14b** (-20.2 kcal mol⁻¹) compared with that of **10** (-24.4 kcal mol⁻¹) poses a problem. Chemical intuition militates against such a small energy difference of biradical and closed shell cyclization product.

As a check on the reliability of the computational results, we subjected some of the single-point calculations of Table 2 (UHF/3-21G* geometry) to optimization on the UB3LYP/6-31G* level; admittedly, the computation times amounted sometimes to several weeks of CPU (Athlon 2000+ processor). For some stationary points a frequency analysis was carried out to obtain ZPVEs, likewise with UB3LYP/6-31G* (Table 3); for maxima of the reaction coordinate, the estimates of ZPVEs reported in Table 2 were used. Geometry parameters of the new UB3LYP/6-31G* structures are given in the corresponding formulas. Whereas the relative energy of dithiolane **10** at -22.8 kcal mol⁻¹ is modestly changed (-24.4 kcal mol⁻¹ before), biradical **14b** turns out to be at -15.4 kcal mol⁻¹, i.e. higher by 4.8 kcal mol⁻¹ than the calculation based on the UHF/3-21G* geometry.

The new reaction coordinate calculation found an apparent TS **13b** at a CS separation of 2.60 Å and provides a positive value of +0.8 kcal mol⁻¹ (Table 3). Thus, a tiny barrier of biradical formation results at this level of theory. The TS **15** of

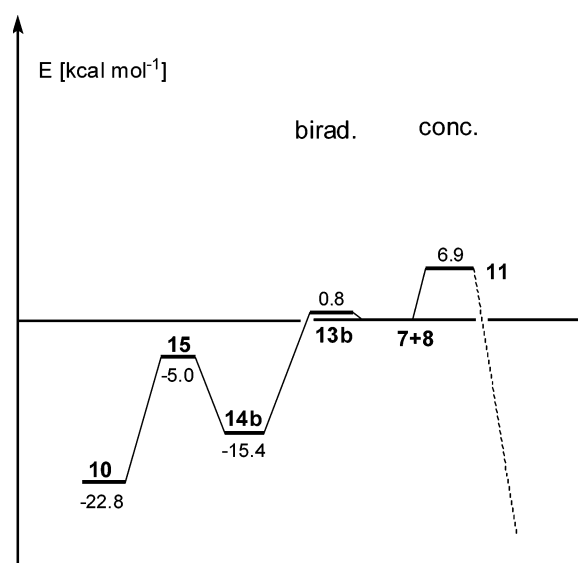


Figure 3. (U)B3LYP/6-31G* potential energy surface for the biradical pathway of cycloaddition of **7** to **8** (kcal mol⁻¹).

biradical cyclization remains at a CS distance of 2.7 Å, but the energy rises from -8.6 to -5.0 kcal mol⁻¹ (Table 3). The optimized energy of *C,C*-biradical **14b** is now 7.4 kcal mol⁻¹ above the level of dithiolane **10** (Figure 3), i.e. sufficient to preclude direct evidence for an equilibrium concentration of **14b** in the solution of **10**. Nevertheless, doubts remain about the calculated biradical energies.

Bond Dissociation Energies and the B(3)LYP Functional. B3LYP DFT calculations have been used with great success to evaluate closed shell systems. The calculation of radicals and biradicals is no easy task. In particular, it is not clear within density functional theory what the significance of the calculations is, as the electron density and not the wave function with a proper *S*² value is determined. Since we used the B3LYP functional³⁰ throughout, we checked its reliability for the calculation of bond dissociation energies (BDEs). The influence of different basis sets was tested; in particular, the influence of additional polarization functions was investigated. BDEs were calculated for several C-C bonds, a C-S bond, and a S-S bond. The DFT results are compared with those of the advanced method CBS-QB3 (Table 4). The results for the latter procedure provide agreement of the experimental BDEs (ΔH_{298}) with the calculated values within 0.0–1.0 kcal mol⁻¹ for four out of five systems, a very satisfactory result. In the case of C₆H₅-CH₂• + CH₃•, the CBS-QB3 calculated value may even be better than the two experimental data reported.

UB3LYP reproduces the dissociation of ethane to two methyl radicals fairly well with the basis sets BS1 (3-21G*), BS2 (6-31G*), and BS3 (6-31G*(2d,p)), but the extended basis sets BS4 (6-311++G**) and BS5 (6-311+G(3df,2p)) overestimate the stability by 3.1 kcal mol⁻¹ per methyl radical. When the isopropyl radical combines with methyl, the BDE (ΔH_{298}), calculated with BS2 and BS3, is too low by about 6 kcal mol⁻¹, i.e., the stability of isopropyl is overestimated, 3 kcal mol⁻¹ per stabilizing methyl group. A better agreement is found with the 3-21G* basis set (BS1).

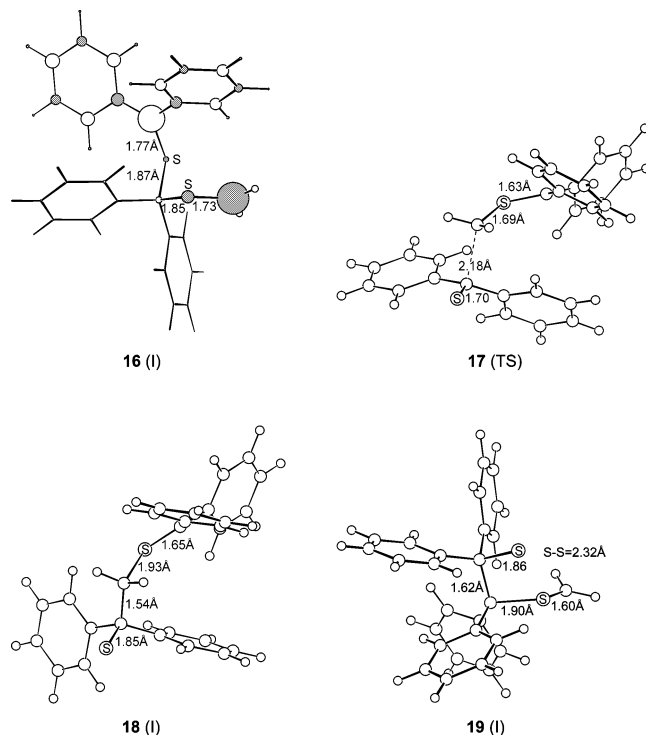
The same irritating trend is observed in generating sulfur-centered radicals. UB3LYP/6-31G* calculated BDEs for CH₃-

(30) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648.

Table 5. UB3LYP/6-31G**/UHF/3-21G* Calculations on Intermediates **14b**, **16**, **18**, and **19** and TS **17**; Energies Relative to Reactants in kcal mol⁻¹

structure	$\Delta ZPVE$	E_{rel}	%BRC			$E_{rel} + \Delta ZPVE$
			CAS(m,n)/ 3-21G*	m,n	$m[D]$	
14b (I)	1.4 ^a	-21.4	98.0	2,2	0.4	-20.0
16 (I)	1.4 ^a	10.6	96.3	2,2	0.9	12.0
17 (TS)	0.9 ^b	9.9	29.0	6,5	6.2	10.8
18 (I)	2.5 ^b	-6.7	82.7	2,2	7.6	-4.2
		+2.8 ^c			0.7	
		-4.7 ^d			10.5	
19 (I)	2.5 ^b	21.1	14.1	2,2	2.9	23.6

^a $\Delta ZPVE$ taken from **14b** (UB3LYP/6-31G* geometry), ^b $\Delta ZPVE$ taken from RHF/3-21G* calculation, see text, ^c Triplet energy (UB3LYP/6-31G**/(RHF/3-21G*)), ^d Closed shell energy (RB3LYP/6-31G**/(RHF/3-21G*)).

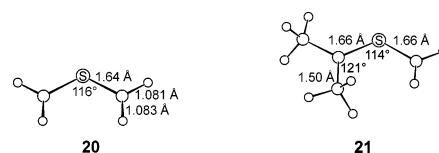


mol⁻¹ above the reactants. Nevertheless, the pathway to intermediate **18** can hardly compete with that via *C,C*-biradical **14** which is formed without activation energy at this level of calculation. The terminal CS bond lengths, those with the unpaired electron at carbon, are 1.77 Å for (C₆H₅)₂C-S in **14a** and **16** and 1.73 Å for H₂C-S in **16**. Thus, they are intermediate in length between a CS double and a CS single bond (see **8**, **9**, and **10**). The BRCs for **16** and **18** are 96 and 83% according to CAS(2,2). In **19**, a compact structure, where the sulfur atoms come close to each other (2.32 Å), indicating some covalent interaction, the BRC is 14%.

It came as a surprise that the relevant CS bond lengths in **18** and **19** are quite different from those in **14a**, being close to a CS double bond ((C₆H₅)₂C-S 1.65 in **18** and H₂C-S 1.60 Å in **19**) and to a CS single bond ((C₆H₅)₂C-S 1.85 in **18** and 1.86 Å in **19**), respectively. The C-S bond lengths of thiocarbonyl ylide **7** amount to 1.68 and 1.61 Å and in thiobenzophenone (**8**) to 1.66 Å. This suggests a strong zwitterionic character of the ground states of **18** and **19** as represented in **18a** and **19a** (Scheme 2), which is also supported by the fact that UHF and RHF wave functions are identical. This would indicate that

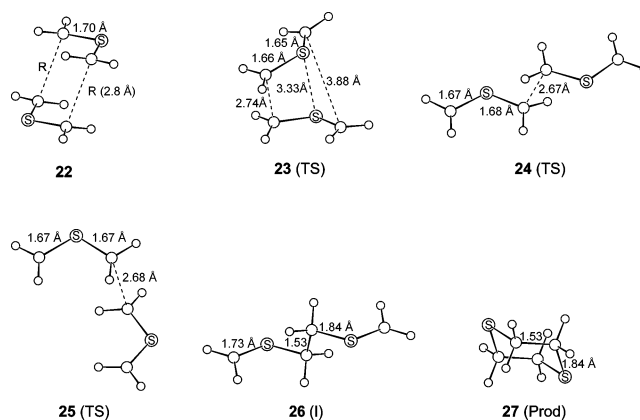
the (insufficient) CAS(2,2) calculation strongly exaggerates the % BRC of **18**. To check on this, the UB3LYP/6-31G* and RB3LYP/6-31G* single-point calculations on structure **18** were compared. Although the calculated percent BRC is >80, the energy difference is only 2 kcal mol⁻¹ in favor of the unrestricted calculation, pointing to a small BRC. The comparison of singlet and triplet energies—the triplet is 9.5 kcal mol⁻¹ higher in energy—also supports the zwitterionic, closed shell representation **18a** of a sulfonium thiolate (Scheme 2). The dipole moment of 7.6 D (UB3LYP/6-31G**/UHF/3-21G*) is a further hint in the direction of the zwitterion; for biradicals **14b** and **16** values of 0.4 and 0.9 D were obtained. It has to be concluded that CAS(2,2)-determined BRCs alone are not a sufficient measure of the correct ground-state character.

The formation of **10** via cyclization of **14** has been discussed above. It is expected that **19** will be less stable than **14** and, therefore, will not be a candidate as intermediate to **10**. *C,C*-Biradical **16** and zwitterion **18**, both lead to **9**, but they do not provide pathways to the cycloadduct, which are energetically comparable to the formation of **10** via **14**, as shown above.



Dimerization of Thiocarbonyl Ylides to 1,4-Dithianes. This dimerization is formally a $\pi 4_s + \pi 4_s$ cycloaddition which is forbidden to take a concerted pathway according to the rules of conservation of orbital symmetry.³⁴ A two-step process via a biradical intermediate is expected instead.

Thiocarbonyl ylides are not isolable. In the case of thiobenzophenone *S*-methylide (**7**), the dimerization to form 2,2,3,3-tetraphenyl-1,3-dithiane (**33**) in a second-order reaction is preferred to the electrocyclization to give 2,2-diphenylthiirane; the latter is a first-order reaction which was observed in very dilute solution.^{12,13} On the other hand, aliphatic thione *S*-methylides exclusively form thiiranes, and a dimerization was not reported. For reasons of comparison, the dimerizations of *S*-methylides **20** and **21** were likewise analyzed.



Dimerization of Thioformaldehyde *S*-Methylide (20**).** The symmetrical approach of two molecules of **20** was considered

(34) Woodward, R. B.; Hoffmann, R. *Angew. Chem.* **1969**, *81*, 797–869; Woodward, R. B.; Hoffmann, R. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 781.

Table 6. Dimerization of Thioformaldehyde *S*-Methylide (**22**) ((U)B3LYP/6-31G*), Thioacetone *S*-Methylide (**21**) ((U)B3LYP/6-31G*), and Thiobenzophenone *S*-Methylide (**7**) ((U)B3LYP/6-31G*//((U)HF/3-21G*); Energies Relative to Reactants in kcal mol⁻¹

structure	$\Delta ZPVE$	E_{rel}	%BRC CAS(<i>m,n</i>)/ 6-31G*	<i>m,n</i>	$E_{rel}+\Delta ZPVE$
22 ^a		10.1			
23 (TS)	+1.0	0.5	28.9	8,6	1.5
24 (TS)	-0.5	2.9	35.4	8,6	2.4
25 (TS)	-0.4	2.6	34.1	8,6	2.2
26 (I)	+3.3	-50.3	97.4	2,2	-47.0
27 (Prod)	+9.3	-125.8			-116.5
28 (TS)	-0.1	3.0	39.8	8,6	2.9
29 (I)	+3.9	-50.3	97.9	2,2	-46.4
30 (Prod)	+8.6	-109.2			-100.6
31 (TS) ^a	-0.1 ^b	2.5	28.2 ^c	8,6	2.4
32 (I)	+3.9 ^b	-68.0	93.6 ^c	2,2	-64.1
33 (Prod)	+8.6 ^b	-70.2			-61.6

^a See text. ^b $\Delta ZPVE$ from dimerization of thioacetone *S*-methylide. ^c CAS(*m,n*)/3-21G*.

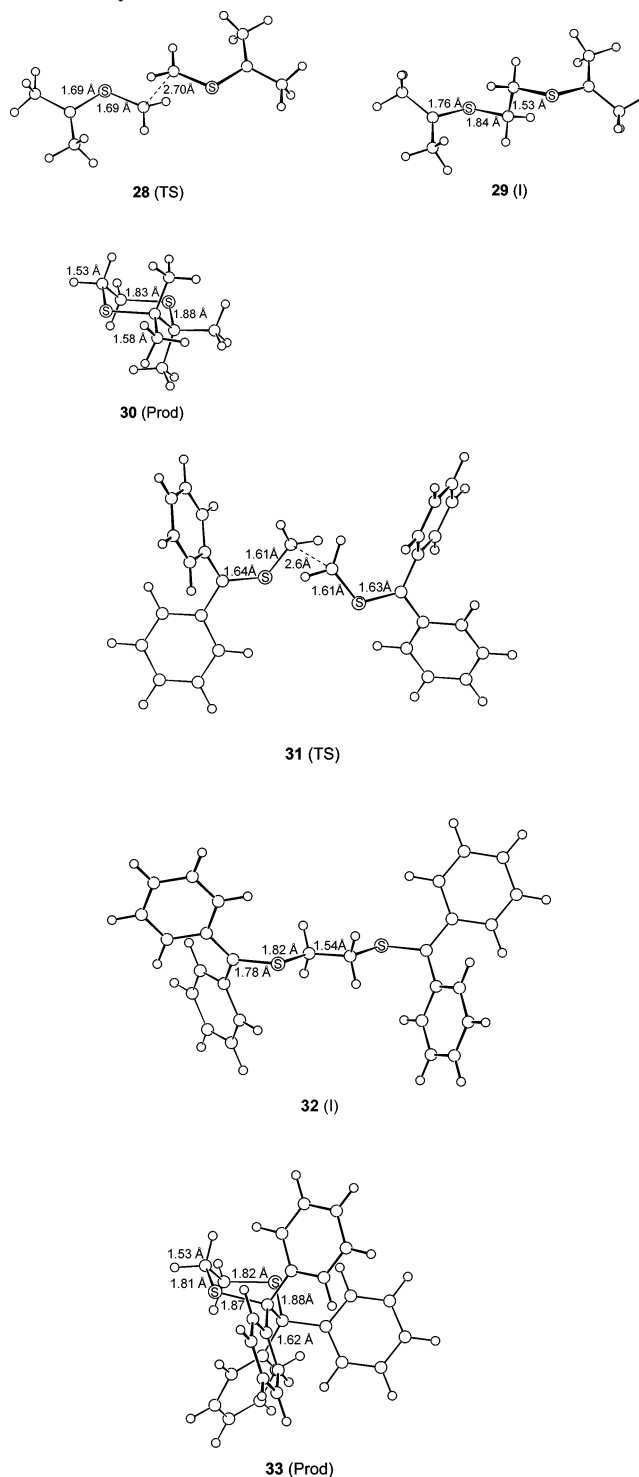
first, and the distances of the new CC σ -bonds were chosen as reaction coordinate (marked in **22**). As anticipated, a TS for the “forbidden” concerted cycloaddition could not be found. It is fascinating to learn that the system escapes to structures in which only one new σ -bond is formed. The TSs **23** – **25** are different conformations on the way to *C,C*-biradicals. These TSs are located slightly above the reactants level (Table 6). The smaller value for **23** results from the close distance of the two sulfur atoms (3.3 Å), which generates some covalent interaction with concomitant reduction of BRC to 29%, whereas both **24** and **25** show 35% BRC. It should be remembered that the concerted cycloaddition of **20** with H₂C=S proceeds without activation energy.⁷

The formation of the extended biradical **26** (BRC 97%) via TS **24** is exothermic by 47.0 kcal mol⁻¹ with respect to the reactants level. The dithiane **27** assumes a chair conformation which lies at -116.5 kcal mol⁻¹.

Dimerization of Thioacetone *S*-Methylide (21**) and Thiobenzophenone *S*-Methylide (**7**).** The TS **28** was considered for the generation of the extended *C,C*-biradical **29** from two molecules of **21**. The activation energy is 2.9 kcal mol⁻¹ (Table 6). The biradical **29** is formed with liberation of 46.4 kcal mol⁻¹, and the 1,4-dithiane **30** is found at -100.6 kcal mol⁻¹ relative to two molecules of **21**. The BRC of intermediate **29** amounts to 98%.

Of special interest in our context is the dimerization of thiobenzophenone *S*-methylide (**7**). The size of the system limits the method of calculation, and an approximate TS **31** (+2.4 kcal mol⁻¹) was determined by a reaction coordinate calculation on the UB3LYP/6-31G*//UHF/3-21G* level (Table 6). The extended, C₂-symmetric biradical **32** and the dithiane **33** were found at -68.0 and -70.2 kcal mol⁻¹, respectively. When ZPVE was taken into account, the *C,C*-biradical **32** (-64.1 kcal mol⁻¹) comes out even more stable than product **33** (-61.6 kcal mol⁻¹). The dithiane **33** assumes a chair conformation, placing two phenyl groups each in equatorial and axial positions. The energy level (based on reactants) of the unsubstituted dithiane **27** is by 55 kcal mol⁻¹ lower than that of the tetraphenyl derivative **33**; steric crowding in the product and the loss of phenyl conjugation in **7** are responsible.

According to the energy data, the dithiane **33** should be in equilibrium with biradical **32**, the latter even prevalent. However, the tetraphenyl dithiane **33** is a stable colorless substance with mp 205–207 °C; the blue color of the melt signals thiobenzophenone as decomposition product. Qualitative observations suggest that the thermal stability of **33** exceeds that of tetraphenyl-1,3-dithiolane **10**. This result demonstrates once more that B3LYP density functional calculations overestimate the stability of biradicals.



Conclusions

Concerted and two-step cycloadditions of thiobenzophenone *S*-methylide (**7**) with thiobenzophenone (**8**) to yield 4,4,5,5-

tetraphenyl-1,3-dithiolane (**10**) were studied by density functional theory, mainly the B3LYP functional. The results suggest an intermediate *C,C*-biradical **14** which is stabilized by two adjacent thioether functions and two pairs of phenyl groups. Concerted cycloadditions require higher activation energies, and the energetically more favorable 2,2,4,4-tetraphenyl-1,3-dithiolane (**9**) would be preferred. Interestingly, attack of **7** at the carbon atom of **8** does not furnish *C,S*-biradicals, but rather closed-shell species, represented as sulfonium thiolates.

An overestimation of radical stability by the B3LYP functional was unveiled when the BDEs of model systems were calculated. In particular, substituent effects (alkyl, methylthiyl, phenyl) are not properly reproduced. CBS-QB3 gave correct results and is well suited to calculate radicals but, unfortunately, can thus far not be applied to systems of a size greater than benzyl. The stabilization (B3LYP) of *C,C*-biradical **14** likewise comes out too high, and its value depends on the basis set. However, the biradical pathway of the cycloaddition can be considered as well substantiated. CAS(2,2) determined BRCs may not always be reliable. Comparison of energy differences of restricted and unrestricted calculations, together with structural data, provide additional criteria for assessment of biradical character.

For several intermediates and TSs described above, the energies achieved by restricted calculation were lowered by

some kcal mol⁻¹ in the unrestricted mode. This would be in harmony with a mixture of zwitterionic and biradical character. In our opinion, zwitterion and singlet biradical are not separate entities, strictly defined, but rather extremes on a continuous scale.^{25c} The conjugative isolation of the left and right parts of the species by a tetrahedral C atom does not block the delocalization of one electron.

Thiocarbonyl ylide **7** dimerizes to 2,2,3,3-tetraphenyl-1,4-dithiane (**30**). B3LYP calculation not only discloses a biradical intermediate, but attempts of finding a TS for a concerted $\pi 4_s + \pi 4_s$ cycloaddition failed, in accordance with the rules of orbital control.

Acknowledgment. We thank Professor G. Jansen, Essen for helpful discussions. The generous allocation of computer time by the Hochschulrechenzentrum of the University of Essen and support by the Fonds der Chemischen Industrie, Frankfurt, are gratefully acknowledged.

Supporting Information Available: Tables with absolute energies at 0 K (PDF); a text file with Cartesian coordinates of structures **7** to **33** and the CBS-QB3 structures of the molecules in Table 4. This material is available free of charge via the Internet at <http://pubs.acs.org>.

JA0377551