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# **Electrophilicities of Bissulfonyl Ethylenes**

# Haruyasu Asahara and Herbert Mayr<sup>\*[a]</sup>

Dedicated to Professor Stefan Toma on the occasion of his 75<sup>th</sup> birthday

**Abstract:** Kinetics of the reactions of bissulfonyl ethylenes with various carbanions, a sulfur ylide, and siloxyalkenes have been investigated photometrically at 20°C. The second-order rate constants have been combined with the known nucleophile-specific parameters N and  $s_N$  for the nucleophiles to calculate the empirical electrophilicity parameters E of bissulfonyl ethylenes according to the linear free energy relationship log  $k(20^\circ\text{C}) = s_N(N+E)$ . Structure-reactivity relationships are discussed, and it is shown that the electrophilicity parameters E derived in this work can be employed to define the synthetic potential of bissulfonyl ethylenes as Michael acceptors.

Keywords: electrophilicity • kinetics • linear free-energy relationship • Michael additions • sulfones

SO<sub>2</sub>Ph

ŚO₂Ph

## Introduction

Bissulfonyl ethylenes **1** are widely used reagents in organic synthesis<sup>[1]</sup> because they are active Michael acceptors, dienophiles, and dipolarophiles.<sup>[1–3]</sup> In particular, asymmetric conjugate additions of nucleophiles to bissulfonyl ethylenes are of considerable importance for stereoselective carbon-carbon bond-forming reactions. After the first report of organocatalytic Michael additions of aldehydes to bissulfonyl ethylenes mediated by *N*-isopropyl-2,2'-bipyrrolidine by Alexakis and coworkers,<sup>[4]</sup> there has been considerable research on conjugate additions to bissulfonyl ethylenes. Cinchona alkaloids,<sup>[5]</sup> thiourea derivatives,<sup>[6]</sup> prolinol silyl ethers,<sup>[7]</sup> primary amines,<sup>[8]</sup> aminal-pyrrolidines,<sup>[9]</sup> chiral diamines,<sup>[10]</sup> and tricyclic secondary amines<sup>[11]</sup> have been used as catalysts.

To define the scope of potential reaction partners of bissulfonyl ethylenes, we have now quantified the electrophilicities of representatives of these electron-deficient  $\pi$ -systems (Scheme 1). Previously, we have shown that a large variety of reactions of electrophiles with nucleophiles can be described by Equation (1), in which  $k_2$  corresponds to the second-order rate constant in  $M^{-1}s^{-1}$ , N and  $s_N$  are nucleo-

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Scheme 1. Bissulfonyl ethylenes 1a-g used in this study.

SO<sub>2</sub>Ph

ŚO₂Ph

phile-specific parameters, and E is an electrophilicity parameter.<sup>[12]</sup>

$$\log k_2(20\,^\circ\mathrm{C}) = s_\mathrm{N}(N+E) \tag{1}$$

By using diarylcarbenium ions and quinone methides as reference electrophiles and donor-substituted ethylenes and carbanions as reference nucleophiles, we have succeeded to construct comprehensive nucleophilicity and electrophilicity scales.<sup>[13]</sup> Michael additions of carbanions to benzylidenemalononitriles,<sup>[14]</sup> benzylidene-1,3-indandiones,<sup>[15]</sup> benzylidene barbituric and thiobarbituric acids,<sup>[16]</sup> benzylidenemalonates,<sup>[17]</sup> benzylidene Meldrum's acids,<sup>[18]</sup> and iminium ions<sup>[19]</sup> have previously been shown to follow Equation (1).

We now report on the kinetics of the reactions of **1a–g** with nucleophiles of known N and  $s_N$  parameters, i. e., carbanions **2a–g**,<sup>[13,14]</sup> sulfur ylide **3**,<sup>[20]</sup> and silyl enol ethers **4a–d**<sup>[13]</sup> (Table 1), and show that the second-order rate constants of these reactions follow Equation (1).

	Nucleophile	Solvent	Ν	s <sub>N</sub>	Ref.
2a	√NO2 <sup>Θ</sup>	DMSO	21.54	0.62	[14]
2b	H₂C <sup>₂NO2<sup>⊕</sup></sup>	DMSO	20.71	0.60	[13e]
2 c	$EtO_2C \underbrace{CO_2Et}_{\Theta}$	DMSO	20.22	0.65	[13b]
2 d	NC CO2E1	DMSO	19.62	0.67	[13b]
2 e		DMSO	19.36	0.67	[13b]
2 f	OEt	DMSO	18.82	0.69	[13b]
2 g		DMSO	17.64	0.73	[13b]
3	Me <sub>2</sub> S O O Br	DMSO	13.78	0.72	[20]
4a	OSiMe <sub>3</sub>	MeCN CH <sub>2</sub> Cl <sub>2</sub>	12.34 12.56	0.72 0.70	[13i] [13a.c]
4b	OSiMe <sub>3</sub>	MeCN CH <sub>2</sub> Cl <sub>2</sub>	10.52 10.61	0.78 0.86	[13i] [13a.c]
4c	OSiMe <sub>3</sub> OMe	MeCN CH <sub>2</sub> Cl <sub>2</sub>	9.11 9.00	0.88 0.98	[13i] [13a,c]
4d	OSiMe <sub>3</sub>	MeCN CH <sub>2</sub> Cl <sub>2</sub>	6.43 6.57	0.89 0.93	_ <sup>[a]</sup> [13a,c]

Table 1. Nucleophilicity parameters of carbanions **2a–g**, sulfur ylide **3**, and silyl enol ethers **4a–d**.

[a] This work.

# **Results and Discussion**

### **Product Studies**

The combination of the bissulfonyl ethylenes **1b**–g with 1.1 equivalents of the potassium salts of **2a**–g in dry DMSO, followed by workup with aqueous acetic acid gave the adducts **5**, which were isolated and characterized (Scheme 2). In case of the reaction of **1c** with the cyano-substituted carbanions **2d** and **2e**, and of the benzylidenedithiane tetroxide **1g** with **2g**, the anionic adducts **5cd**<sup>-</sup>, **5ce**<sup>-</sup>, and **5gg**<sup>-</sup> were identified by <sup>1</sup>H and <sup>13</sup>C NMR spectroscopy because retro-Michael additions occurred during acidic workup of these adducts. The bissulfonyl ethylene **1a** reacted with the sulfur ylide **3** to form the cyclopropane **6** (Scheme 3) in analogy to



Scheme 2. Reactions of the potassium salts of the carbanions **2b–g** with the bissulfonyl ethylenes **1b–g** in DMSO.

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Scheme 3. Reactions of sulfur ylide 3 with the bissulfonyl ethylene 1a in DMSO.

other cyclopropanation reactions of sulfur ylides,<sup>[21,22]</sup> and 4keto-1,1-bissulfonyl alkanes were obtained from the reaction of **1a** with the silylated ketene acetals and enol ethers **4a–d** (Scheme 4). Since analogous products can be expected for other combinations of the bissulfonyl ethylenes **1a–g** with the nucleophiles **2–4**, product studies have not been performed for all combinations which were studied kinetically.



Scheme 4. Reactions of the silvl enol ethers 4a-d with the bissulfonyl ethylene 1a in CH<sub>3</sub>CN.

# **Kinetic Measurements**

To achieve pseudo-first-order kinetics, solutions of the bissulfonyl ethylenes **1a-g**  $(1.0 \times 10^{-5} \text{ to } 1.0 \times 10^{-3} \text{ M})$  were mixed with an excess of compounds 2a-g, 3, or 4a-d. The decay of the absorption of the electrophiles was then followed spectrophotometrically either with stopped-flow instruments or, for reactions with half-lives of more than about 60 seconds, with conventional UV/Vis diode-array spectrometers equipped with fiber optics and a submersible probe. Because of an overlap of the absorption bands of the bissulfonyl ethylenes and the carbanions, the absorbances did not reach zero at the monitored wavelengths at the end of the reactions with 1b,e. From the fit of the exponential function  $A_t = A_0 \exp(-k_{obs}t) + C$  to the observed absorbance  $A_t$ , the first-order rate constants  $k_{obs}$  were derived. As exemplified in Figure 1 for the reaction of 1c with 2e, plots of  $k_{\rm obs}$  versus the concentrations of the nucleophiles were linear with intercepts near zero for all reactions of 1 with 2, **3**, and **4**. The slopes of the plots of  $k_{obs}$  versus [Nu] gave the second-order rate constants  $k_2$  [Equation (2)], which are listed in Table 2.

$$k_{\rm obs} = k_2 [\rm Nu] \tag{2}$$

Figure 2 shows that the rate constants for the reactions of the bissulfonyl ethylenes **1** with various types of nucleophiles (log  $k_2/s_N$ ) correlate well with the corresponding nucleophilicity parameters N listed in Table 1, thus showing the applicability of Equation (1). In most cases, calculated and experimental rate constants agree within a factor of 3

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Figure 1. Exponential decay of the absorbance at 350 nm during the reaction of **1c** with **2e**-K in DMSO at 20 °C ([2e] = 1.00 mM;  $k_{obs} = 9.36 \text{ s}^{-1}$ ). Inset: Determination of the second-order rate constant  $k_2 = 9.95 \times 10^3 \text{ m}^{-1} \text{ s}^{-1}$  from the slope of the correlation of the first-order rate constants  $k_{obs}$  with the concentrations of **2e**.



Figure 2. Correlations of  $(\log k_2)/s_N$  for the reactions of bissulfonyl ethylenes **1a–d** with nucleophiles in DMSO at 20°C versus the corresponding *N* parameters [correlation lines are fixed at a slope of 1.0, as required by Equation (1); reactions of **4a–d** in CH<sub>3</sub>CN]. Open symbols were not included for the calculation of the correlation lines. For the correlations of the bissulfonyl ethylenes **1e-g**, see Figure S1 in the Supporting Information.

(Table 2). Though deviations of this magnitude are within the reliability limits of Equation (1), some systematic deviations are obvious. The anion of malononitrile (2e) commonly reacts 2–3 times faster than expected from the correlations, whereas the malonate anion 2c is always 2–4 times less reactive than expected. While analogous deviations have also been observed for the reactions of these two carbanions with benzylidene Meldrum's acids and benzylidene barbituric and thiobarbituric acids, the origin of these deviations is still not understood.

Table 2. Experimental and calculated second-order rate constants for the reactions of **1a–g** with the carbanions **2a-g**, S-ylide **3**, and silyl enol

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ethers <b>4a–d</b> at 20°C in DMSO.							
Electrophile $(E)^{[a]}$	Nucleophile	$k_2^{exp}$	$k_2^{\text{calcd[b]}}$	$k_2^{\text{exp}}/k_2^{\text{calcd}}$			
		$[M^{-1} S^{-1}]$	$[M^{-1} S^{-1}]$				
<b>1a</b> (-7.50)	3	$1.70 \times 10^{4}$	$3.30 \times 10^{4}$	0.52			
SO₂Ph	4a	$3.42 \times 10^{3[c]}$	$3.03 \times 10^{3}$	1.1			
I SO₂Ph	4b	$5.08 \times 10^{2[c]}$	$2.25 \times 10^{2}$	2.3			
	4c	9.03 <sup>[c]</sup>	$2.59 \times 10^{1}$	0.36			
	4 d	$2.33 \times 10^{-1[c]}$	$1.11 \times 10^{-1}$	2.1			
<b>1b</b> (-12.93)	2b	$3.97 \times 10^{4}$	$4.66 \times 10^{4}$	0.85			
SO <sub>2</sub> Ph	2 c	$3.35 \times 10^{4}$	$5.49 \times 10^{4}$	0.61			
SO <sub>2</sub> Ph	2 d	$3.13 \times 10^{4}$	$3.04 \times 10^{4}$	1.0			
-	2e	$3.79 \times 10^{4}$	$2.04 \times 10^{4}$	1.9			
	2 f	$1.13 \times 10^4$	$1.16\!\times\!10^4$	0.97			
<b>1c</b> (-13.88)	2b	$1.54 \times 10^{4}$	$1.25 \times 10^{4}$	1.2			
SO <sub>2</sub> Ph	2 c	$6.14 \times 10^{3}$	$1.31 \times 10^{4}$	0.47			
SO <sub>2</sub> Ph	2 d	$6.28 \times 10^{3}$	$6.96 \times 10^{3}$	0.90			
MeO 🗸 -	2e	$9.95 \times 10^{3}$	$4.66 \times 10^{3}$	2.1			
	2 f	$2.08 \times 10^{3}$	$2.54 \times 10^{3}$	0.82			
	2 g	$6.03 \times 10^2$	$5.51 \times 10^2$	1.1			
<b>1d</b> (-16 53)	29	$1.04 \times 10^{3}$	$1.27 \times 10^{3}$	0.82			
<b>10</b> (10.55)	2a 2h	$4.17 \times 10^2$	$3.21 \times 10^2$	13			
SO-Ph	2 c <sup>[d]</sup>	$4.17 \times 10^{1}$	$2.50 \times 10^2$	0.32			
Me <sub>2</sub> N	20 2 d	$1.04 \times 10^2$	$1.17 \times 10^2$	0.89			
	2 u 2 u <sup>[d]</sup>	$1.04 \times 10^{2}$ 2.77 × 10 <sup>2</sup>	$7.85 \times 10^{1}$	3.5			
	20 2f	$3.12 \times 10^{1}$	$7.03 \times 10^{1}$ 3 79 × 10 <sup>1</sup>	0.82			
	2 g	8.31	6.45	1.3			
$1_{0}(11.79)$	<b>2</b> h	$2.60 \times 10^5$	$2.28 \times 10^{5}$	11			
re (-11.78)	20 2 o <sup>[d]</sup>	$2.00 \times 10$	$2.26 \times 10^{5}$	1.1			
S S	201	$0.13 \times 10$ 1 44 × 10 <sup>5</sup>	$5.06 \times 10^{5}$ 1.70 × 10 <sup>5</sup>	0.20			
025	2u 2o	$1.44 \times 10$ 2.42 \times 10 <sup>5</sup>	$1.79 \times 10^{5}$ $1.20 \times 10^{5}$	2.0			
	20 21	$2.43 \times 10^{4}$	$1.20 \times 10^{4}$	2.0			
	21 2g	$3.22 \times 10^{4}$	$1.89 \times 10^4$	1.2			
	-8						
<b>1 f</b> (-13.02)	2 b	$8.30 \times 10^{4}$	$4.13 \times 10^{4}$	2.0			
	2 c	$2.10 \times 10^{4}$	$4.81 \times 10^{4}$	0.44			
	2 d	$1.97 \times 10^{4}$	$2.66 \times 10^4$	0.74			
MeOr V	2e	$4.24 \times 10^{4}$	$1.78 \times 10^{4}$	2.4			
	2 f	$5.33 \times 10^{3}$	$1.01 \times 10^{4}$	0.53			
	2g	$3.04 \times 10^{3}$	$2.37 \times 10^{3}$	1.3			
<b>1</b> g (-14.55)	2 a	$9.12 \times 10^{3}$	$2.14 \times 10^{4}$	0.43			
O <sub>2</sub>	2 <b>b</b> <sup>[d]</sup>	$2.93 \times 10^{4}$	$4.93 \times 10^{3}$	5.9			
	<b>2</b> c <sup>[d]</sup>	$1.34 \times 10^{3}$	$4.81 \times 10^{3}$	0.28			
MeO 20	2 d	$1.60 \times 10^{3}$	$2.48 \times 10^{3}$	0.65			
	2 e	$3.64 \times 10^{3}$	$1.66 \times 10^{3}$	2.2			
	2 f	$1.26 \times 10^{3}$	$8.77 \times 10^{2}$	1.4			
	2 g	$1.90 \times 10^{2}$	$1.79 \times 10^{2}$	1.1			

[a] The *E* parameters for **1a–g** result from a least-squares minimization of  $\Delta^2$ , with  $\Delta = \log k_2^{exp} - s_N(N+E)$ ;  $k_2^{exp}$  is taken from this table, and *N* and  $s_N$  of the nucleophiles are from Table 1. [b] Calculated by using Equation (1) with *E* from this table and *N* and  $s_N$  from Table 1. [c] Solvent: CH<sub>3</sub>CN. [d] Excluded for the calculation of the correlation lines because of relatively large deviations from the correlation line.

## **Structure–Reactivity Relationships**

According to Figure 3, the bissulfonyl ethylene 1a is about five orders of magnitude more reactive than its benzylidene analogue **1b**. Thus, phenyl substitution at the  $\beta$ -position (reaction site) of bissulfonyl ethylenes has a large retarding effect. Figure 3 furthermore shows that the cyclic bissulfones

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Figure 3. Comparison of E parameters for different bissulfonyl ethylenes with neutral and charged electrophiles. Data are from Table 2 and ref. [13i].

1e and 1f are approximately one order of magnitude more electrophilic than their acyclic counterparts 1b and 1c, respectively.

The 3-point correlation log *k* versus Hammett's  $\sigma_p^{[23a]}$  for compounds **1b–1d**, that is,  $E=4.40\sigma_p-12.8$  ( $r^2=0.9955$ ), gives a Hammett reaction constant  $\rho=2.95$  for reactions with nucleophiles of  $s_N=0.67$ , which is significantly larger than for *p*-substituted nitrostyrenes and quinone methides and even exceeds that of benzylidenemalonates, which have so far shown the strongest influence of the *p*-substitutents on electrophilicity.<sup>[23b]</sup>

Comparison of the crystal structures of compounds **1c** and **1f** (Figure 4) shows the different orientation of the sulfonyl groups with respect to the C=C double bond in the acyclic and cyclic compound.<sup>[24]</sup> The conformationally flexible bissulfone **1c** adopts a structure in which one of the S= O bonds of each sulfonyl group is coplanar with the C=C bond (torsion angle of  $C_1$ - $C_2$ - $S_1$ - $O_1$ ; 1.12°,  $C_1$ - $C_2$ - $S_2$ - $O_4$ ; -178.13°), while the ring structure of **1f** enforces a bisected conformation.

From the small difference between the electrophilicities of 1c and 1f (as well as of 1b and 1e) one can derive that the conformations of the sulfonyl groups have little effect on the Michael acceptor ability of the C=C double bond. A completely different situation has previously been found for Michael acceptors with conformationally fixed and flexible ester groups: Benzylidene Meldrum's acid was reported to be 10 orders of magnitude more electrophilic than diethyl benzylidenemalonate (Scheme 5).<sup>[17]</sup>



Figure 4. ORTEP drawings of a) **1c** and b) **1f** (for which one out of two asymmetric formula in a unit cell is shown); 50% probability ellipsoids, hydrogen atoms omitted for clarity (details of the X-ray single-crystal structure determinations for **1c** and **1f** are discussed in references [24a,b]).



Scheme 5. Comparison of the electrophilicities of acyclic and cyclic diesters.

The somewhat lower electrophilicity of the 1,3-dithiane derivative 1g compared with the other *p*-methoxybenzylidene derivatives 1c and 1f can be explained by the electron-donating effect of the saturated  $(CH_2)_3$ -substituent in 1g. From the almost identical reactivities of 1g and *p*-methoxy- $\beta$ -nitro-styrene (Figure 3, right) one can derive that two sulfonyl groups have a similar activating effect as one nitro group.

Comparison of the cyclic bissulfone 1f with the analogously substituted indane-1,3-dione (Figure 3, right) shows that the conformationally fixed sulfonyl groups activate the double bonds by almost two orders of magnitude less than the carbonyl groups in the indane-1,3-dione.

## **Reactions with Other Types of Nucleophiles**

As reactions of bissulfonyl ethylenes with enamines and secondary amines are key steps of the organocatalytic asymmetric additions of aldehydes and ketones to bissulfonyl ethylenes, we have examined whether the electrophilicity parameters of 1a-g listed in Table 2 are suitable for predicting the rates of their reactions with these nucleophiles.

The reaction of the vinyl bissulfone **1a** with the enamine **8** gave the ordinary Michael adduct **9a** after hydrolysis (Scheme 6). However, the reaction of the anisylidene bissulfone **1c** with **8** did not give the expected addition product after aqueous workup, but instead led to compounds **12** and **13**, which may be formed by the mechanism depicted in

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Scheme 6. Reaction of bissulfonyl ethylene 1a with pyrrolidinocyclohexene 8.



Scheme 7. Plausible mechanism for the reaction of 1 with enamine 8.

Scheme 7. The initially generated zwitterion **10** undergoes an intra- or intermolecular 1,3-proton shift to give the enamine **11**, which is stable for R=H and gives the Michael adduct **9a** upon hydrolytic workup. For  $R=pMeO-C_6H_4$ , the enamine **11** undergoes retro-Michael addition with formation of **14** and **15** during aqueous workup because the iminium ion **14** ( $R=pMeOC_6H_4$ ) is stabilized by the electron-donating effect of the *p*-methoxy group. The generation of the bissulfonylmethyl anion **15** by retro-Knoevenagel reactions has previously been observed when the bissulfonylstyrene **1b** was treated with pyrrolidine.<sup>[4b]</sup>

The kinetics of the reactions of 1c with the enamine 8 and the amines 16a,b were studied photometrically in the same manner as described above. The second-order rate constants for the reaction of the bissulfonyl ethylene 1c with the enamine 8 in MeCN is in good agreement with the rate constant calculated from Equation (1) using the reactivity parameters N and  $s_N$  of  $8^{[25]}$  and the E parameter of 1c listed in Table 2 ( $k_2^{exp}/k_2^{calcd}=0.53$ , Table 3). Attempts to measure the rate of the reaction of bissulfonyl ethylene 1a with enamine 8 failed due to an increase in absorption caused by unknown side products.

Table 3. Experimental and calculated second-order rate constants for the reactions of **1c** with enamine **8** and the secondary amines **16a** and **16b** at 20 °C in MeCN.

Nucleophile $(N, s_N)$	$k_2^{exp}$	$k_2^{\text{calcd}[a]}$	$k_2^{\text{exp}}/k_2^{\text{calcd}}$
	$[M^{-1} S^{-1}]$	$[M^{-1} S^{-1}]$	
Pyrrolidinocyclohexene (8) (16.42, 0.70)	$3.15 \times 10^1$	$6.00 \times 10^1$	0.53
Pyrrolidine (16a) (18.64, 0.60)	$2.23 \times 10^{3}$	$7.18\!\times\!10^2$	3.1
Piperidine (16b) (17.35, 0.68)	$1.00\!\times\!10^2$	$2.29 \times 10^{2}$	0.44

[a] Calculated by Equation (1) from  $E(\mathbf{1c}) = -13.88$  (Table 2) and N and  $s_N$  (from reference [25] for **8** and reference [26a] for **16a,b**).

Combination of **1c** with 10 to 1000 equivalents of pyrrolidine (**16a**) or piperidine (**16b**) resulted in monoexponential decays of the absorbance at 340 nm, from which the firstorder rate constants  $k_{obs}$  were derived (Figure 5). Unlike the



Figure 5. Plots of  $k_{obs}$  vs. [16b] and of [16b]/ $k_{obs}$  vs. 1/[16b] (inset) for the reaction of the bissulfonyl ethylene 1c with piperidine 16b. The  $k_2$  value for the reaction is  $1/(9.96 \times 10^{-3} \text{ mol } \text{L}^{-1} \text{ s}) = 1.00 \times 10^2 \text{ Lmol}^{-1} \text{ s}^{-1}$ .

situation described in Figure 1, plots of  $k_{obs}$  versus the amine concentrations were not linear, however. The upward curvatures in the plots of  $k_{obs}$  versus [16] indicate a higher reaction order in amine. A rationalization for this observation is presented in Scheme 8, in which the addition step is as-



Scheme 8. Reaction mechanism of bissulfonyl ethylenes with secondary amines 16.

sumed to be reversible, and a second molecule of the amine is involved as a base catalyst, as previously reported for the reactions of secondary amines with quinone methides<sup>[26a]</sup> and azodicarboxylates.<sup>[26b]</sup>

The concentration of intermediate I can be represented by Equation (3).

$$\frac{d[\mathbf{I}]}{dt} = k_2[\mathbf{I}][\mathbf{16}] - k_{-2}[\mathbf{I}] - k_a[\mathbf{I}][\mathbf{16}] - k_p[\mathbf{I}]$$
(3)

By assuming a steady-state concentration for the intermediate **I** and neglecting the direct proton-transfer pathway

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 $(k_p)$ , the first-order rate constant  $k_{obs}$  can be expressed by Equation (4), which can be transformed into Equation (5).

$$k_{\rm obs} = k_2 \frac{k_{\rm a} [16]^2}{k_{.2} + k_{\rm a} [16]}$$
(4)

$$\frac{[\mathbf{16}]}{k_{\text{obs}}} = \frac{1}{k_2} + \frac{k_{.2}}{k_2 k_{\text{a}} [\mathbf{16}]}$$
(5)

As shown in the inset of Figure 5, the plot of  $[16]/k_{obs}$  versus 1/[16] is linear with an intercept corresponding to the reciprocal of the second-order rate constants  $k_2$ , which are listed in Table 3. Again, one finds a fair agreement between experimental and calculated rate constants.

The observation that pyrrolidine **16a** reacts 70 times faster with the bissulfonyl ethylene **1c** than the corresponding enamine **8** furthermore confirms Alexakis' conclusion that organocatalytic additions of aldehydes to nitro olefins proceed via initial, reversible additions of the secondary amines to the electron-deficient C=C double bond.<sup>[27]</sup>

## Conclusions

We have shown that the rate constants for the reactions of the bissulfonyl ethylenes 1a-g with carbanions and siloxyalkenes follow the linear free-energy relationship (1), which allows us to derive the empirical electrophilicity parameters E of these compounds and to compare them with those of other electrophiles (Figure 3). As a rule of thumb, one can assume that two geminal phenylsulfonyl groups at a C=C double bond have a similar activating effect as one nitro group. Since the electron-withdrawing effect of sulfonyl groups operates predominantly through polarization and not through mesomeric effects, the electrophilicities of 1a-g are not strongly affected by the conformations of the sulfonyl groups. The E parameters, which have been determined in this study, are useful to calculate rate constants for the reactions with various nucleophiles and make synthetic strategies more easily predictable. Analogous investigations on bissulfinyl ethylenes (alkylidenebissulfoxides) would be desirable, as these compounds have also been reported to be potent Michael acceptors.<sup>[28]</sup>

## **Experimental Section**

#### Materials

Commercially available DMSO (Acros 99.7%, extra dry, Acro seal) and acetonitrile (Acros 99.9%, extra dry, Acro seal) were used without further purification.

Preparation of Potassium Salts 2 K

Potassium salts (2c-g)-K were generated by mixing solutions of *t*BuOK in dry THF with a solution of the corresponding CH-acids (2c-g)-H in dry THF under a nitrogen atmosphere. To precipitate the product, dry *n*-

pentane was added. The precipitates were filtered and dried in vacuo to obtain (2c-g)-K as colorless solids.

### Bis(phenylsulfonyl) Ethylenes 1 a-d

Bissulfonyl ethylenes **1a,b** were prepared according to a literature procedure.<sup>[4b]</sup> **1c,d** were synthesized by modification of a method by Alexakis.<sup>[4b]</sup> **A** mixture of *p*-substituted benzaldehyde (118 mmol), bis(phenylsulfonyl)methane (5.00 g, 16.9 mmol), diethylammonium chloride (32.1 mmol) and potassium fluoride (2.5 mmol) in dry toluene (150 mL) was stirred and refluxed under a Dean–Stark water separator. The product formation was followed by <sup>1</sup>H NMR spectroscopy. After cooling, the solvent was evaporated and the residue was partitioned between water (50 mL) and CH<sub>2</sub>Cl<sub>2</sub> (150 mL). The organic phase was separated and the aqueous phase was extracted with CH<sub>2</sub>Cl<sub>2</sub> (3×25 mL). The combined organic layers were dried over Na<sub>2</sub>SO<sub>4</sub>, filtered, and concentrated under reduced pressure. The crude mixture was purified by flash column chromatography on silica gel (pentane/EtOAc, from 95:5 to 80:20), followed by recrystallization from pentane/CHCl<sub>3</sub> to afford bissulfonyl ethylenes.

#### Benzylidene Benzodithiole Tetroxides 1e and 1f

These compounds were synthesized analogously to 1c,d using a mixture of *p*-substituted benzaldehyde (5.0 mmol), benzodithiole tetroxide<sup>[29]</sup> (220 mg, 1.00 mmol), diethylammonium chloride (1.9 mmol), and potassium fluoride (0.15 mmol) in dry toluene (25 mL).

## Benzylidene Dithiane Tetroxide (1g)

This compound was synthesized by following the procedure for 1c,d using a mixture of *p*-anisaldehyde (84.5 mmol), dithiane tetroxide<sup>[30]</sup> (2.2 g, 11.9 mmol), diethylammonium chloride (22.6 mmol), and potassium fluoride (1.8 mmol) in dry toluene (100 mL), with the exception that the obtained residue after workup was washed with diethyl ether, followed by recrystallization from ethanol to afford **1g**.

#### Reactions of Bissulfonyl Ethylenes 1 with Nucleophiles 2

**Method A**: Bissulfonyl ethylenes **1** (1 equiv) were added to a solution of nucleophile **2a**-H or **2b**-H (1.0–1.5 equiv) and *t*BuOK (1.1–1.6 equiv) in DMSO at room temperature, and the solution was stirred until the disappearance of the starting materials (monitored by TLC). The reaction mixtures were then poured on ice water and acidified with acetic acid. Subsequently, the products were extracted with diethyl ether. The combined organic layers were washed with water, dried over Na<sub>2</sub>SO<sub>4</sub>, and the solvent was evaporated under reduced pressure. The crude products were purified by column chromatography on silica gel (pentane/EtOAc, 95:5). **Method B**: As method A except that bissulfonyl ethylenes **1** (1 equiv) were added to a solution of potassium salts **2**-K (1.0–1.5 equiv) in DMSO at room temperature.

## Reactions of Bissulfonyl Ethylenes 1 a with Nucleophiles 4

Bissulfonyl ethylenes 1 (1 equiv) were added to a solution of nucleophiles 4 (1.0–1.5 equiv) in CH<sub>3</sub>CN at room temperature. The solution was stirred until the disappearance of the starting materials (monitored by TLC) at room temperature. The reaction was then quenched by the addition of water and extracted with diethyl ether. The combined organic layers were washed with water, dried over  $Na_2SO_4$ , and evaporated under reduced pressure. The crude products were purified by column chromatography on silica gel(pentane/EtOAc, 95:5).

#### Kinetics

The rates of the reactions between the bissulfonyl ethylenes **1a**–g and the reference carbanions **2a–g**, S-ylides **3**, and silyl enol ether **4a–d** were measured photometrically under pseudo-first-order conditions (excess of nucleophile; for the reactions of **1a,e** with the colored S-ylides **3**, the first-order rate constants  $k_{obs}$  were determined with **3** as the minor component) at or close to the absorption maximum of **1** by using UV-Vis spectrometers (conventional diode-array or stopped-flow) at 20°C in dry DMSO or acetonitrile. First-order rate constants  $k_{obs}$  (s<sup>-1</sup>) were obtained by least-squares fitting of the mono-exponential  $A_i = A_0 \exp(-k_{obs}t) + C$  to the time-dependent absorbances. Since  $k_{obs} = k[Nu]$ , the second-order

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rate constants  $k_2$  (M<sup>-1</sup>s<sup>-1</sup>) were derived from the slopes of the linear plots of  $k_{obs}$  (s<sup>-1</sup>) versus [Nu].

Details of the individual runs of the kinetic experiments as well as preparative procedures and product characterizations are presented in the Supporting Information.

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# **Electrophilicity Parameters**

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Electrophilicities of Bissulfonyl Ethylenes



Quantifying Electrophilicity: Kinetics of the reactions of 1,1-bissulfonyl-ethylenes with carbon nucleophiles have been determined to integrate these Michael acceptors in our comprehensive electrophilicity scales and to compare them with other electrophiles. The electrophilicities depend only slightly on conformational restrictions, and as a rule of thumb, one can assume that two geminal phenylsulfonyl groups exert a similar activation as one nitro group.

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