J. Am. Chem. Soc. **1993,** *115,* 8002–8007

Catalysis with Inorganic Cations. 2. The Effect of Some Perchlorates on Diels–Alder Reaction Rates[1]

Adele Casaschi, Giovanni Desimoni, Giuseppe Faita, Anna Gamba Invernizzi, Simonetta Lanati, and PierPaolo Righetti*

Contribution from the Dipartimento di Chimica Organica, Università di Pavia, V.le Taramelli 10, 27100 Pavia, Italy

Received January 25, 1993

Abstract: The effects of sodium, lithium, barium, and magnesium perchlorate in acetone solution on the rates of different Diels–Alder reactions were kinetically investigated, ^{13}C-NMR spectroscopy being used as a tool to infer the mechanism of coordination of the solvated cations acting as catalysts. The Diels–Alder reactions, whose rates increase with increasing electrophilic character of the solvent, are strongly accelerated in the presence of the metal cation. The order of the cation activity, $Mg^{2+} > Ba^{2+} \geq Li^{+} > Na^{+}$, parallels the order of their respective charge:radius ratios. The Diels–Alder reactions characterized by a nucleophilic or nonspecific solvent effect are nearly insensitive to the presence of any metal cation, since it cannot act as an electrophile. The small increase in the rate of such reactions can be due to nonspecific interactions.

Introduction

The effect of lithium perchlorate (LP), dissolved in organic solvents, on the rates of Diels–Alder (DA) reactions is a subject of much current interest. Two studies first revealed the influence of LP on DA reactions: Braun and Sauer[2] determined the [*endo*]:[*exo*] ratio in ether solutions of LP and derived the E_T values of these media; Breslow and Guo[3] studied the effect of LP in the "water-like" solvents (ethylene glycol and formamide) and observed a modest acceleration of the reaction.

The importance of LP in organic solvents, as a powerful medium for DA reactions, was discovered by Grieco and co-workers.[4] They observed dramatic accelerations of DA reactions when performed in 5 M LP–diethyl ether solutions, and these results were usefully applied to organic syntheses.[5] Two independent studies, performed by Forman and Dailey[6] and by our group,[1] investigated the influence of LP–organic solvent solutions on the rate of both DA and hetero DA (HDA) reactions. The results indicated that the rate acceleration is due to a catalysis promoted by the lithium cation acting as a Lewis acid.

We thought it of interest to study the effect of differing inorganic perchlorates on rates. Solubility reasons forced us to limit the investigation to lithium (LP), sodium (SP), magnesium (MP), and barium (BP) perchlorates in acetone solutions.[7]

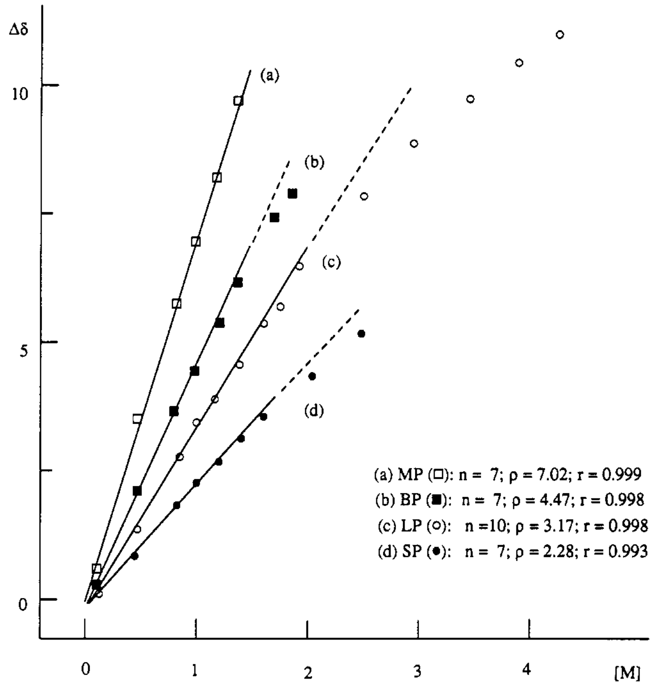


Figure 1. Plot of the Δδ of the ^{13}C acetone carbonyl for acetone solutions of LP (○), SP (●), BP (■), and MP (□) *vs* the salt concentration.

^{13}C-NMR Investigation of Inorganic Perchlorate–Acetone Solutions

When a Lewis acid coordinates either diene or dienophile to promote DA catalysis, its effect on reagents' MOs depends either on the dispersion of its charge or on the energy of its LUMO (hard and soft concepts), both being affected by solvation. To compare the kinetic effects of the different inorganic perchlorates, a single catalytic species for each salt has to be involved in the mechanism of the catalysis. Hence the coordination between acetone and the cations had to be studied.

A good starting point was the research of Popov and co-workers,[8] performed by ^{1}H-NMR, about the solvation of LP in acetone. The chemical shift of the acetone methyl protons increased with increasing LP concentration.

Hence we investigated the perchlorate–acetone solutions by determining the change of the ^{13}C-NMR chemical shift of the acetone carbonyl with increasing concentrations of LP, SP, MP, and BP. When the Δδ values of the ^{13}C-NMR carbonyl chemical shift (data available as supplementary material) were plotted *vs* the perchlorate concentration, the graphs reported in Figure 1 were obtained.

---

(1) Part 1: Desimoni, G.; Faita, G.; Righetti, P. P.; Tacconi, G. *Tetrahedron* **1991,** *47,* 8399.

(2) Braun, R.; Sauer, J. *Chem. Ber.* **1986,** *119,* 1269.

(3) Breslow, R.; Guo, T. *J. Am. Chem. Soc.* **1988,** *110,* 5613.

(4) Grieco, P. A.; Nunes, J. J.; Gaul, M. D. *J. Am. Chem. Soc.* **1990,** *112,* 4595.

(5) A comprehensive review of the synthetic use of LP–diethyl ether solutions was recently published: Grieco, P. A. *Aldrichimica Acta* **1991,** *24,* 59.

(6) Forman, M. A.; Dailey, W. P. *J. Am. Chem. Soc.* **1991,** *113,* 2761.

(7) A recent report demonstrated that the rate of the DA reaction of anthracene-9-carbinol and *N*-ethylmaleimide in aqueous sodium salt solution decreases with increasing anion size: Rizzo, C. *J. Org. Chem.* **1992,** *57,* 6382.

(8) Wong, M. K.; McKinney, W. J.; Popov, A. I. *J. Phys. Chem.* **1971,** *75,* 56.

0002-7863/93/1515-8002$04.00/0

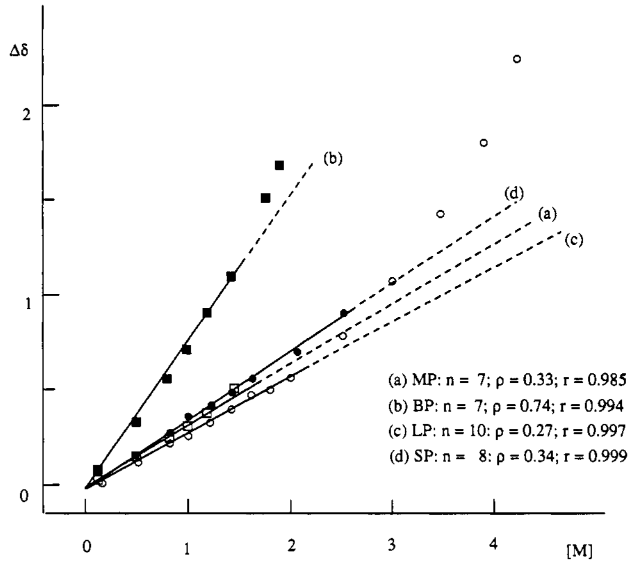


Figure 2. Plot of the Δδ of the ^{13}C naphthoquinone carbonyl for acetone solutions of LP (○), SP (●), BP (■), and MP (□) *vs* the salt concentration.

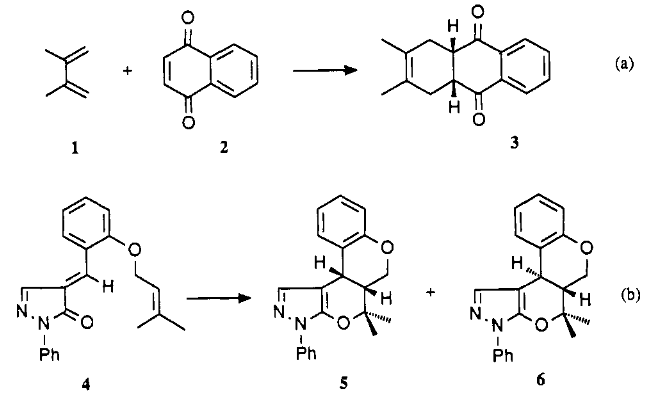
The relationships were linear up to 1.4 M for MP (concentration corresponding to the solubility limit) and BP, 2.0 M for LP, and 1.6 M for SP. *For higher values of concentration, the graphs diverged from linearity* (the deviation is particularly evident for LP), and these behaviors are very close to that evidenced by Pocker and Buchholz[9] for LP–diethyl ether solutions. The values of the slope (ρ) for each linear relationship, the number of points (n), and the corresponding correlation coefficient (r) are reported in Figure 1. The ρ values are in the order MP > BP > LP > SP and support the stronger interaction being between MP and acetone, while the other ones decrease in the above order. The deviation from linearity, clearly observed for LP, may be due either to a change in the solvation number of the Li^+ ion or to a replacement of one or more acetone molecules in the solvation shell by the ClO_4^- ion.[8] *In any case, the deviation reveals that a different catalytic species is present in solution.*

To catalyze a DA reaction the solvated cation, acting as a Lewis acid, has to coordinate diene or dienophile. This was again studied by ^{13}C-NMR, and the chemical shift of the carbonyl carbon atom of 1,4-naphthoquinone (the dienophile of one of the DA reactions kinetically investigated; see below) was measured with increasing concentrations of perchlorates in acetone solutions. When the Δδ values of the ^{13}C naphthoquinone CO group (data available as supplementary material) were plotted *vs* the perchlorate concentrations, the graphs reported in Figure 2 were obtained. The increase of the chemical shift is again linear in the same range of concentrations as that for acetone (Figure 1), but the order of the slopes of the linear relationships, BP > SP ≥ MP ≥ LP, is quite different from that previously observed in Figure 1. This result is obtained for 1,4-naphthoquinone only, since either cyclohexenone or α-tetralone[10] showed an order of the ρ values for their respective carbonyl groups that parallels that observed for acetone.

At higher concentrations, deviations from linearity (Figure 2) are again observed, but the curves have opposite convexities than those of acetone. This seems to be clear evidence that a stronger Lewis acid (probably a less solvated cation) is now coordinating naphthoquinone.

In conclusion, from the data in Figures 1 and 2, the linear sectors observed for each salt–acetone system determine regions of homogeneous Lewis acid catalysts and allow a homogeneous comparison between the kinetic effects of the different perchlorates.

Scheme I



Effect of Inorganic Perchlorates on DA and HDA Reactions

The effect of the acetone solutions of the inorganic perchlorates was tested on the DA reaction with direct electron demand[11] between 2,3-dimethylbutadiene (**1**) and 1,4-naphthoquinone (**2**) (Scheme I, eq a) and on the intramolecular HDA reaction, with inverse electron demand,[11] of (*E*)-1-phenyl-4-[2-(3-methyl-2-butenyloxy)benzylidene]-5-pyrazolone (**4**) (eq b).

The kinetic determinations were performed in the same range of perchlorate concentrations as that used in the NMR investigation: up to 1.4 M for MP, 2.0 M for BP, 4.0 M for LP, and 2.6 M for SP, acetone always being the solvent. The kinetic runs were studied by UV–VIS spectroscopic analysis of the disappearing naphthoquinone **2** or benzylidenepyrazolone **4** at 30 and 20 °C, respectively, and followed to about 60–70% completion. The second-order rate constants for the reactions of **1** and **2** were calculated from the pseudo-first-order values determined in the presence of a significant excess of **1** (see Experimental Section for details). The rate constants, reported in Tables I and II, respectively, are the average of at least three kinetic runs on different samples.

If the effect of the differing cations on DA and HDA reactions is compared at the same salt concentration, sodium is 2–3 times less effective than lithium, which is 2–3 times less effective than barium. But the outstanding result is that magnesium is about 10–20 times more effective than lithium.

If the divergencies from linearity in ^{13}C-NMR relationships are taken (as seen before) as an indication of a change in the catalytic species, for a homogeneous comparison of the kinetic data only those in the range of linearity of NMR have to be considered. When these log k_{rel} values (k_{rel} being $k_{catal}/k_{acetone}$) were plotted *vs* –log χ (χ, the salt molar fraction), the graphs reported in Figure 3 were obtained. For each perchlorate the relationship is a curve at low salt concentrations (<0.5 M); for medium concentrations (0.5–2.0 M) the experimental data approach a linear relationship, allowing an easy comparison of the different salt effects. If the kinetic data at higher concentrations of salt (fast unstarred rates in Tables I and II) were placed in the graphs, they would remarkably diverge from linearity; the graphs thus obtained would be analogous to those described by Pocker and co-workers[12] for the rearrangement of 1-phenylallyl chloride in LP–diethyl ether solutions.

Both a DA with direct electron demand and a HDA with inverse electron demand are significantly catalyzed by the different inorganic cations, and Figure 3 clearly shows the order of this effect. This increases with increasing charge density of each

---

(9) Pocker, Y.; Buchholz, R. F. *J. Am. Chem. Soc.* **1970**, *92*, 2075.

(10) For cyclohexenone the order of ρ values is MP, 5.55; BP, 2.68; LP, 1.92; and SP, 1.07. For α-tetralone the order of ρ values is MP, 4.20; BP, 3.17; LP, 1.90; and SP, 1.29.

(11) Sustmann, R.; Trill, H. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 838.

(12) Pocker, Y.; Buchholz, R. F. *J. Am. Chem. Soc.* **1970**, *92*, 4033; Pocker, Y.; Ellsworth, D. L. *J. Am. Chem. Soc.* **1977**, *99*, 2276.

Table I. Rate Constants for the DA Reaction of **1** and **2** at 30 °C in Different Concentrations of Metal Perchlorate–Acetone Solutions[a]

salt	[M]	$10^2\chi$	10^5k (L mol^{-1} s^{-1})	salt	[M]	$10^2\chi$	10^5k (L mol^{-1} s^{-1})
			1.0 ± 0.1[b]	LP	0.05	0.38	1.30 ± 0.02
					0.10	0.76	1.50 ± 0.03
MP	0.05	0.39	1.84 ± 0.02		0.16	1.19	1.55 ± 0.05
	0.10	0.77	3.1 ± 0.2		0.32	2.33	2.2 ± 0.1
	0.15	1.12	5.05 ± 0.1		0.5	3.66	3.8 ± 0.1*
	0.30	2.25	11.5 ± 0.3		0.80	5.78	5.9 ± 0.1*
	0.50	3.67	15.4 ± 0.3*		1.00	7.16	8.1 ± 0.1*
	0.60	4.44	29.2 ± 0.4*		1.20	8.51	11.1 ± 0.1*
	0.80	5.72	63.0 ± 0.5*		1.40	9.74	14.6 ± 0.1*
	1.00	7.12	102 ± 2*		2.01	13.50	38.3 ± 0.5*
	1.20	8.45	207 ± 3*		2.50	16.60	84 ± 1
	1.40	9.85	324 ± 4*		3.00	19.75	196 ± 2
					3.50	22.65	443 ± 2
BP	0.05	0.375	1.34 ± 0.01		4.00	25.60	814 ± 3
	0.10	0.745	1.70 ± 0.02	SP	0.28	2.09	1.72 ± 0.02
	0.15	1.15	2.6 ± 0.1		0.50	3.62	2.20 ± 0.05*
	0.30	2.24	4.7 ± 0.1		0.68	4.87	2.94 ± 0.03*
	0.50	3.72	6.43 ± 0.05*		0.80	5.75	3.27 ± 0.05*
	0.60	4.47	10.1 ± 0.2*		1.00	7.13	4.19 ± 0.03*
	0.80	5.89	16.9 ± 0.1*		1.20	8.37	5.7 ± 0.1*
	1.03	7.44	28.7 ± 0.1*		1.40	9.75	7.1 ± 0.1*
	1.20	8.80	45.8 ± 0.2*		1.80	12.47	10.7 ± 0.1*
	1.40	10.24	74.9 ± 0.3*		2.29	15.61	17.5 ± 0.1
	1.75	12.83	186 ± 2		2.60	17.51	22.7 ± 0.1
	2.00	14.80	267 ± 4				

[a] The kinetic data used in the linear regressions in Figure 3 are starred. [b] Rate constant extrapolated from the Arrhenius diagram (see Experimental Section for details).

Table II. Rate Constants for the HDA Reaction of **4** at 20 °C in Different Concentrations of Metal Perchlorate–Acetone Solutions[a]

salt	[M]	$10^2\chi$	10^6k (s^{-1})	salt	[M]	$10^2\chi$	10^6k (s^{-1})
			0.63 ± 0.08[b]	LP	0.10	0.76	1.07 ± 0.02
					0.25	1.87	1.65 ± 0.05
MP	0.05	0.38	1.7 ± 0.2		0.50	3.66	2.4 ± 0.1*
	0.10	0.77	2.0 ± 0.2		0.80	5.74	4.2 ± 0.1*
	0.30	2.21	5.2 ± 0.2		1.00	7.16	5.3 ± 0.2*
	0.50	3.67	10.8 ± 0.1*		1.20	8.51	7.1 ± 0.1*
	0.65	4.57	14.7 ± 0.2*		1.40	9.74	9.0 ± 0.1*
	0.80	5.72	20.5 ± 0.1*		2.00	13.50	14.6 ± 0.1*
	1.00	7.12	30.5 ± 0.2*		2.50	16.60	23.8 ± 0.3
	1.11	7.85	35.8 ± 0.2*		3.11	19.95	47.9 ± 0.2
	1.21	8.51	43.4 ± 0.3*		3.50	22.65	79.3 ± 2
	1.40	9.85	59.6 ± 0.5*		4.00	25.60	137 ± 3
	1.49	10.47	70.0 ± 0.5*				
BP	0.05	0.375	1.3 ± 0.1	SP	0.50	3.62	1.29 ± 0.01*
	0.10	0.745	1.23 ± 0.05		0.80	5.75	1.51 ± 0.02*
	0.30	2.24	1.5 ± 0.1		1.00	7.13	1.69 ± 0.03*
	0.50	3.72	2.75 ± 0.05*		1.20	8.27	1.77 ± 0.04*
	0.80	5.89	4.1 ± 0.1*		1.40	9.75	2.1 ± 0.1*
	1.00	7.29	5.6 ± 0.1*		1.80	12.47	3.13 ± 0.03
	1.20	8.80	8.7 ± 0.1*		2.29	15.61	4.00 ± 0.05
	1.40	10.24	12.1 ± 0.2*		2.79	18.51	5.4 ± 0.1
	1.75	12.83	22.1 ± 0.1				
	2.00	14.80	32.2 ± 0.1				
	2.27	16.98	43.0 ± 0.3				

[a] The kinetic data used for linear regressions in Figure 3 are starred. [b] Rate constant extrapolated from the Arrhenius diagram (see Experimental Section for details).

cation, since the order of the charge:radius values ($Mg^{2+} > Ba^{2+} \approx Li^+ > Na^+$)[13] parallels the order of reactivity shown in Figure 3.

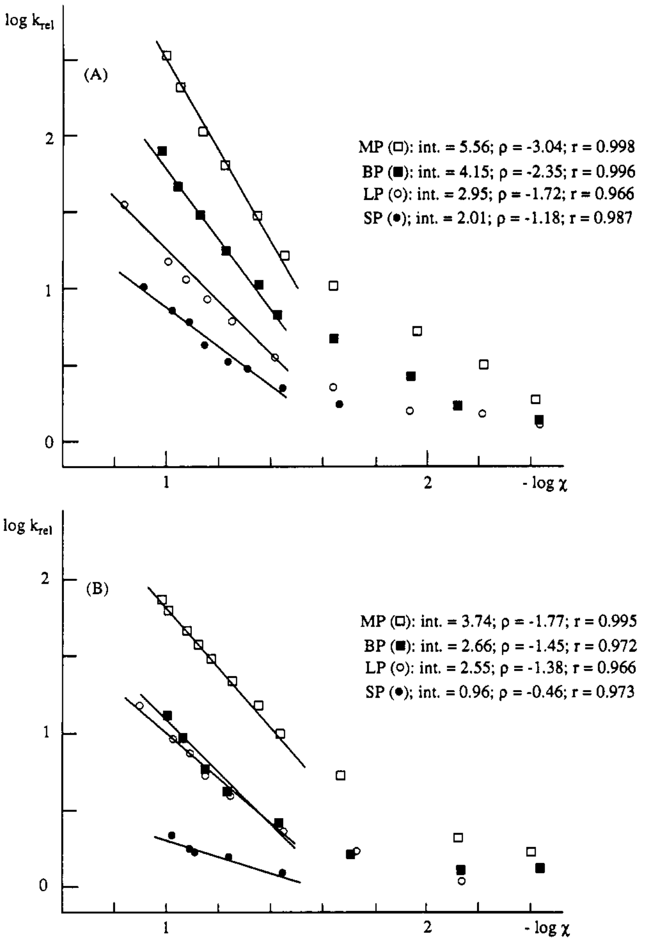


Figure 3. (A) Plot of log k_{rel} *vs* –log χ for the DA reaction of **1** and **2** at 30 °C in the presence of the different perchlorates (Table I). (B) Same for the HDA reaction of **4** at 20 °C (Table II). The regression data for each linear relationship are calculated with the starred values in Tables I and II.

If the effect of lithium on reactions in Scheme I is compared with that observed by Forman and Dailey[6] on the DA reaction of 9,10-dimethylanthracene (DMA) with acrylonitrile, a further important point results. Whereas examples a and b in Scheme I have k_{rel} values at 1.40 M LP of 15 and 14, respectively, the k_{rel} value of the DA reaction in ref 6 at the same concentration is only 3.5. Why are there such different sensitivities of the above mentioned DA reactions to the cationic catalysis? Perhaps there is a parallel between the different types of solvent effects in the DA reactions (type a, solvent behaves as an electrophile; type b, solvent behaves as a nucleophile; type c, solvent acts through its internal cohesive pressure)[14] and the behavior with inorganic cations. Both reactions in Scheme I are type a[14] DA, and these can be catalyzed by inorganic cations acting as electrophiles. How can these electrophiles interact with a type b or c DA reaction?

Effect of Inorganic Perchlorates on Type b and Type c DA reactions

The effect of acetone solutions of the above four inorganic perchlorates was tested on the type b solvent effect DA reaction between *trans,trans*-1,4-diphenylbutadiene (**7**) and 4-phenyl-1,2,4-triazoline-3,5-dione (**8**)[14] and on the type c DA reaction between DMB (**1**) and 4-bromonitrosobenzene (**10**)[14] (Scheme II), both at 20 °C.

The rate constants of the reaction between **7** and **8** were determined under second-order conditions (Table III), whereas those of the reaction between **1** and **10** were determined under pseudo-first-order conditions, the second-order rate constants then being calculated (Table IV; see Experimental Section for details).

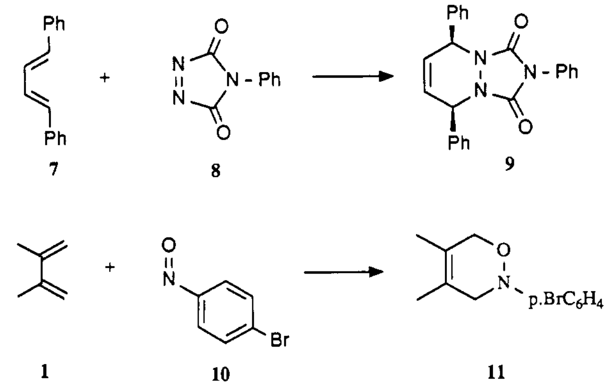
At a first glance both DA reactions in Scheme II are much less sensitive to the perchlorate catalysis than the type a DA reactions.

---

(13) *Handbook of Chemistry and Physics*, 66th ed.; CRC Press: Boca Raton, FL, 1986.

(14) Desimoni, G.; Faita, G.; Righetti, P. P.; Toma, L. *Tetrahedron* **1990**, *46*, 7951.

Scheme II



7 8 9

1 10 11

Table III. Rate Constants for the DA Reaction of **7** and **8** at 20 °C in Different Concentrations of Metal Perchlorate–Acetone Solutions[a]

salt	[M]	$10^2\chi$	k (L mol^{-1} s^{-1})	salt	[M]	$10^2\chi$	k (L mol^{-1} s^{-1})
			0.85 ± 0.1	LP	0.10	0.76	0.85 ± 0.01
					0.31	2.25	0.94 ± 0.05
MP	0.10	0.77	0.88 ± 0.02		0.50	3.66	1.03 ± 0.05
	0.30	2.17	0.91 ± 0.01		0.80	5.82	1.09 ± 0.01*
	0.50	3.67	1.02 ± 0.03*		0.99	7.01	1.20 ± 0.02*
	0.80	5.72	1.23 ± 0.01*		1.20	8.51	1.32 ± 0.02*
	1.00	7.12	1.47 ± 0.03*		1.40	9.74	1.51 ± 0.03*
	1.20	8.51	1.64 ± 0.02*		2.00	13.50	2.08 ± 0.07*
	1.40	9.85	1.94 ± 0.01*		2.50	16.60	2.97 ± 0.05
					3.00	19.75	4.26 ± 0.07
BP	0.10	0.745	0.82 ± 0.02				
	0.30	2.24	0.90 ± 0.01	SP	0.11	0.79	0.88 ± 0.01
	0.50	3.72	1.02 ± 0.01*		0.29	2.13	0.95 ± 0.01
	0.80	5.89	1.4 ± 0.1*		0.50	3.62	1.06 ± 0.04
	1.00	7.29	1.7 ± 0.1*		0.80	5.75	1.20 ± 0.03*
	1.20	8.80	1.8 ± 0.1*		0.99	7.05	1.24 ± 0.02*
	1.40	10.24	2.0 ± 0.1*		1.20	8.37	1.41 ± 0.01*
	1.75	12.83	2.83 ± 0.03		1.40	9.78	1.57 ± 0.02*
	2.00	14.80	3.11 ± 0.04		1.80	12.47	1.88 ± 0.05*
					2.20	14.92	2.51 ± 0.05
					2.60	17.51	3.64 ± 0.04

[a] Data used for the linear regressions in Figure 4A are starred.

Whereas these were found to experience catalytic effects with the rate increasing even 100 times, in Tables III and IV the greatest acceleration is only 5 times.

When the log k_{rel} values were plotted *vs* –log χ, the graphs reported in Figure 4 were obtained. Their shapes are similar to those previously shown in Figure 3: for medium concentrations of salt they again become linear (values of k_{rel} at higher salt concentrations, deviating from linearity, are omitted), but the small catalytic effect makes the whole figure flat. The kinetic effects are in the order BP ≈ MP ≥ LP ≈ SP, but their distinctive character is *a generally small effect.*

This small effect excludes acid catalysis of both these reactions by inorganic perchlorates. The absence of any significant specific interaction between salt and reagents was confirmed by measuring the effect of perchlorate–acetone solutions on the carbonyl carbon atom of **8** by ^{13}C-NMR spectra. The ρ values of the four linear relationships between $\Delta\delta$(CO) and [M] are small, very similar, and all negative ($\rho_{\mathrm{MP}} = -0.09$; $\rho_{\mathrm{BP}} = -0.07$; $\rho_{\mathrm{LP}} = -0.05$; $\rho_{\mathrm{SP}} = -0.01$), pointing out the absence of coordination between the cation and **8**.

The behavior of the above four DA reactions *vs* the inorganic perchlorates can be discussed by comparing k_{rel} values at a given common concentration. This result, reported in Table V for –log χ = 1.0 (but similar results are obtained for any value of concentration chosen in the linear sector of the graphs), is of dramatic significance because some reactions are accelerated 100 times more than other ones.

Table IV. Rate Constants for the DA Reaction of **1** and **10** at 20 °C in Different Concentrations of Metal Perchlorate–Acetone Solutions[a]

salt	[M]	$10^2\chi$	10^3k (L mol^{-1} s^{-1})	salt	[M]	$10^2\chi$	10^3k (L mol^{-1} s^{-1})
			3.7 ± 0.1[b]	LP	0.06	0.45	3.9 ± 0.1
					0.10	0.76	4.1 ± 0.1
MP	0.05	0.39	4.2 ± 0.3		0.31	2.25	4.5 ± 0.1
	0.10	0.77	4.5 ± 0.2		0.50	3.66	5.00 ± 0.05*
	0.30	2.17	4.9 ± 0.1		0.82	5.82	5.39 ± 0.04*
	0.50	3.67	5.5 ± 0.2*		1.00	7.16	5.77 ± 0.03*
	0.80	5.72	7.0 ± 0.1*		1.20	8.51	6.38 ± 0.06*
	1.00	7.12	8.1 ± 0.1*		1.40	9.74	7.0 ± 0.1*
	1.20	8.45	10.6 ± 0.1*		1.94	12.97	8.7 ± 0.1*
	1.30	9.16	11.5 ± 0.2*		2.46	16.31	11.5 ± 0.2
					3.00	19.75	15.8 ± 0.1
BP	0.05	0.375	4.32 ± 0.03				
	0.10	0.745	4.6 ± 0.1	SP	0.06	0.43	4.0 ± 0.2
	0.30	2.24	5.2 ± 0.1		0.10	0.76	4.1 ± 0.1
	0.50	3.72	5.8 ± 0.2*		0.29	2.13	4.4 ± 0.1
	0.80	5.89	6.82 ± 0.03*		0.50	3.62	4.85 ± 0.15
	1.00	7.29	7.65 ± 0.15*		0.79	5.71	5.30 ± 0.05*
	1.20	8.85	9.0 ± 0.1*		1.00	7.13	5.84 ± 0.05*
	1.40	10.24	9.7 ± 0.2*		1.20	8.37	6.3 ± 0.1*
	1.75	12.83	14.3 ± 0.3		1.40	9.75	6.85 ± 0.1*
	2.00	14.80	16.0 ± 0.6		1.79	12.47	8.1 ± 0.1*
					2.29	15.61	9.5 ± 0.1
					2.59	17.51	10.5 ± 0.2

[a] Data used for the linear regressions in Figure 4B are starred. [b] Value taken from ref 14.

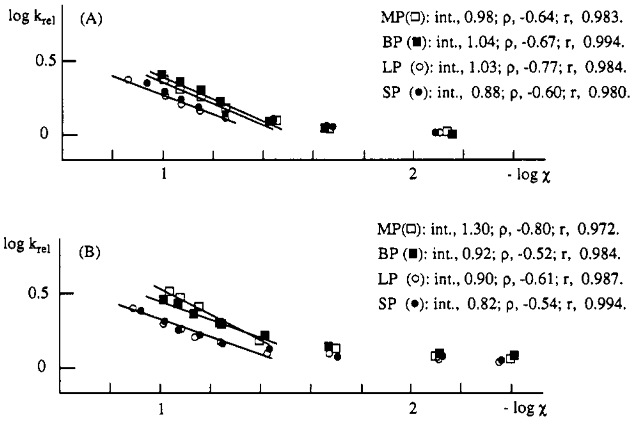


Figure 4. (A) Plot of log k_{rel} *vs* –log χ for the DA reaction of **7** and **8** at 20 °C in the presence of the different perchlorates (Table III). (B) Same for the DA reaction of **1** and **10** at 20 °C (Table IV). The regression data for each linear relationship are calculated with the starred values in Tables III and IV.

Table V. Values of $k_{\mathrm{catal}}/k_{\mathrm{acetone}}$ Determined at –log χ = 1.0 of the Four Inorganic Perchlorates for the Different DA Reactions

	reaction			
salt	**1** + **2**	**4**	**7** + **8**	**1** + **10**
	1	1	1	1
SP	6.8	5.2	1.9	1.9
LP	17.0	14.8	1.8	1.9
BP	63.1	16.2	2.3	2.5
MP	331	93	2.2	3.2

Discussion and Conclusion

The activation parameters (Table VI), determined for each DA reaction either in the presence or in the absence of inorganic perchlorates, do not support dramatic changes of mechanism from noncatalyzed to cation-catalyzed DA reactions, and the changes in $\Delta S^{\ddagger}$ are analogous to those found for the DA reactions catalyzed by AlCl$_3$ and GaCl$_3$ of anthracene with *N*-arylmaleimide.[15]

---

(15) Kiselev, V. D.; Khzyasheva, D. G.; Konovalov, A. I. *J. Org. Chem. USSR* **1983**, *19*, 1133.

Table VI. Activation Parameters for the Different DA Reactions in the Presence of the Four Inorganic Perchlorates at a Concentration of 1.0 M

	reaction							
	1 + 2		**4**		**7 + 8**		**1 + 10**	
salt	$\Delta H^{\ddagger}$ [a]	$-\Delta S^{\ddagger}$ [b]	$\Delta H^{\ddagger}$ [a]	$-\Delta S^{\ddagger}$ [b]	$\Delta H^{\ddagger}$ [a]	$-\Delta S^{\ddagger}$ [b]	$\Delta H^{\ddagger}$ [a]	$-\Delta S^{\ddagger}$ [b]
	12.8 ± 0.6	39 ± 2	19.1 ± 0.5	22 ± 2	7.5 ± 0.7	33 ± 2	10 ± 0.5	36 ± 1
SP	11.0 ± 0.3	42 ± 1	16.8 ± 0.5	27 ± 2	8.1 ± 0.7	30 ± 2	9.2 ± 0.2	37 ± 1
LP	11.5 ± 0.5	39 ± 2	16.8 ± 0.8	25 ± 2	9.0 ± 0.4	28 ± 2	9.2 ± 0.2	37 ± 1
BP	10.8 ± 0.4	39 ± 1	15.9 ± 0.5	28 ± 2	7.4 ± 0.2	32 ± 2	11 ± 0.5	31 ± 2
MP	9.1 ± 0.4	42 ± 2	13.5 ± 0.2	33 ± 1	9.3 ± 0.4	26 ± 2	7.6 ± 0.5	42 ± 2

[a] In kcal mol^{-1}. [b] In cal K^{-1} mol^{-1}.

Nevertheless, inorganic perchlorates are useful catalysts for only some DA reactions. If the cation behaves as an electrophile, its LUMO interacts with the HOMO of one cycloaddend (the dienophile **2** in the DA reaction with direct electron demand, the heterodiene **4** in HDA with inverse electron demand), and the LUMO of this latter is stabilized by electrostatic interaction. The result is a lower energy separation between the FMOs of the diene and the dienophile, and the rate of the reaction is increased. This is the same mechanism for any acid catalysis of the DA reaction[16] with a close parallel between protic acid catalysis and solvent effect when the solvent behaves as an electrophile.[17] Thus, DA reactions showing a type a solvent effect are expected to undergo significant rate accelerations by inorganic perchlorates.

The effect of the different cations is the result of their different electrophilic character, and MO calculations strongly support this. The coordination of acrolein with H^+,[18] Li^+, and Na^+ [19] lowers its LUMO in the order $H^+ > Li^+ > Na^+$. Hence, the higher the cation charge density, the stronger the catalytic effect, and this rationalizes the increase of the rate with the increase of the charge:radius ratio.

The cations cannot act with the above specific interaction on type b and type c DA reactions. In DA with a type b solvent effect, the solvent behaves as a nucleophile whose HOMO interacts and destabilizes the LUMO of the heterodienophile **8**. Obviously the HOMO of a cation is, by definition, a highly stabilized MO far from any reasonable interaction.

It was shown,[14] through the multiparametric Kamlet–Taft equation, that some borderline reactions have contributions from both electrophilic and nucleophilic solvent properties. The DA reaction between DMA and acrylonitrile, tested by Forman and Dailey,[6] belongs to this class, and it gives a poor answer to cation catalysis.

In a type c solvent effect, the solvent does not give any specific interaction with **10** and there is a small increase of the rate with an increasing cohesive pressure (δ_H^2) of the medium. The small, but nevertheless significant, kinetic effect, shown by the reaction between **1** and **10** in the presence of perchlorate (Figure 4b), could be the result of this.

In the data there is an additional inside result. If we consider the $\Delta\delta$ values of the acetone carbonyl carbon atom as an empirical measure of the electrophilic interaction between the latter with the metal cation, then we can expect a correlation between the kinetic data and the $\Delta\delta$ values for only those DA reactions characterized by cationic catalysis.

When all the log k_{rel} values of the DA reactions in Scheme I were plotted *vs* the corresponding $\Delta\delta$ data, the graphs reported in Figure 5 were obtained. These correlations can be roughly simplified to linear relationships, good for 1,4-naphthoquinone ($r = 0.985$), perhaps less satisfactory for the HDA reaction ($r = 0.962$). Nevertheless, it seems that all four salt–acetone systems, independently from the concentration, tend to be described by a unified model.

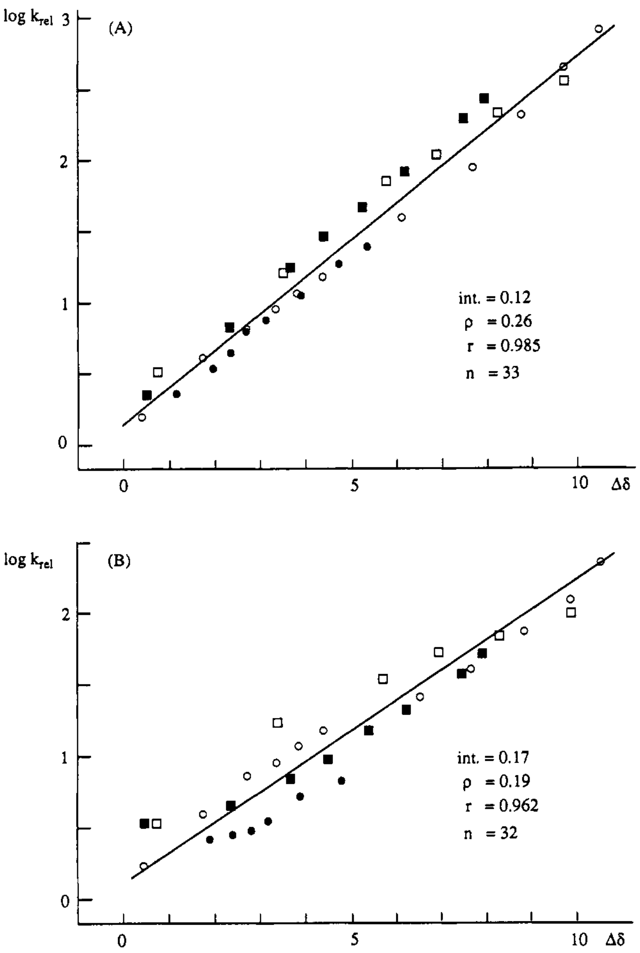


Figure 5. Plot of log k_{rel} for the DA reaction of **1** and **2** (A) and for the HDA reaction of **4** (B) *vs* the $\Delta\delta$ values of the acetone carbonyl (Figure 1) in the presence of increasing amounts of LP (○), SP (●), BP (■), and MP (□).

In the case of the DA reactions characterized by type b and type c solvent effects such correlations are meaningless since the cations do not act as electrophiles.

Experimental Section

Materials. Dimethylbutadiene (**1**) was a commercial, freshly distilled product. *trans,trans*-1,4-Diphenylbutadiene (**7**) was a commercial product. The acetone for the kinetic runs was distilled, anhydrous, UV–VIS spectroscopic grade reagent. 1,4-Naphthoquinone (**2**) was a commercial recrystallized product. The metal perchlorates were reagent grade; with the exclusion of MP, all other salts were dried under vacuum at 140 °C for 8 h (CAUTION: **All perchlorates are potential explosives and must be handled with care**).[20] The water content of each salt, as

---

(16) Fleming, I. *Frontier Orbitals and Organic Chemical Reactions*; John Wiley and Sons: Chichester, 1976; p 161.

(17) Corsico Coda, A.; Desimoni, G.; Faita, G.; Righetti, P. P.; Tacconi, G. *Tetrahedron* **1989**, *45*, 775.

(18) Houk, K. N.; Strozier, R. W. *J. Am. Chem. Soc.* **1973**, *95*, 4094.

(19) Lefour, J. M.; Loupy, A. *Tetrahedron* **1978**, *34*, 2597.

(20) Schumacher, J. C. *Perchlorates—Their Properties, Manufacture and Uses*; ACS Monograph Series; Reinhold: New York, 1960.

determined by the Karl Fischer titrations, are available as supplementary material.

(*E*)-1-Phenyl-4-[2-(3-methyl-2-butenyloxy)benzylidene]-5-pyrazolone (4). This was prepared as previously described.[17]

4-Phenyl-1,2,4-triazoline-3,5-dione (8). This was prepared in accordance with the literature method.[21]

4-Bromo-1-nitrosobenzene (10). This was prepared from *p*-bromoaniline as reported in the literature.[22]

Reaction of 1 and 2. The reaction was performed as reported in the literature,[23] and 2,3-dimethyl-1,4,4a,10a-tetrahydroanthraquinone **3** was obtained in nearly quantitative yield; mp 149 °C (lit.[23] mp 150 °C).

Reaction of 4. The reaction and the product separation were performed as previously described.[16] *cis*- and *trans*-[5a,11b]5,5-Dimethyl-3-phenylchromano[4′,3′:4,5]pyrano[3,2-*d*]pyrazoles (**5** and **6** respectively) were obtained in a nearly quantitative yield with a relative ratio of ≈4:1; mp **5** 129–130 °C (lit.[24] mp 128.5–130 °C), **6** 173–174 °C (lit.[24] mp 173–175 °C).

Reaction of 7 and 8. The reaction was performed as reported in the literature,[25] and 5,8-dihydro-2,5,8-triphenyl-1*H*-[1,2,4]triazolo[1,2-*a*]pyridazine **9** was obtained in nearly quantitative yield; mp 163–164 °C (lit.[26] mp 163 °C).

Reaction of 1 and 10. The reaction was performed as previously described,[14] and 2-(*p*-bromophenyl)-4,5-dimethyl-3,6-dihydro-1,2-oxazine (**11**) was obtained in nearly quantitative yield; mp 83–84 °C (lit.[27] mp 81–82 °C).

Determination of the [5]:[6] Ratios. These were performed by HPLC on a Waters Associated ALC/CPC 244 liquid chromatograph with a Waters Model 490E detector operating at 254 nm: stainless column (25-cm length × 4-mm i.d.) prepacked with Lichrospher Si100 (5 μm) Merck; eluant, cyclohexane–ethyl acetate, 9:1; flow, 1.2 mL min^{-1}; retention times, **5**, 6.7 min, **6**, 8.15 min.

Three solutions of known composition of **5** and **6** were prepared with the [**5**]/[**6**] ratio in the range 80:20–90:10, each composition being tested on two independent samples at least three times each. The determination of the correction factor by an appropriate integrator program enables the determination of the relative concentration of the two cycloadducts. Solutions of **4** (about 0.005 M) for a selected number of salt concentrations were thermostated at 20 °C. At different degrees of reaction completion, a portion of the reaction mixture was quenched in water and extracted with dichloromethane. After drying and evaporation of the solvent, the residue, dissolved in a small amount of ethyl acetate, was analyzed. Each salt concentration was tested on two independent samples at least three times each. The diastereomeric product ratio is kinetically controlled, and it is nearly constant with variation of both perchlorates and concentrations: for pure acetone the ratio is 83:17, while for MP solutions the ratio is (83 ± 1):17, and for SP solutions the ratio is (87 ± 1):13 in the whole range of the explored concentrations (additional data available as supplementary material).

Kinetics. The overall reaction rates were measured by following the disappearance of the chromophores **2**, **4**, **8**, and **10** on a Perkin-Elmer Lambda 5 spectrophotometer provided with a thermostated-cell transport assembly and an automatic multicell programmer. The solutions were measured in 1.00-cm OS Hellma cuvettes with a 3-mL capacity. Measurements were taken at the wavelengths of 360–370 nm for **2**, 430–460 nm for **4**, 420–450 nm for **8**, and 745–755 nm for **10**, depending on the salt and on its concentration.

In a 10-mL volumetric flask the salt–acetone solution was prepared by weighing the needed amount of metal perchlorate. The flask was filled with acetone and then weighed again in order to determine the salt concentration. Weighed amounts of the dienophile **2** (2–3 mg), **8** (0.025–0.035 g), or **10** (0.02–0.3 g) were added to the salt–solvent solution. The diene solution was prepared by adding **1** (0.3–0.5 g) or **7** (0.12–0.15 g) to an accurately weighed 5-mL volumetric flask containing *ca.* 3 mL of acetone. After the diene addition, the flask was again weighed for an accurate determination of the diene amount, then filled with the solvent, and again weighed. Three samples of the solution containing the dienophile (**2**, **8**, or **10**, 2.00 mL measured with a calibrated syringe) were placed in three cuvettes thermostated at the required temperature, and constant amounts (from 0.25 to 0.50 mL, accurately measured with a microsyringe) of the diene solution were added. After vigorous mixing, the kinetic determinations were initiated. For the HDA reaction of **4**, a slightly different procedure was followed. Variable amounts of the salt solutions (2.0–2.5 cm^3), prepared as described above, were directly thermostated at 20 °C. Amounts of **4** were then added to the solution in order to obtain absorbance values in the range 0.8–1.6 *A*. After vigorous mixing, the kinetic determinations were initiated.

The pseudo-first-order rate constants for the DA reactions **1** + **2** and **1** + **10** were calculated from the slope of the graph obtained by plotting $\log(A^\circ/A_t)$ *vs* t, A° and A_t being the absorbance values at time 0 and t, respectively. For the HDA reaction of **4**, the first-order rate constants were analogously obtained. The second-order rate constants for the DA reaction of **7** and **8** were calculated from the slope of the graph obtained by plotting the left side of eq 1 *vs* t,

$$[1/(B^\circ - A^\circ)]\log[(A^\circ B_t)/(B^\circ A_t)] = kt \qquad (1)$$

A° and B° are the starting concentrations of **7** and **8**, and A_t and B_t the actual concentrations calculated from the residual absorbance of **8** at time t. In each case good linear relationships ($r \geq 0.999$) were obtained up to 60–70% completion.

Activation Parameters. In order to determine the activation parameters, kinetic runs at four different temperatures were performed. The rates in the range 20–35 °C were determined as above, by adjusting the thermostat temperature. The DA reaction of **1** and **2** and the HDA reaction of **4** in pure acetone were too slow to allow kinetic determinations below 50 °C. For the determinations of the rate constants at higher temperatures, a solution of **1** (5.00 mL) was added to the half-filled volumetric flask containing **2** dissolved in the solvent, and acetone was then added up to 25 mL. For the HDA reaction, **4** was directly dissolved in the solvent in a 25-mL volumetric flask. Portions (ca. 3 mL) of these homogeneous solutions were placed into glass tubes, which were sealed. Approximately seven samples were prepared for each run. At $t = 0$, the samples were placed in a thermostat at the required temperature, and the initial absorbance of the solution was determined on an additional sample. At appropriate time intervals (10–100 min) the reaction was quenched, and the residual absorbance of **2** or **4** was determined. The rate constants of the four investigated DA reactions at the different temperatures are available as supplementary material.

^{13}C-NMR Investigation. The spectra were recorded on a Bruker 300 spectrometer. The deuterated acetone was commercial grade reagent. In a 2-mL volumetric flask the required amount of perchlorate was weighed. The flask was filled with deuterated acetone and again weighed in order to determine the salt concentration, and then 0.020–0.030 g of **2** or **8** as added to each solution. The data reported in Figures 1 and 2 are the average of two independent experiments, and the error is in the limit of ±0.01 ppm.

Acknowledgment. We are grateful to the National Research Council (CNR) and MURST for financial support of this research and to Professor K. N. Houk for useful suggestions and valuable comments.

Supplementary Material Available: ^{13}C NMR shift data, Karl Fischer titration data, product distribution of HDA products **5** and **6**, rate constants of DA and HDA reactions (4 pages). Ordering information is given on any current masthead page.

---

(21) Cookson, R. C.; Gupta, S. S.; Stevens, I. D. R.; Watts, C. T. *Org. Synth.* **1971**, *51*, 121. Stickler, J. C.; Pirkle, W. H. *J. Org. Chem.* **1966**, *31*, 3444.

(22) Hamer, J.; Ahmad, M.; Holliday, E. *J. Org. Chem.* **1963**, *28*, 3034.

(23) Allen, C. F. H.; Bell, A. *Organic Syntheses*; Wiley: New York, 1955; Collect. Vol. III, p 310.

(24) Tietze, L. F.; Brumby, T.; Pretor, M.; Remberg, G. *J. Org. Chem.* **1988**, *53*, 810.

(25) Konovalov, A. I.; Breus, I. P.; Sharagin, I. A.; Kiselev, I. D. *Zh. Org. Khim.* **1979**, *15*, 361.

(26) Burrage, M. E.; Cookson, R. R.; Gupta, S. S.; Stevens, I. D. R. *J. Chem. Soc., Perkin Trans. 2* **1975**, 1325.

(27) Kojima, S. *Kogyo Kagaku Zasshi* **1956**, *59*, 951; *Chem. Abstr.* **1958**, *52*, 12870.

(28) Corsico Coda, A.; Desimoni, G.; Ferrari, E.; Righetti, P. P.; Tacconi, G. *Tetrahedron* **1984**, *40*, 1611.