3198 *Organometallics* **1996,** *15,* 3198−3203

Marked Changes in Relative Nucleophilicity in Comparing S$_N$2Ar Reactions of Free Arenes and Coordinated Arenes. Kinetic Studies of Reactions of (η^6-Chlorobenzene)(η^5-cyclopentadienyl)iron(II) Tetrafluoroborate with Anionic and Neutral Nucleophiles

Paulo C. B. Gomes, Eduardo J. S. Vichi,* Paulo J. S. Moran,
Alberto Federman Neto,[†] Maria Lourdes Maroso, and Joseph Miller*,[‡]

Instituto de Quimica, Universidade Estadual de Campinas, CP 6154,
13083-970 Campinas SP, Brazil

Received March 7, 1996[⊗]

Quantitative kinetic studies have been made of reactions of the (η^6-chlorobenzene)(η^5-cyclopentadienyl)iron(II) cation, $(C_6H_5Cl)Fe(C_5H_5)^+$ (**1**), with methoxide, phenoxide, methanethiolate, benzenethiolate, and azide ions in methanol, piperidine, morpholine, aniline, and thiourea in methanol, and guanidine in ethanol. The results were compared with the same nucleophile−solvent combinations in reactions with 1-chloro-2,4-dinitrobenzene, $C_6H_3(NO_2)_2Cl$ (**2**). In general, the reactivity decreases on passing from **2** to **1**. The decrease is small ($\leq 10^{-1}$) for phenoxide (PhO^-), methanethiolate (MeS^-), and guanidine (gua) and large (*ca.* 10^{-5}) for benzenethiolate (PhS^-), azide (N_3^-), piperidine (pip), morpholine (morph), aniline (anil), and thiourea (thiou). The differences in reactivity when comparing the S$_N$2Ar reactions of **1** and **2** is discussed in terms of the different location of the negative charge generated in the transition state by the electrons displaced from the reaction center by the entering groups (arenide electrons).

Introduction

Nucleophilic substitution reactions in halogenoarene transition metal complexes have gained synthetic importance in organic chemistry[1] because the parent organic molecules are virtually inert to nucleophiles under normal conditions.[2] The report by Nicholls and Whiting[3] that the $Cr(CO)_3$ moiety of (η^6-chlorobenzene)tricarbonylchromium activates methoxy dechlorination led to the publication of many papers on S$_N$2Ar reactions activated by arene complexation to a transition metal. These papers reported kinetic studies and synthetic applications of halogenoarenes coordinated to transition metal−ligand residues, such as $Cr(CO)_3$,[4] $[(\eta^5\text{-}C_5H_5)Fe]^+$,[5] $[(\eta^5\text{-}C_5H_5)Ru]^+$,[6] and $[(CO)_3Mn]^+$.[7]

It was established that π-coordination to $Cr(CO)_3$ activates the halogenoarene ligand toward methoxide to an extent similar in magnitude to the effect of a 4-nitro substituent,[4a−c] although different mechanisms of electron withdrawal have been suggested for the two systems.[4e] The effect of π-complexation with $[(\eta^5\text{-}C_5H_5)Fe]^+$,[5b] $[(CO)_3Mn]^+$,[7c] and $[(\eta^5\text{-}C_5H_5)Ru]^+$ [6c] is even more marked; the effect of the $[(\eta^5\text{-}C_5H_5)Fe]^+$ moiety is equivalent to that of *o*- and *p*-nitro groups combined. The greater activating power of the $[(\eta^5\text{-}C_5H_5)Fe]^+$ moiety[5b] compared with $Cr(CO)_3$[4a] includes a significant entropic contribution, since the reaction of methoxide with the iron(II) salt is between an anion and a cation.

In view of the interest in these S$_N$2Ar reactions[8] we have studied the kinetics of the reactions of **1** with a varied range of nucleophiles. In this paper we report

---

[†] Present address: Faculdade de Ciências Farmaceuticas, Universidade de São Paulo, 14040-900 Ribeirão Preto, SP, Brazil.

[‡] Present address: Laboratório de Tecnologia Farmaceutica e Departamento de Química/CCEN, Universidade Federal da Paraiba, CP 5009, 58051-970 João Pessoa, Pb, Brazil.

[⊗] Abstract published in *Advance ACS Abstracts,* June 1, 1996.

[1] See: (a) Semmelhack, M. F. *J. Organomet. Chem.* **1961**, *1,* 36. (b) Jouen, G. In *Transition Metal Organometallics in Organic Synthesis*; Alper, H., Ed.; Academic Press: New York, 1978; Vol. II, Chapter 2, and references therein.

[2] Miller, J. *Aromatic Nucleophilic Substitution*; Elsevier: Amsterdam, London, and New York, 1968.

[3] Nicholls, B.; Whiting, M. C. *J. Chem. Soc.* **1956**, 551.

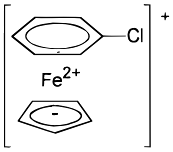
[4] (a) Brown, D. A.; Raju, J. R. *J. Chem. Soc. A* **1966,** 40. (b) Bunnett, J. F.; Herrmann, H. *J. Org. Chem.* **1971**, *36*, 4081. (c) Tchissambon, L.; Jouen, G.; Dabard, R. *C. R. Seances Acaad. Sci.* **1972**, *274C*, 654, 806. (d) Semmelhack, M. F.; Hall, H. T. *J. Am. Chem. Soc.* **1974**, *96*, 7091, 7092. (e) Kreindlin, A. Z.; Khandarova, U. S.; Gubin, S. P. *J. Organomet. Chem.* **1975**, *92*, 197. (f) Mahaffy, C. A. L.; Pauson, P. L. *J. Chem. Res., Synop.* **1979**, 128; *J. Chem. Res., Miniprint* **1979**, 1773. (g) Semmelhack, M. F.; Clarck, G. R.; Garcia, J. L.; Harrison, J.J.; Thebteraronth, Y.; Yamashita, A. *Tetrahedron* **1981**, *37*, 3959. (h) Ostrowiski, S.; Mokoska, M. *J. Organomet. Chem.* **1989**, *367*, 95.

[5] (a) Nesmeyanov, A. N.; Vol'kenau, N. A.; Bolesova, I. N. *Dokl. Acad. Nauk SSSR* **1967**, *175*, 106, 606. (b) Nesmeyanov, A. N.; Vol'kenau, N. A.; Isaeva, L. S.; Bolesova, I. N. *Dokl. Acad. Nauk SSSR* **1968**, *183*, 184 and earlier papers cited therein. (c) Helling, J. F.; Hendrickson, W. A. *J. Organomet. Chem.* **1979**, *168*, 87. (d) Khand, I. V.; Pauson, P. L.; Watts, W. F. *J. Chem. Soc. C* **1969**, 2024. (e) Lee, C. C.; Azogu, C. I.; Chang, P. C.; Sutherland, R. G. *J. Organomet. Chem.* **1981**, *220*, 181. (f) Lee, C. C.; Gill, U. S.; Iqbal, M.; Azogu, C. I.; Sutherland**,** R. G. *J. Organomet. Chem.* **1982**, *231*, 151. (g) Astruc, D. *Tetrahedron* **1983**, *39*, 4027. (h) Moriarty, R. M.; Gill, U. S. *Organometallics* **1986**, *5*, 253. (i) Lee, C. C.; Abd-el-Aziz, A. S.; Chowdhury, R. L.; Gill, U. S.; Piorko, A.; Sutherland, R. G. *J. Organomet. Chem.* **1986**, *315*, 79. Sutherland, R. G.; Choudhury, R. L.; Piorko, A.; Lee, C. C. *Can. J. Chem.* **1986**, *64*, 2031. (j) Terrier, F.; Vichard, D.; Chatrousse, A. P.; Top, S.; McGlinchey, M. J. *Organometallics* **1994**, *13*, 690.

[6] a) Sagall, J. A. *J. Chem. Soc., Chem. Commun.* **1985**, 1338. (b) Vol'kenau, N. A.; Bolesova, I. N.; Shulpina, L. S.; Kitaigorodskii, A. N.; Kravtsov, D. N. *J. Organomet. Chem.* **1985**, *288*, 341. (c) Moriarty, R. M.; Gill, U. S.; Ku, Y. Y. *J. Organomet. Chem.* **1988**, *350*, 157. (d) Moriarty, R. M.; Ku, Y. Y.; Gill, U. S. *Organometallics* **1988**, *7*, 660.

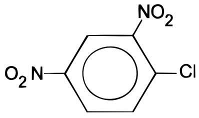
[7] a) Walker, P. J. C.; Mawby, R. J. *Inorg. Chem.* **1971**, *10*, 404; *J. Chem. Soc., Dalton Trans.* **1973**, 622. (b) Pauson, P. L.; Segal, J. A. *J. Chem. Soc., Dalton Trans.* **1975**, 1677, 1683. (c) Knipe, A. C.; Guiness, S. J.; Watts, W. E. *J. Chem. Soc., Perkin Trans. 2* **1981**, 193. (d) Bhasin, K. K.; Balkeen, W. G.; Pauson, P. L. *J. Organomet. Chem.* **1981**, *204*, C25.

S0276-7333(96)00181-1 CCC: $12.00



1

quantitative and semiquantitative studies of reactions with (a) azide (N_3^-), phenoxide ($C_6H_5O^-$), methanethiolate (CH_3S^-), and benzenethiolate ($C_5H_5S^-$) ions in methanol, (b) piperidine (pip), morpholine (morph), aniline (anil), and thiourea (thiou) in methanol, and (c) guanidine (gua) in ethanol. The results are compared with data for the same—or very similar—nucleophile—solvent combinations in reactions with $C_6H_3(NO_2)_2Cl$ (**2**).[9−16] Since there were no data in the literature for the reactions of **2** with morpholine and guanidine, we carried out a complete kinetic study of these reactions.



2

Results and Discussion

It is generally accepted that activated S_N2Ar reactions of halogenoarenes, inter alia, proceed *via* a σ-complex intermediate (Meisenheimer complex[2,17]) with flanking transition states and that in the majority of such reactions the formation of the first transition state is rate-limiting.[2,18,19] All available evidence suggests that the S_N2Ar reactions of coordinated halogenoarenes follow the same reaction path.[4a,c,d,5a,d,7c] The nucleophilic reactivity order is determined by both Coulombic and covalent contributions, whose relative contribution depends on the initial charge distribution in the halogenoarene and the position of the transition state along the reaction coordinate.

Rate Data. The rate data for the reactions studied in this work are presented in Table 1, while Figure 1 shows Arrhenius plots for all the reactions studied. Table 2 presents the derived kinetic parameters and the rate coefficients calculated at 0 °C for the reactions of **1**. A comparison of the values of $\Delta G^\ddagger$ shows that in reactions with **1** the anionic nucleophiles, apart from N_3^-, are more reactive than pip and morph. The neutral nucleophile gua is also an exception, showing a reactivity similar to that of the anionic nucleophiles MeS^- and PhS^-. The values of $\Delta H^\ddagger$ and $\Delta S^\ddagger$ show, as expected, that the differences in reactivity between the anionic and neutral nucleophiles are mainly entropic. Again, the exceptions are N_3^-, which has abnormally high values of entropy and enthalpy of activation, and gua, which has an exceptionally low enthalpy of activation while the entropy of activation is highly negative.

Table 1. Rate Coefficients for Reactions of $(C_6H_5Cl)Fe(C_5H_5)^+$ (1) and of $2,4\text{-}(NO_2)_2C_6H_3Cl$ (2) with Nucleophiles

substrate	nucleophile (solvent)	temp (°C)	k_2[a] ($dm^3\ mol^{-1}\ s^{-1}$)
1	MeO^- (MeOH)	13.6	2.41×10^{-2}
1	PhO^- (MeOH)	20.8	1.72×10^{-4}
1	PhO^- (MeOH)	25.2	2.95×10^{-4}
1	PhO^- (MeOH)	31.2	6.03×10^{-4}
1	PhO^- (MeOH)	33.2	7.23×10^{-4}
1	PhO^- (MeOH)	41.4	1.83×10^{-3}
1	MeS^- (MeOH)	10.9	4.08×10^{-3}
1	MeS^- (MeOH)	20.3	1.04×10^{-2}, 1.07×10^{-2}
1	MeS^- (MeOH)	30.5	2.74×10^{-2}, 2.89×10^{-2}
1	PhS^- (MeOH)	10.3	1.46×10^{-3}
1	PhS^- (MeOH)	15.4	2.60×10^{-3}, 2.73×10^{-3}
1	PhS^- (MeOH)	20.4	4.36×10^{-3}
1	PhS^- (MeOH)	25.0	7.62×10^{-3}
1	PhS^- (MeOH)	29.9	1.30×10^{-2}, 1.29×10^{-2}
1	N_3^- (MeOH)	81.1	4.60×10^{-4}, 4.74×10^{-4}
1	N_3^- (MeOH)	85.2	7.29×10^{-4}
1	N_3^- (MeOH)	89.0	1.22×10^{-3}
1	N_3^- (MeOH)	90.0	1.27×10^{-3}
1	pip[b] (MeOH)	102.9	3.54×10^{-3}, 3.66×10^{-3}
1	pip (MeOH)	118.8	9.37×10^{-3}, 9.43×10^{-3}
1	pip (MeOH)	138.9	3.00×10^{-2}, 3.01×10^{-2}
1	morph[c] (MeOH)	138.8	9.04×10^{-3}, 9.13×10^{-3}
1	morph (MeOH)	150.6	1.81×10^{-2}, 1.82×10^{-2}
1	morph (MeOH)	156.8	2.48×10^{-2}, 2.65×10^{-2}
1	gua[d] (EtOH)	28.2	4.05×10^{-3}, 4.06×10^{-3}
1	gua (EtOH)	38.4	6.10×10^{-3}, 6.19×10^{-3}
1	gua (EtOH)	48.6	9.08×10^{-3}
1	anil[e] (MeOH)	100	*ca.* 20% reacn after 72 h
1	thiou[f] (MeOH)	130	*ca.* 25% reacn after 72 h
2	morph (MeOH)	30.0	1.52×10^{-2}
2	morph (MeOH)	40.2	2.92×10^{-2}
2	morph (MeOH)	50.5	5.33×10^{-2}
2	gua (MeOH)	0.2	3.91×10^{-3}, 3.61×10^{-3}
2	gua (MeOH)	10.0	7.01×10^{-3}
2	gua (MeOH)	20.1	1.52×10^{-2}
2	gua (MeOH)	32.9	4.30×10^{-2}, 4.40×10^{-2}

[a] Standard deviation in calculating k_2 was less than 3%, and the correlation coefficient was not less than 0.998. [b] Piperidine. [c] Morpholine. [d] Guanidine. [e] Aniline. [f] Thiourea.

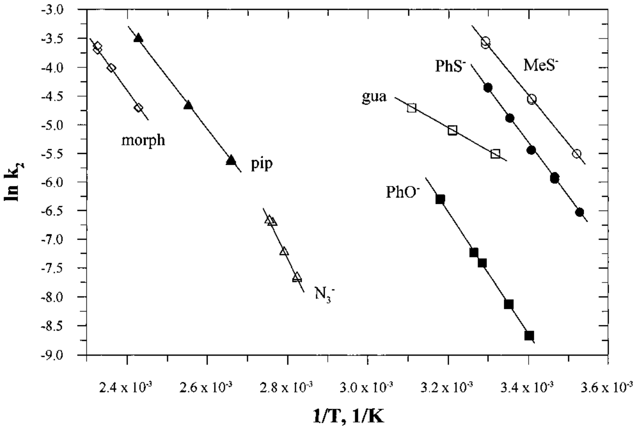


Figure 1. Arrhenius plots for reactions of the (η^6-chlorobenzene)(η^5-cyclopentadienyl)iron(III) cation with PhO^-, MeS^-, PhS^-, N_3^-, piperidine, morpholine, and guanidine.

---

(8) See: Crampton, M. R. In *Organic Reaction Mechanisms*; Knipe, A. C., Watts, W. E., Eds.; Wiley: New York, 1991, and previous volumes.

(9) (a) Beckwith, A. L.; Miller, J.; Leahy, G. D. *J. Chem. Soc.* **1952**, 3552. (b) Miller, J.; Wong, K. W. *Aust. J. Chem.* **1965**, *18*, 117. (c) Miler, J.; Sakazaki, E. Unpublished work.

(10) Leahy, G. D.; Liveris, M.; Miller, J.; Parker, A. J. *Aust. J. Chem.* **1956**, *9*, 382.

(11) Lok, C. T.; Miller, J.; Stansfield, F. *J. Chem. Soc.* **1964**, 1213.

(12) Bunnett, J. F.; Merritt, W. D. *J. Am. Chem. Soc.* **1957**, *79*, 5967.

(13) Coniglio, B. O.; Giles, D. E.; McDonald, W. R.; Parker, A. J. *J. Chem. Soc. B* **1966**, 152.

(14) Bunnett, J. F.; Garbisch, E. W.; Pruitt, K. M. *J. Am. Chem. Soc.* **1957**, *79*, 385.

(15) Chapman, N. B.; Parker, R. E. *J. Chem. Soc.* **1951**, 3301.

(16) Miller, J.; Yeung, H. W. *J. Chem. Soc., Perkin Trans. 2* **1972**, 1553.

(17) For reviews of Meisenheimer complexes see: (a) Terrier, F. *Chem. Rev.* **1982**, *82*, 77. (b) Artamkina, G. A.; Egorov, M. P.; Beletskaya, J. P. *Chem. Rev.* **1982**, *82*, 427. (c) Buncel, E.; Crampton, M. R.; Strauss, M. J.; Terrier, F. *Electron Deficient Aromatic- and Heteroaromatic-Base Interactions*; Elsevier: Amsterdam, Oxford, New York, Tokyo, 1984.

(18) Crampton, M. *Adv. Phys. Org. Chem.* **1969**, *7*, 211.

(19) Ritchie, C. D.; Sawada, M. *J. Am. Chem. Soc.* **1977**, *99*, 3754.

Table 2. Rate Coefficients, Calculated at 0 °C, and Derived Kinetic Parameters for Reactions of $(C_6H_5Cl)Fe(C_5H_5)^+$ [a]

nucleophile (solvent)	k_2, 0 °C ($dm^3\ mol^{-1}\ s^{-1}$)	$\Delta E^{\ddagger}$ [b] ($kJ\ mol^{-1}$)	log A[b] (A, $L\ mol^{-1}\ s^{-1}$)	$\Delta H^{\ddagger}$ ($kJ\ mol^{-1}$)	$\Delta S^{\ddagger}$ ($J\ mol^{-1}\ K^{-1}$)	$\Delta G^{\ddagger}$ ($kJ\ mol^{-1}$)
MeO^- (MeOH)	4.83×10^{-3}	81.5	13.3			
PhO^- (MeOH)	1.12×10^{-5}	88.0 ± 0.9	11.9 ± 0.2	85.5	−26.2	93.3
MeS^- (MeOH)	1.23×10^{-3}	71 ± 1	10.6 ± 0.2	68	−50.1	83
PhS^- (MeOH)	4.10×10^{-4}	79 ± 1	11.8 ± 0.2	76.6	−28.5	85.1
N_3^- (MeOH)	1.90×10^{-9}	124 ± 5	15.0 ± 0.7	121	30.8	112
pip (MeOH)	3.37×10^{-7}	76.0 ± 0.7	8.1 ± 0.1	73.5	−98.0	103
morph (MeOH)	3.08×10^{-9}	85 ± 2	8.7 ± 0.2	82	−105	114
gua (EtOH)	1.09×10^{-3}	31.9 ± 0.3	3.13 ± 0.05	29.4	−193	87.0

[a] Values with MeO^-/MeOH from ref 5b. [b] The standard deviations were obtained from the experimental data of Table 1.

Table 3. Rate Coefficients, k_2, at 0 °C, and Ratios $k_2(Nu)/k_2(MeO^-)$ and $k_2(1)/k_2(2)$, at 0 °C, for $C_6H_3(NO_2)_2Cl$ (2) and $(C_6H_5Cl)Fe(C_5H_5)^+$ (1)

	$C_6H_5(NO_2)_2Cl$		$(C_6H_5Cl)Fe(C_5H_5)^+$		
nucleophile (solvent)	k_2 (dm^3 mol−1 s−1)	$k_2(Nu)/k_2(MeOH^-)$	k_2 ($dm^3\ mol^{-1}\ s^{-1}$)	$k_2(Nu)/k_2(MeOH^-)$	$k_2(\mathbf{1})/k_2(\mathbf{2})$
MeO^- (MeOH)	2.00×10^{-3}[a]	1.0	4.83×10^{-3}	1.0	2.42
PhO^- (MeOH)	4.89×10^{-5}[b]	2.4×10^{-2}	1.12×10^{-5}	2.3×10^{-3}	2.3×10^{-1}
MeS^- (MeOH)	3.66×10^{-3}[c]	1.8	1.2×10^{-3}	2.55×10^{-1}	3.3×10^{-1}
PhS^- (MeOH)	3.90[d,e]	2.0×10^{3}	4.1×10^{-4}	8.5×10^{-2}	1.1×10^{-4}
N_3^- (MeOH)	3.31×10^{-5}[f]	1.7×10^{-2}	1.7×10^{-9}	3.5×10^{-7}	5.1×10^{-5}
pip (MeOH)	1.95×10^{-3}[g]	9.8×10^{-1}	3.8×10^{-7}	7.8×10^{-5}	1.9×10^{-4}
morph (MeOH)	1.70×10^{-3}	8.5×10^{-1}	3.1×10^{-8}	6.4×10^{-6}	1.8×10^{-5}
gua (EtOH)	3.50×10^{-3}	1.8	1.09×10^{-3}	2.3×10^{-1}	3.1×10^{-1}
anil (EtOH)	1.08×10^{-5}[h]	5.4×10^{-3}	20% reacn, 72 h, 100 °C		
thiou (MeOH)	7.1×10^{-8}[e]	3.5×10^{-5}	25% reacn, 72 h, 130 °C		

[a] Reference 9. [b] Reference 10. [c] Reference 11. [d] Reference 12. [e] Reference 16. [f] Reference 13. [g] Reference 14. [h] Reference 15.

Table 4. Absolute Values $\Delta E^{\ddagger}$ ($kJ\ mol^{-1}$) and log A (A, $dm^3\ mol^{-1}\ s^{-1}$) and Relative Values Related to Reaction with MeO^-/MeOH $\Delta\Delta E^{\ddagger}$ ($kJ\ mol^{-1}$) and Δ log A of the Arrhenius Parameters for Reactions of $C_6H_3(NO_2)_2Cl$ and $(C_6H_5Cl)Fe(C_5H_5)^+$

nucleophile (solvent	$C_6H_3(NO_2)_2Cl$				$(C_6H_5Cl)Fe(C_5H_5)^+$			
	$\Delta E^{\ddagger}$	$\Delta\Delta E^{\ddagger}$	log A	Δ log A	$\Delta E^{\ddagger}$	$\Delta\Delta E^{\ddagger}$	log A	Δ log A
MeO^- (MeOH)	73.0[a]	0	11.2	0	81.5	0	13.3	0
PhO^- (MeOH)	78.5[b]	+5.5	10.7	−0.5	88.0	+6.5	11.9	−1.4
MeS^- (MeOH)	59.0[c]	−14.0	8.9	−2.3	71	−10.5	10.6	−2.7
PhS- (MeOH)	43.1[d,e]	−29.9	8.9	−2.3	79	−2.5	11.8	−1.5
N_3^- (MeOH)	74.9[f]	+1.9	9.9	−1.3	124	+42.5	15.0	+1.7
pip (MeOH)	48.6[g]	−24.4	6.7	−4.5	76.0	−5.5	8.10	−5.2
morph (MeOH)	49.4	−23.6	6.7	−4.5	85	+3.5	8.7	−4.6
gua (EtOH)	52.2	−20.8	7.5	−3.7	31.9	−49.6	3.13	−10.2
anil (EtOH)	46.5[h]	−26.5	4.0	−7.2				
thiou (MeOH)	76.6[e]	+3.6	7.5	−3.7				

[a] Reference 9. [b] Reference 10. [c] Reference 11. [d] Reference 12. [e] Reference 16. [f] Reference 13. [g] Reference 14. [h] Reference 15.

Table 3 shows the rate coefficients, at 0 °C, for the reactions of **1** and **2** compared with MeO^- as the standard nucleophile, and Table 4 shows the absolute and relative kinetic parameters for these reactions. From the values of k_2 at 0 °C, the following order of reactivities toward **1** is apparent for the anionic nucleophiles: $N_3^- << PhO^- < PhS^- < MeS^- < MeO^-$. These nucleophiles show a completely different order of reactivity toward **2**, *viz.*, $N_3^- < PhO^- < MeO^- < MeS^- << PhS^-$. The order of reactivity of the neutral nucleophiles is the same for both substrates, that is, thiou < anil << morph < pip < gua.

We now examine these differences in reactivity in more detail.

Reactions of MeO^-, MeS^-, PhO^-, and PhS^-. The relative reactivities of these anionic nucleophiles with the neutral substrate **2** and cationic substrate **1** might be affected by at least three factors: (i) ion pairing of the nucleophile with the iron center in **1**, (ii) the position of the transition state along the reaction coordinate, and (iii) stereoelectronic factors in the transition state for nucleophilic attack.

Evidence exists that the cationic substrate **1** readily forms an ion pair with MeO^-, resulting in reduction of its reactivity toward nucleophilic attack.[7c] The reduction in the second-order rate constant is *ca.* 10 times when the concentration of MeO^- increases by *ca.* 100 times. From the rate coefficients shown in Table 3, one finds that MeO^- is *ca.* 2 times more reactive toward the cationic substrate **1** when compared with the neutral substrate **2**, in spite of ion pairing with **1**. The same comparison with PhS^- shows that it is *ca.* 10^4 less reactive toward **1**. Also from Table 3 one finds that the reactivities of PhO^- and MeS^- toward **1** are 0.2 and 0.3 times its reactivities toward **2**, respectively. The reduction of the relative reactivity of PhS^- compared to the other anionic nucleophiles seems too pronounced to be caused solely by a long-distance interaction such as ion pairing, and some additional explanation is required.

An explanation based on the position of the transition state along the reaction coordinate could be advanced when comparing the reactivities of MeO^- and MeS^- toward **1** and **2**. In reactions with **1** the *hard* nucleophile MeO^- is 4 times more reactive than the *soft* nucleophile MeS^-. This order is reversed for **2**, which reacts with MeS^- almost twice as fast as with MeO^-. This comparison suggests that in reactions of **1** with these anionic nucleophiles there might be a tendency toward greater Coulombic contributions and less covalent contribution to the transition state[20] in comparison to the corresponding reactions of **2**. In other words, there might be a tendency toward *earlier* transition states with **1**. When the reactivities of PhS^- and MeO^- toward **1** and **2** are compared, PhS^- is *ca.* 2×10^3 times more reactive than MeO^- [12,21] with **2**, whereas, in complete contrast, it is 8.5×10^{-2} as reactive with **1**. This is a change of well over 10^4 in relative reactivities.

---

[20] See: Hudson, R. F. In *Chemical Reactivity and Reaction Paths*; Klopman, G., Ed.; Wiley: New York, USA, 1974; p. 167.

[21] Bartoli, G.; Todesco, P. E.; Fiorentino, M. *J. Am. Chem. Soc.* **1977**, *99*, 6874.

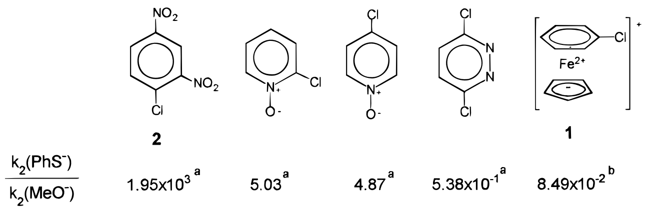
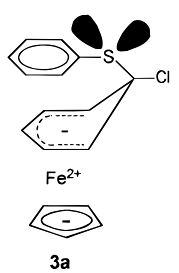


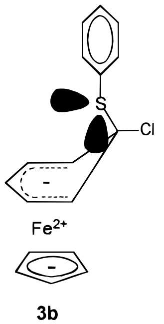
Figure 2. PhS^-/MeO^- rate coefficient ratios, in methanol, at 0 °C: (a) ref 25; (b) this work.

This can hardly be ascribed exclusively to a greater covalent contribution to the transition state in the reactions with **2**, though polarizability–polarizability interactions[22] seem to be important in determining the thiolate reactivities toward aryl halides.[11,23]

A third explanation should also be considered, and it turns out to be preferable. In general, the approach of a nucleophile to a reaction center results in displacement of substrate electrons from the reaction center to other locations in the substrate. The site of this relocation and its effects are likely to be different with different substrates. Thus, it has been suggested[24] that, in the reactive intermediates formed by **2**, electrons have been displaced onto the β-exocyclic oxygen atoms of the two nitro groups. (These displaced electrons were conveniently called *arenide electrons*.[24]) This displacement is relatively facile. On the other hand, the marked reduction in the relative nucleophilicities of PhS^- toward a series of heterocyclic arenes was attributed[24] to the fact that the arenide electrons are now located mainly in the heteroarene ring itself. As a consequence, an entering group such as PhS^-, with its substantial steric and electronic requirements, will suffer considerable repulsion from the arenide electrons on the nearby ring when forming the reaction intermediates. On the basis of the values of the ratios $k_2(PhS^-)/k_2(MeO^-)$ for reactions with the substrates shown in Figure 2, we can conclude that this stereoelectronic repulsion effect is operating in the S_N2Ar reactions of **1**, to an even greater extent than in reactions of the heteroarenes. This repulsion occurs in spite of the transfer of some π-electron density from the C_6H_5Cl ligand to the Fe^{2+} center. It could involve repulsion between the arenide electrons and either the π-electrons on the phenyl ring of PhS^- (**3a**) or the lone pairs on the S atom in PhS^- (**3b**), the σ-complex being used to represent the first, and rate-determining, transition state of the reactions. If the ratios $k_2(MeS^-)/(MeO^-)$ and $k_2(PhS^-)/k_2(MeO^-)$ in Table 3 are considered, it can be seen that they decrease by factors of 7 and 2×10^4, respectively, on changing from **2** to **1**. This suggests that it is repulsion between the arenide electrons and the phenyl ring of PhS^- that is important.



3a



3b

On the other hand, the corresponding effects for the ratio $k_2(PhO^-)/k_2(MeO^-)$, compared with $k_2(PhS^-)/k_2(MeO^-)$, is much smaller, a decrease of 10^1 instead of 2×10^4, and it can be concluded that the shorter bond formed between PhO^- and the reaction center precludes the conformation in which the phenyl ring attached to the oxygen lies above and close to the arenide electrons in the ring undergoing substitution. The only repulsions are due to the lone-pair electrons on the oxygen atoms, and these are evidently less important.

Reactions of N_3^-. The azide anion shows an abnormally low reactivity toward the cationic substrate **1** ($k_2(0\ °C) = 1.7 \times 10^{-9}$ dm^3 mol^{-1} s^{-1}) when compared to the other nucleophiles studied (*ca.* 10^{-3}–10^{-5}). It is also much less reactive with **1** than with neutral **2** ($k_2(0\ °C) = 3.31 \times 10^{-5}$ dm^3 mol^{-1} s^{-1}). These results are rather surprising, since N_3^- reacts with carbocations[25] much faster than with **2**.[26] The enthalpy of activation (121 kJ mol^{-1}) is much higher than those of the other anionic nucleophiles (see Table 2).

A possible explanation for this surprisingly low reactivity of N_3^- toward **1** involves incipient coordination of the azide ion to the Fe^{2+} center, stabilizing the ground state. The highly positive entropy of activation (33 J K^{-1} mol^{-1}) favors this hypothesis.

Reactions of pip, morph, and anil. The question of ion pairing in the reactivities of these neutral nucleophiles with **1** does not arise. In the reactions of **1** with these amines, greater covalent contribution to the rate-limiting transition state is expected compared with reactions of the anionic nucleophiles. The formation of the new bonds is accompanied by the development of formal positive charge in the nucleophile. This is consistent with the entropies of activation that are much more negative for the neutral nucleophiles compared with those of anionic nucleophiles (see Table 2).

The larger contribution of the new covalent bonds leads to more stringent geometrical requirements in the reaction intermediates. With pip, morph, and anil the short C–N bonds and the multivalent character of nitrogen are likely to lead to adverse interactions, which become still more effective when the arenide electrons remain in the electrophilic ring. This could be responsible for the marked changes in relative reactivities of pip, morph, and anil toward **1** and **2**.

In the reaction of pip and morph with **2** the amines show roughly the same reactivity as MeO^-, *viz.* $k_2(\text{amine})/k_2(MeO^-) \approx 1$ and 0.9, respectively. However, the changes in the Arrhenius parameters are large. The values of $\Delta E^\ddagger$ are much smaller for the amines with $\Delta\Delta E^\ddagger = \Delta E^\ddagger(\text{amine}) - \Delta E^\ddagger(MeO^-)$ of *ca.* -24 kJ mol^{-1}. This is slightly overcompensated by the low values of $\log A$ ($\Delta \log A = -4.5$ for both amines). In the reactions with cation **1** the rate coefficient ratios $k_2(\text{amine})/k_2(MeO^-)$ are much smaller, *viz.* 7.8×10^{-5} and 6.4×10^{-6} for pip and morph, respectively. Associated with this, the larger values of $\Delta E^\ddagger$, with $\Delta\Delta E^\ddagger$ values of -5.5 kJ mol^{-1} for pip and $+3.5$ kJ mol^{-1} for morph, are noteworthy. The difference among the amines ($k_2(\text{pip})/k_2$-

---

[22] Bunnett, J. F.; Nudelman, N. S. *J. Org. Chem.* **1969**, *34*, 2038.

[23] Bunnett, J. F.; Kato, T.; Nudelman, N. S. *J. Org. Chem.* **1969**, *34*, 785.

[24] Cito, A. M. G. C.; Lopes, J. A. D.; Miller, J.; Moran, P. J. S. *J. Chem. Res., Synop.* **1983**, 184; *J. Chem. Res., Miniprint* **1983**, 1586.

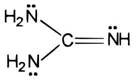
[25] Bunton, C. A.; Moffat, J. R.; Rodenas, E. *J. Am. Chem. Soc.* **1982**, *104*, 2653.

[26] Ritchie, C. D. *J. Am. Chem. Soc.* **1975**, *97*, 1170.

(morph) ≈ 10) possibly involves greater repulsion to the arenide electrons when an oxygen in morph is substituted for the 4-CH_2 group in pip. The former, with its unshared electrons and fractional negative charge, can reasonably be assumed to repel the arenide electrons more.

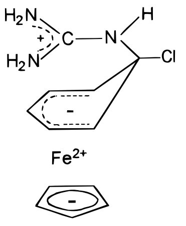
Aniline is significantly less reactive toward **2** than MeO^-, pip, and morph, and the rate-coefficient k_2(anil)/k_2(MeO^-) is 5.4×10^{-3}. As with the other amines, the value of $\Delta E^\ddagger$ is low and $\Delta\Delta E^\ddagger$ is -26.5 kJ mol^{-1}. This effect is overcompensated by a very low value of log A, corresponding to Δ log $A = -7.2$. Only about 20% of the reaction with **1** had occurred after 72 h at 100 °C. From this we estimated, very crudely, a drop in the reactivity compared with **2** of the order of 10^4, similar to the more precise values obtained for pip and morph.

Reactions of gua and thiou. The behavior of guanidine is completely different from that of the other amines, differing also in belonging to the class of unsaturated nucleophiles of the type Z—C═Nu. The internal conjugation in **4** increases the nucleophilic strength of the NH group. In addition to this, gua has much smaller steric demand than pip and morph. Guanidine thus shows a reactivity toward **2** *ca.* 2 times greater than MeO^- compared with the rate-coefficient ratios (1 and 0.9) observed for pip and morph. This value is related to a drop in the activation energy ($\Delta\Delta E^\ddagger = \Delta E^\ddagger$(gua) $- \Delta E^\ddagger$(MeO^-)) of *ca.* 21 kJ mol^{-1} which is compensated for by a drop of 3.7 in log A.



4

In the reactions with **1** the results show a complete contrast with the other amines, its reactivity being comparable to that of MeO^-. Thus, k_2(gua)/k_2(MeO^-) = 0.23, which is about 3 and 4 orders of magnitude greater than the values for pip and morph, respectively. Arrhenius parameters show reductions in $\Delta E^\ddagger$ of 50 kJ mol^{-1} compared with MeO^-, instead of -5.5 kJ mol^{-1} for pip and +3.5 kJ mol^{-1} for morph, and a drop in log A of 10 instead of *ca.* 5 for pip and morph. This can be interpreted in terms of the development of positive charge delocalized over the terminal nitrogen atoms when the saturated nitrogen atom reacts with the substrate leading to the intermediate **5**. It is reasonable to suppose that the favorable electrostatic interaction is responsible for the stabilization of the transition state.



5

Finally, we consider the reaction of thiou, another Z—C═Nu type nucleophile. Results for thiou and a series of methylated thioureas[9c] suggest that the internal conjugation has relatively little importance, so that their nucleophilicity is mainly due to the intrinsic behavior of the C═S group. As a consequence, there is relatively little development of positive charge on the nitrogen atoms to counteract unfavorable interactions of the lone pairs of electrons on the sulfur atom with the *arenide electrons* in the transition state. With **2**, k_2(thiou)/k_2(MeO^-) is 3.5×10^{-5} with $\Delta\Delta E^\ddagger = 3.6$ kJ mol^{-1} and Δ log $A = -3.7$. We have a crude quantitative result for reaction with **1**, *viz.* about 25% reaction in 72 h at 130 °C. From this we estimate a drop in reactivity relative to MeO^- of *ca.* 100 times in contrast with the drop of only *ca.* 4 times observed for gua.

Experimental Section

Materials. Chlorobenzene, (η^5-cyclopentadienyl)iron(II), sodium tetrafluoroborate, sodium azide, piperidine, morpholine, guanidine, aniline, thiourea, phenol, and hydrogen phthalate were commercial reagents and were recrystallized under argon, or sublimed under argon, as appropriate. Melting points and boiling points of all organic reagents agreed with those reported in the literature.

(η^6-Chlorobenzene)(η^5-cyclopentadienyl)iron tetrafluoroborate was prepared as described in the literature,[5b,27] without important modifications. Methanol was dried over Mg and I_2 and distilled, then refluxed over $AgNO_3$, and distilled again. The fraction collected distilled between 63.5 and 64.8 °C. Ethanol was dried over CaO, refluxed over $AgNO_3$, then over KOH, and finally over diethyl phthalate, and distilled. The fraction used was collected at 78 °C. Sodium methoxide in methanol was prepared from purified methanol and previously cleaned sodium and stored under dinitrogen, with protection against entrance of CO_2. Its concentration was determined periodically by standard titrimetric procedures, against hydrogen phthalate. Sodium phenoxide in methanol was obtained from phenol and methanolic sodium methoxide.

Apparatus. A Metrohm-Herisau automatic titrator was used in all the chloride titrations and pH measurements. In the chloride titrations, silver chloride/saturated calomel conjugated electrodes were used. In the pH measurements glass and saturated calomel electrodes were used. The ^1H NMR spectra were obtained on a Varian T-60 spectrometer, using TMS as internal standard. The IR spectra were recorded on a Perkin-Elmer 283 spectrometer, using KBr pellets. Elemental analyses were carried out using a Perkin-Elmer 2400 CHN elemental analyzer.

General Procedure for Isolation of Reaction Products. Substitution products were isolated by recrystallization of the picrate salts. (η^6-Chlorobenzene)(η^5-cyclopentadienyl)iron(II) tetrafluoroborate was dissolved in methanol (or ethanol) and treated with the nucleophile. After the reaction was completed, the reaction mixture was filtered and evaporated to dryness under vacuum below 40 °C. The residue was dissolved in water, excess base was neutralized with 10% aqueous HCl, and the product was precipitated by addition of a saturated aqueous solution of picric acid. It was then filtered by suction, dried under vacuum, and recrystallized from ethanol. The products were characterized by ^1H NMR and infrared spectra. Elemental analyses of the stable products were in good agreement with calculated values. ^1H NMR spectra of previously known compounds were identical with those reported. The data are as follows.

(η^6-Methoxybenzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with 0.054 g (1 mmol) of $NaOCH_3$ in 10 cm^3 of methanol, for 3 h, at room temperature, yielding 0.343 g (75%) of pale yellow needles; mp 273 °C. ^1H NMR (in DMSO-d^6): δ 8.60 (s, 2H, $C_6H_2N_3O_7$), 6.00 (m, 5H, C_6H_5), 4.80 (s, 5H, C_5H_5), 2.80 (s, 3H, CH_3O). IR (KBr): 470 (iron-ring stretching), 490 cm^{-1} (ring tilt). Anal. Calcd for $C_{18}H_{15}FeN_3O_8$: C, 47.29; H, 3.31; N, 9.19. Found: C, 47.33; H, 3.30, N, 9.40.

(η^6-(Methylthio)benzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with 0.070 g (1 mmol) of $NaSCH_3$ in 10

---

[27] Federman Neto, A.; Miller, J. *An. Acad. Bras. Cienc.* **1982**, *54*, 331.

cm^3 of methanol, for 3 h, at room temperature, yielding 0.317 g (67%) of deep yellow needles sensitive to air and light; mp 170 °C dec. ^{1}H NMR (in DMSO-d^6): δ 8.55 (s, 2H, $C_6H_2N_3O_7$), 6.20 (m, 5H, C_6H_5), 4.95 (s, 5H, C_5H_5), 3.15 (s, 3H, CH_3S; IR (KBr): 450 (iron-ring stretching), 490 cm^{-1} (ring tilt). Anal. Calcd for $C_{18}H_{15}FeN_3O_7S$: C, 45.67; H, 3.20; N, 8.88. Found: C, 45.65; H, 2.84; N, 9.06.

(η^6-Phenoxybenzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with a mixture of 0.054 g (1 mmol) of $NaOCH_3$ and 0.24 g (2.5 mmol) of C_5H_5OH[28] in 10 cm^3 of methanol for 3 h under reflux,[29] yielding 0.321 g (62%) of pale yellow needles; mp 210−214 dec. ^{1}H NMR (DMSO-d^6): δ 8.40 (s, broad, 2H, $C_6H_2N_3O_7$), 6.00−6.70 (m, 10H, $C_6H_5OC_6H_5$), 5.10 (s, broad, 5H, C_5H_5). IR (KBr): 660 (bending, C−C aromatic), 470 (iron-ring stretching), 485 cm^{-1} (ring tilt). Anal. Calcd for $C_{23}H_{17}FeN_3O_8$: C, 53.18; H, 3.30; N, 8.09. Found: C, 53.45; H, 2.97; N, 7.87.

(η^6-(Phenylthio)benzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with a mixture of 0.054 g (1 mmol) of $NaOCH_3$ and 0.13 g (1.2 mmol) of C_6H_5SH[30] in 10 cm^3 of methanol, for 3 h, at room temperature, yielding 0.342 g (64%) of deep yellow crystals sensitive to air and light); mp 120 °C dec. ^{1}H NMR (DMSO-d^6): δ 8.45 (s, 2H, $C_6H_2N_3O_7$), 5.90−6.50 (m, broad, 10H, $C_6H_5SC_6H_5$), 5.00 (s, 5H, C_5H_5). IR (KBr): 450 (iron-ring stretching), 480 cm^{-1} (ring tilt). Anal. Calcd for $C_{23}H_{17}FeN_3O_7S$: C, 51.59; H, 3.20; N, 7.85. Found: C, 51.23; H, 2.84; N, 7.83.

(η^6-Azidobenzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with 0.065 g (1 mmol) of NaN_3 in 20 cm^3 of methanol[31] for 2 h, under reflux, yielding 0.257 g (55%) of yellow needles very sensitive to light; mp 156−158 °C. ^{1}H NMR (CH_3CN-d_6): δ 8.60 (s, 2H, $C_6H_2N_3O_7$), 5.80−6.50 (m, 5H, C_6H_5N), 5.00 (s, 5H, C_5H_5). IR (KBr): 2030−2150 (N−N−N stretching), 640 (N−N−N bending), 470−480 cm^{-1} (ring tilt and iron-ring stretching). Anal. Calcd for $C_{17}H_{12}FeN_6O_7$: C, 43.59; H, 2.58; N, 17.95. Found: C, 43.08; H, 2.46; N, 17.27.

(η^6-Piperidinobenzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with 2.3 g (27 mmol) of piperidine[32] in 10 cm^3 of methanol for 4 h at room temperature, yielding 0.301 g (59%) of orange needles, sensitive to light; mp 110−113 °C dec. ^{1}H NMR (DMSO-d^6): δ 8.50 (s, 2H, $C_6H_5N_3O_7$), 6.00 (m, 5H, C_6H_5), 4.90 (s, 5H, C_5H_5), 3.00−3.60 (m, 10H, $C_5H_{10}N$). IR (KBr): 2850, 2915 (C−H stretching), 420−520 cm^{-1} (skeletal C−C deformation on N-alkyl groups, iron-ring stretching, and ring tilt). Anal. Calcd for $C_{22}H_{22}FeN_4O_7$): C, 51.76; H, 4.35; N, 10.98. Found: C, 51.23; H, 4.28; N, 10.86.

(η^6-Morpholinobenzene)(η^5-cyclopentadienyl)iron(II) Picrate. Following the general procedure, 0.320 g (1 mmol) of **1** reacted with 0.174 g (2 mmol) of morpholine in 10 cm^3 of methanol, for 2 h under reflux, yielding 0.323 g (63%) of orange needles; mp 157−159 °C dec. ^{1}H NMR (DMSO-d^6): δ 8.40 (s, 2H, $C_6H_2N_3O_7$), 6.90 (m, 5H, C_6H_5), 5.00 (s, 5H, C_5H_5), 3.00−3.40 (m, 8H, C_4H_8NO). IR (KBr): 2980−2800 (C−H stretching), 470−460 (skeletal C−C deformation on *N*-alkyl groups), 440 (ring tilt), 420 cm^{-1} (iron-ring stretching). Anal. Calcd for $C_{21}H_{20}FeN_4O_8$: C, 49.21; H, 3.94; N, 10.94. Found: C, 49.42; H, 3.84; N, 10.47.

Some of the organometallic cations reported in this paper have previously been reported in the literature with other counterions, *viz.* (η^6-methoxybenzene)(η^5-cyclopentadienyl)iron(II) as the tetrafluoroborate and hexafluorophosphate salts, (η^6-(phenylthio)benzene)(η^5-cyclopentadienyl)iron(II) as the tetraphenylborate salt,[5b] and (η^6-phenoxybenzene)- and (η^6-azidobenzene)(η^5-cyclopentadienyl)iron(II) as the hexafluorophosphate salts.[5e]

Kinetics. The reactions at temperatures below 45 °C were carried out in thermostated standard volumetric flasks, under a purified dinitrogen atmosphere. Aliquots measured with calibrated pipettes, withdrawn from reaction solutions, were added to an excess of diluted nitric acid, and the concentrations of the displaced chloride ions were measured. The reactions at temperatures above 45 °C were carried out with samples, previously measured with calibrated pipets, sealed in glass ampules. In both procedures the chloride ions displaced by the reacting nucleophile were titrated potentiometrically against standard 0.05 M $AgNO_3$ solution. The reactions of (η^6-chlorobenzene)(η^5-cyclopentadienyl)iron(II) tetrafluoroborate, as substrate, with sodium methoxide and sodium azide in methanol were carried out with equimolar concentrations of reagent and substrate. To prevent the interference of methoxide ions from the solvent, the reactions of the substrate with benzenethiolate, methanethiolate, and phenoxide ions in methanol were carried out with equimolar concentrations of reagents and their conjugated acids, as well as the substrate. For the same reason the reactions of the substrate with aniline, morpholine, and thiourea in methanol and with guanidine in ethanol were carried out with 2 equiv of the conjugated acid, 2 equiv of the free base, and 1 equiv of the substrate. The initial concentration of the substrate in all the kinetic runs was 0.025 M.

The values of the rate coefficients were obtained by the method of least squares from a linear correlation of $1/(a - x)$ *versus* time in seconds. In the case of reactions with aniline, morpholine, piperidine, thiourea, and guanidine the values of k_2 were obtained from a linear correlation of $1/\{2(a - x)\}$ *versus* time in seconds. The Arrhenius and derived kinetic parameters were obtained by the same procedure, from a linear correlation of $\log k_2$ (rate coefficients in dm^3 mol^{-1} s^{-1}) *versus* reciprocal temperature, $1/T$.

We did not carry out a complete study of the reaction with methoxide ion, since this had been studied by Nesmeyanov *et al.*[5b] However, as a precaution, we have determined the k_2 value at 13.6 °C as 2.41×10^{-2} dm^3 mol^{-1} s^{-1} with a correlation coefficient of 0.9996. Nesmeyanov's data[5a] lead to the value 2.485×10^{-2} dm^3 mol^{-1} s^{-1}, in satisfactory agreement.

Acknowledgment. E.J.S.V. thanks Prof. Anthony J. Poe and Mr. Jianbin Hao for their help in the final edition of the manuscript.

OM9601817

---

[28] Excess phenol is used to avoid possible competition from methoxide.

[29] No reaction is observed at room temperature.

[30] Excess thiophenol is used to avoid possible competition from methoxide.

[31] A larger volume of methanol is used compared to the other reactions because NaN_3 is less soluble in methanol than the other reagents.

[32] If a smaller excess of piperidine is used, the methoxide product is obtained.