1 Hz, 1 H), 5.17 (ddd, J = 3, 7, 10 hZ, 1 H), 7.52 (d, J = 1 Hz, 1 H); HRMS calcd for $C_{12}H_{18}O_6$ 258.1103, found 258.1109. Anal. Calcd for $C_{12}H_{18}O_6$: C, 55.81; H, 7.03. Found: C, 55.69; H, 6.81.

For **16**: IR 3550, 1700, 1625 cm^{-1}; ^{1}H NMR δ 1.44 (d, J = 6 Hz, 3 H), 1.52 (m, 3 H), 3.2–3.6 (m, 1 H), 3.48 (s, 3 H), 3.91 (s, 3 H), 4.75 (dq, J = 6, 10 Hz, 1 H), 5.05 (dd, J = 3, 10 Hz, 1 H), 5.4 (t, J = 1.5 hZ, 1 H), 7.55 (d, J = 1 Hz, 1 H).

***exo*-2-Methyl-5-(methoxymethylene)-*exo*-10-methoxy-3,9-dioxa-*cis*-bicyclo[4.4.0]decane-4,8-dione (18).** To a stirred solution of 195 mg (0.756 mmol) of hemiacetal **17** in 15 mL of purified dichloromethane (washed with sulfuric acid and aqueous carbonate and then distilled) was added all at once 1.70 g (4.53 mmol, 6 equiv) of freshly prepared pyridinium dichromate. The orange mixture was stirred vigorously at room temperature and monitored by TLC (EtOAc, R_f 0.60). After approximately 40 h, conversion to the lactone was complete and the reaction was then diluted with 30 mL of ether and filtered through a short column of silica gel. The column was washed with 30 mL of ethyl acetate, and the combined filtrates were concentrated. Recrystallization of the resulting white solid from ethyl acetate–hexane afforded 180 mg (93%) of pure lactone: mp 130–131 °C; IR 1750, 1700, 1620 cm^{-1}; ^{1}H NMR δ 1.49 (d, J = 6 Hz, 3 H), 2.09 (ddd, J = 3, 7, 9 Hz, 1 H), 2.43 (dd, J = 9, 18 Hz, 1 H), 3.08 (d, J = 8, 18 Hz, 1 H), 3.4–3.65 (m, 1 H), 3.59 (s, 3 H), 3.94 (s, 3 H), 4.48 (dq, J = 6, 9 Hz, 1 H), 5.19 (d, J = 3 Hz, 1 H), 6.56 (d, J = 2 Hz, 1 H); HRMS calcd for $C_{12}H_{16}O_6$ 256.0947, found 256.0953. Anal. Calcd for $C_{12}H_{16}O_6$: C, 56.25; H, 6.29. Found: C, 56.46; H, 6.35.

Methyl ((4α,5β,6α)-2-Oxo-3-(methoxymethylene)-5-formyl-6-methyltetrahydropyran-4-yl)acetate (19). To a solution of 10 mg (0.04 mmol) of bislactone **18** in 8 mL of methanol was added 38.6 mg (6 equiv) of anhydrous zinc chloride with stirring at room temperature. After 2 h the reaction solution was concentrated (<30 °C) and the residue was partitioned between 3 mL of dichloromethane and 2 mL of water. The aqueous layer was saturated with sodium chloride and extracted with four 2-mL portions of the same solvent. The combined organic layers were concentrated and separated by HPLC (μ-Porasil, 1:1) to the following: 1 mg (10%) of starting material, 4.6 mg (46%) of aldehyde **19**, and 1.4 mg (14%) of trans-fused lactone **20**.

For **19**: IR 1735, 1710, 1625 cm^{-1}; ^{1}H NMR δ 1.43 (d, J = 6 Hz, 3 H), 2.42 (dd, J = 5, 15 Hz, 1 H), 2.56 (dd, J = 8, 15 Hz, 1 H), 2.85 (ddd, J = 2, 4, 10 Hz, 1 H), 3.66 (s, 3 H), 3,88 (dddd, J = 2, 4, 5, 8 Hz, 1 H), 3.93 (s, 3 H), 4.82 (dq, J = 6, 10 Hz, 1 H), 7.54 (d, J = 2 Hz, 1 H), 9.76 (d, J = 2 Hz, 1 H); HRMS calcd for $C_{12}H_{16}O_6$ 256.0947, found 256.0953.

***trans*-(1α,2β,10α)-2-Methoxy-3,9-dioxa-5-(methoxymethylene)-10-methylbicyclo[4.4.0]decane-4,8-dione (20).** This material was quite pure as isolated from the above reaction and could be crystallized from ethyl acetate–hexane with essentially quantitative recovery, affording a sample with the following: mp 121.5–122 °C; IR 1740, 1720, 1630, 1025 cm^{-1}; ^{1}H NMR δ 1.43 (d, J = 6 Hz, 3 H), 1.82 (ddd, J = 2, 10, 12 Hz, 1 H), 2.26 (dd, J = 12, 17 Hz, 1 H), 3.16 (dddd, J = 2, 5, 12, 12 Hz, 1 H), 3.52 (s, 3 H), 3.53 (dd, J = 5, 17 Hz, 1 H), 3.91 (s, 3 H), 4.42 (dq, J = 10, 6 Hz, 1 H), 5.68 (d, J = 2 Hz, 1 H), 7.57 (d, J = 2 Hz, 1 H); HRMS calcd for $C_{12}H_{16}O_6$ 256.0947, found 256.0940. Anal. Calcd for $C_{12}H_{16}O_6$: C, 56.25; H, 6.29. Found: C, 56.12; H, 6.42.

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Registry No. 1, 61229-34-3; 4, 63641-33-8; *exo*-2-methyl-*exo*,*exo*-7,8-dihydroxy-*cis*-bicyclo[3.3.0]octan-3-one, 86046-52-8; **5** (isomer 1), 86046-53-9; **5** (isomer 2), 86116-86-1; **6**, 86046-54-0; **7**, 86046-55-1; **8** (isomer 1), 86046-56-2; **8** (isomer 2), 86116-87-2; **9**, 86046-57-3; **11** (isomer 1), 86046-58-4; **11** (isomer 2), 86046-59-5; **12** (isomer 1), 86046-60-8; **12** (isomer 2), 86046-61-9; **13** (isomer 1), 86046-62-0; **13** (isomer 2), 86116-88-3; **14** (isomer 1), 86046-63-1; **14** (isomer 2), 86116-89-4; **15**, 86046-64-2; **16**, 86046-65-3; **17**, 86046-66-4; **18**, 86046-67-5; **19**, 86046-68-6; **20**, 86046-69-7; acetone, 67-64-1; methyl formate, 107-31-3.

Effect of Meta and Para Substituents on the Stannous Chloride Reduction of Nitrobenzenes in Aqueous Ethanol[1]

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The rate of reduction of 24 meta- and para-substituted nitrobenzenes with $SnCl_2$ catalyzed by HCl in ethanol–water (90:10 v/v) at 30 °C has been measured iodometrically. The rate is expressed as $v = k[ArNO_2][SnCl_2][HCl]_{st}^{0.5}$, suggesting that the sole active reducing species is $SnCl_3^-$ and the dissociation of HCl is very small. The effect of meta and para substituents in which the solvation of the substituent is taken into account was examined with the Hammett equation, which gave a ρ value of 2.1 ± 0.1. Yukawa–Tsuno and Taft equations, in which resonance and inductive effects are separated, are also discussed.

Only a few kinetic studies have been reported in the HCl-catalyzed reduction of aromatic nitro compounds to amines with stannous chloride.[4-7] Goldschmidt et al.[4] have reported that the reduction of water-soluble nitrobenzenes ($ArNO_2$) in aqueous solution obeys the rate equation 1,

$$v = k_1[ArNO_2][SnCl_2][Cl^-] = k_1[ArNO_2][SnCl_2][HCl]_{st} \tag{1}$$

where $[\ ]_{st}$ means the stoichiometric concentration. The equation suggests a mechanism that involves $SnCl_3^-$:

$$SnCl_2 + Cl^- \overset{\text{fast}}{\rightleftharpoons} SnCl_3^- \text{ (equilibrium constant } K_2) \tag{2a}$$

$$ArNO_2 + SnCl_3^- \xrightarrow[k_2]{\text{slow}} ArNO + SnOCl_3^- \tag{2b}$$

$$ArNO \xrightarrow{\text{fast}} ArNHOH \xrightarrow{\text{fast}} ArNH_2 \tag{2c}$$

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(4) (a) Goldschmidt, H.; Ingebrechtsen, K. *Z. Phys. Chem.* **1904**, *48*, 435. (b) Goldschmidt, H.; Sunde, E. *Ibid.* **1906**, *56*, 1. (c) Goldschmidt, H.; Storm, E.; Hassel, O. *Ibid.* **1922**, *100*, 197.

(5) Sampey, J. R. *J. Am. Chem. Soc.* **1930**, *52*, 88.

(6) Ogata, Y.; Sugiyama, I. *Kagaku (Tokyo)* **1949**, *19*, 232.

(7) Manabe, O.; Hiyama, H. *Kogyo Kagaku Zasshi* **1953**, *56*, 365.

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Table I. Effect of [HCl] on the Rate of $SnCl_2$ Reduction of Nitrobenzenes in $EtOH-H_2O$ (90:10 v/v) at 30 °C[a]

group in $PhNO_2$	$[HCl]_{st}$, M	$10^2k'$, $M^{-1}\ s^{-1}$	$10^2k'/[HCl]_{st} =$ 10^2k_1, $M^{-2}\ s^{-1}$	$10^2k'/[HCl]_{st}^{0.5} =$ 10^2k, $M^{-1.5}\ s^{-1}$	10^2k (av), $M^{-1.5}\ s^{-1}$
p-CH_3	2.3337	0.0992	0.0425	0.0649	
	1.4642	0.0760	0.0519	0.0628	0.0642
	0.8053	0.0583	0.0724	0.0650	
m-CH_3	2.3299	0.1792	0.0769	0.1174	
	1.4628	0.1387	0.0948	0.1147	0.1166
	0.8069	0.1058	0.1311	0.1178	
	0.4178	0.0775	0.1770	0.1199	
	0.2141	0.0573	0.2347	0.1238	
	0.1131	0.0442	0.3089	0.1314	
none	1.5625	0.1818	0.1164	0.1454	
	1.4512	0.1660	0.1144	0.1378	0.1418
	1.1171	0.1478	0.1323	0.1398	
	0.7999	0.1290	0.1613	0.1442	

[a] $v = k'[ArNO_2][SnCl_2] = k[ArNO_2][HCl]_{st}^{0.5}$. Initial concentration: $[ArNO_2]_0 = 0.0500$ M, $[SnCl_2]_0 \simeq 0.15$ M.

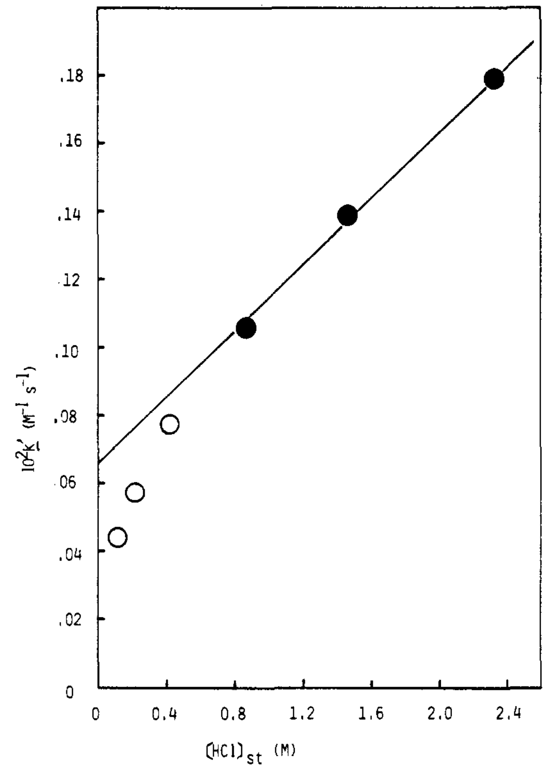

Figure 1. Plot of second-order rate constant $10^2k'$ vs. $[HCl]_{st}$ for $SnCl_2$ reduction of m-nitrotoluene in 90% EtOH at 30 °C. At low $[HCl]_{st}$, k' values deviate from the line.

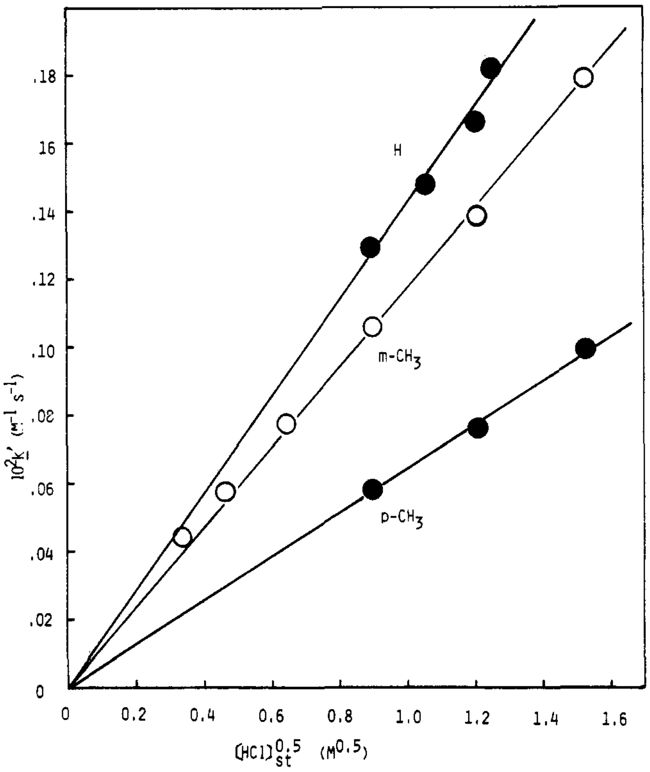

Figure 2. Plot of second-order rate constant $10^2k'$ vs. $[HCl]_{st}^{0.5}$ for $SnCl_2$ reduction of nitrobenzenes in 90% EtOH at 30 °C.

Another rate equation (eq 3) was postulated by Manabe,[7] which leads to a mechanism involving two reducing agents, $SnCl_3^-$ (eq 2b) and $SnCl_2$ (eq 4):

$$v = k_2K_2[ArNO_2][SnCl_2]([HCl]_{st} + k_4/k_2K_2) \quad (3)$$

$$ArNO_2 + SnCl_2 \xrightarrow[k_4]{\text{slow}} ArNO + SnOCl_2 \quad (4)$$

As an extension of our kinetic studies on the reduction of ortho-substituted nitrobenzenes,[8] we summarize herein our kinetic data on HCl-catalyzed $SnCl_2$ reduction of meta- and para-substituted nitrobenzenes in 90% (v/v) ethanol.

As observed with ortho-substituted nitrobenzenes,[8] the rate expression (eq 5) was also found effective for meta- and para-substituted nitrobenzenes in 90% (v/v) aqueous ethanol:

$$v = k_2K_2[ArNO_2][SnCl_2][Cl^-] = k[ArNO_2][SnCl_2][HCl]_{st}^{0.5} \quad (5)$$

The k_1 value of eq 1 did not hold a constancy (see Table I) in disagreement with eq 1, while the k' value in the equation $v = k'[ArNO_2][SnCl_2]$ at $[HCl]_{st} \simeq 0$ approached zero, which also disagrees with eq 3 (see Figure 1). Our rate equation (eq 5) suggests a mechanism involving $SnCl_3^-$ as the sole reducing agent (eq 2b). Figure 2 shows that the reaction does not occur at $[HCl]_{st} \simeq 0$, which supports eq 5 (Table I).

The term $[HCl]_{st}^{0.5}$ is explicable by assuming very poor dissociation of HCl in 90% ethanol. The pK_a of 2.1 for HCl in absolute ethanol of ϵ (dielectric constant) 24.3[9] may be similar to that in 90% ethanol, ϵ 33, and is much smaller than that in water, ϵ 78.3–78.54.[10,11] Hence, $[Cl^-] = K_a$-

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[8] Xing, W.-K.; Ogata, Y. *J. Org. Chem.* **1982**, *47*, 3577.

[9] (a) Davis, M. M. *NBS Monogr.* (*U.S.*) **1968**, 105. (b) Chemical Society of Japan "Chemical Handbook"; Maruzem: Tokyo, 1975; pp 999–1000.

[10] (a) Bates, R. "Detemination of pH"; Wiley: New York, 1963. (b) Kolthoff, I. M.; Bruckenstein, S. "Acid-bases in Analytical Chemistry"; Interscience: New York, 1959.

[11] Meites, L. "Handbook of Analytical Chemistry"; McGraw Hill: New York, 1963.

Table II. Rate of Reduction of Para- and Meta-Substituted Nitrobenzenes with $SnCl_2$ Catalyzed by HCl (Much Excess) in 90% (v/v) $EtOH-H_2O$ at 30 °C*

group in $PhNO_2$	$[HCl]_{st}$, M	$10^2k'$, M^{-1} s^{-1}	$10^2k'/[HCl]_{st}^{0.5}$ = 10^2k, $M^{-1.5}$ s^{-1}	log (k/k_0)	σ^a	$\sigma^{0\,i}$	$\sigma^{+\,l}$ (σ^-)	$\Delta\bar{\sigma}_{R^+}$ ($\Delta\bar{\sigma}_{R^-}$)	$\sigma_I^{\,u}$	$\sigma_R^{0\ x}$
p-HO	1.5038	0.0250	0.0204	−0.8296	−0.38 $(-0.41)^e$	−0.22 ± 0.12 $(-0.28)^p$	−0.980	−0.760 −0.70	0.22	-0.43^y $(-0.6)^‡$
p-CH_3O	1.4228	0.0550	0.0461	−0.4756	−0.28	−0.12	−0.778	−0.658	0.29	−0.45
p-C_2H_5O	1.3808	0.0590	0.0502	−0.4386	−0.24	-0.12^s	-0.71^t	-0.59^t	0.26^v	-0.44^z
p-CH_3	1.4642	0.0760	0.0628	−0.3413	−0.16	−0.14	−0.311	−0.171	−0.04	−0.11
m-HO	1.4689	0.1278	0.1055	−0.1160	0.13 $(-0.07)^f$	0.02 ± 0.08 $(-0.06)^p$	−0.002	−0.022 0.058	0.22	-0.43^y $(-0.6)^‡$
m-CH_3	1.4628	0.1387	0.1147	−0.0797	−0.05	−0.06	−0.066	−0.006	−0.04	−0.11
none	1.4512	0.1660	0.1378	0.0000	0.00	0.00	0.000	0.000	0.00	0.00
p-C_6H_5	1.4280	0.2100	0.1757	0.1055	0.03^b	0.05	−0.179 $(0.02)^q$	−0.229 (−0.03)	0.12	-0.06^b
p-F	1.4226	0.2117	0.1775	0.1100	0.06	0.15 ± 0.06 $(0.06)^n$	−0.073	−0.223 −0.133	0.54	−0.34 $(-0.44)^‡$
m-C_2H_5O	1.3808	0.2185	0.1859	0.1300	0.10	0.07^s	0.06^t	-0.01^t	0.26^v	-0.44^z
m-CH_3O	1.3835	0.2328	0.1979	0.1572	0.11	0.10	0.047	−0.053	0.29	−0.45
p-CH_2Cl	1.3677	0.2720	0.2326	0.2274	0.12^c	0.11^k	−0.010	−0.120	0.15	-0.03^y
p-Cl	1.4065	0.5160	0.4351	0.4993	0.22	0.24	0.114	−0.126	0.47	−0.23
p-Br	1.3645	0.5730	0.4905	0.5514	0.22	0.26	0.150	−0.110	0.46	−0.19
m-HOOC	1.4439	0.6068	0.5050	0.5640	0.35^b $(0.28)^g$	0.35 ± 0.18^j $(0.26)^p$	0.322	−0.028 0.062	0.32^w	0.03^b $(0.08)^‡$
m-CH_3CO	1.3860	0.6095	0.5177	0.5748	0.36^b $(0.31)^h$	0.36 ± 0.07 0.26^s	0.25^t	-0.01^t	0.29	0.16
m-F	1.3677	0.8095	0.6922	0.7010	0.34	0.34	0.352	0.012	0.54	−0.34 $(-0.44)^‡$
m-I	1.3736	0.9483	0.8091	0.7688	0.35	0.34	0.359	0.019	0.39	−0.16
m-Cl	1.3947	1.167	0.9877	0.8554	0.37	0.37	0.399	0.029	0.47	−0.23
p-HOOC	1.4601	1.704	1.410	1.0101	0.45^d	0.44^j	0.421 $(0.73)^h$	−0.019 (0.29)	0.32^w	0.03^b $(0.08)^‡$
p-CH_3CO	1.4647	1.972	1.629	1.0727	0.50	0.47	0.48^m $(0.84)^r$	0.01 (0.37)	0.29	0.16
m-CN	1.4367	3.065	2.557	1.2685	0.61	0.62 ± 0.05 $(0.607)^o$	0.562	−0.058 −0.045	0.57	0.13
p-CN	1.3828	4.44	3.780	1.4382	0.70	0.71 ± 0.08 $(0.653)^o$	0.659 $(0.88)^r$	−0.051 0.006 (0.227)	0.57	0.13
m-NO_2	1.5076	7.317	5.959	1.6359	0.74	0.71 ± 0.04 $(0.75)^p$	0.674	−0.036 −0.076	0.76	0.15

* $v = k'[ArNO_2][SnCl_2] = k[ArNO_2][SnCl_2][HCl]_{st}^{0.5}$. Initial concentration: $[ArNO_2]_0 = 0.0500$ M, $[SnCl_2]_0 \approx 0.15$ M. [a] pK-W: the pK's of substituted benzoic acids (the ordinary Bz reactivity) or of phenylacetic acids (σ^0 reactivity) in water (see ref 15 and also 14, 16, 17). [b] Cor: previous estimates corrected by applying $\sigma_p = a\sigma_I + b\sigma_R$ or $\sigma_m = c\sigma_I + d\sigma_R$ with improved constants.[15,18] [c] Corr: experimental values corrected by less than 0.03 σ unit in order to satisfy $\sigma_p = 1.14\sigma_m$.[15,18] [d] Est: estimated by comparison with similar substituents or with other constants of the same substituent.[14] [e] The secondary σ value for the p-HO group in 90% ethanol–water mixture by Jaffé.[19] [f] The average value of secondary σ values for the m-HO group in 40–100% ethanol–water mixtures by Jaffé.[19] [g] Thamer's value.[20] [h] Jaffé's values.[19] [i] Stat: values obtained by correct statistics by using at least six observed data sets.[15,23] [j] Aver: average values obtained by other procedures.[15,23] [k] Taft: calculated from $\sigma_I = 0.14$ and $\sigma^0_R = -0.03$ (i.e., F NMR values, see y).[15,24] [l] Brown–Okamoto's values.[15,25] [m] Taft: calculated from $\sigma_I = 0.28$, $\sigma^+_R = 0.16$ and $\lambda = 1.14$.[24,26] [n] Wepster's σ^0 value.[27] [o] Yukawa–Tsuno's σ^0 values.[22] [p] Presumptive σ^0 values in estimated limit of uncertainty. [q] AnReac: kinetics of reaction of substituted anilines.[15,28] [r] pK-Ph: the pK's of substituted phenols in water or aqueous ethanol.[15,29] [s] Assumed σ^0 values. [t] Presumptive values of calculation from the Yukawa–Tsuno equation for assumed σ^0 values. [u] pK-Ac: the pK's of substituted acetic acids in water.[15,30] [v] pK: the pK's of all other acids or in other solvents.[15,31] [w] pK-BCO: the pK's of 4-substituted bicyclo[2.2.2]octane-1-carboxylic acids in aqueous ethanol or methanol.[15,32] [x] ←Stat: statistical values.[15,26a] [y] F NMR: chemical shifts of ^{19}F in substituted fluorobenzenes; normal solvents are preferred.[15,24] [z] IR: integrated intensity of the ν_{16a} and ν_{16b} transitions in monosubstituted benzenes.[15,33] ‡ Assumed σ^0_R values.

$[HCl]/[H^+] \simeq (K_a[HCl]_{st})^{0.5}$, if [HCl] is much larger than $[Cl^-]$, since $[Cl^-] = [H^+]$ and $[HCl] \simeq [HCl]_{st}$. Thus the mechanism of eq 2 leads to the observed rate equation.[8]

$$v = k_2K_2[ArNO_2][SnCl_2][Cl^-] = k_2K_2K_a^{0.5}[ArNO_2][SnCl_2][HCl]_{st}^{0.5} = k[ArNO_2][SnCl_2][HCl]_{st}^{0.5} \quad (6)$$

In contrast, the reduction in water, where $[Cl^-] \simeq [HCl]_{st}$, the rate equation 1 can be applied.[4]

In kinetic data on HCl (much excess to the stoichiometric amount) catalyzed $SnCl_2$ reduction of 24 meta- and para-substituted nitrobenzenes in 90% (v/v) ethanol at 30 °C are shown in Table II.[12]

The application of the Hammett equation,[13,14] log $(k/k_0) = \rho\sigma$, to the k values from eq 5 by the regression method gave the following equation: log $(k/k_0) = 2.090\sigma - 0.0136$, with $S = 0.1106$ (standard deviation from the regression line in Table III). Apparently, the electron-withdrawing

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(12) Experimental errors in k' were 1.0–1.4% for H, p-Ph, m-CH_3, m-I, and m-C_2H_5O; 2.0–2.9; for p-Cl, p-CN, p-Br, m-NO_2, p-CH_3, p-C_2H_5O, and m- and p-F; 3.0–6.0% for m-CN, m-HO, m-CH_3CO, m- and p-CH_3O, and m- and p-HOOC; and 7.0–12.0% for m-Cl, p-CH_2Cl, p-CH_3CO, and p-HO.

(13) (a) Hammett, L. P. *J. Am. Chem. Soc.* **1937**, *59*, 96. (b) Hammett, L. P. "Physical Organic Chemistry"; McGraw-Hill: New York, 1940; Chapter 7.

(14) (a) McDaniel, D. H.; Brown, H. C. *J. Org. Chem.* **1958**, *23*, 420. (b) Leffler, J. E. "Rates and Equilibria of Organic Reactions"; Wiley: New York, 1963.

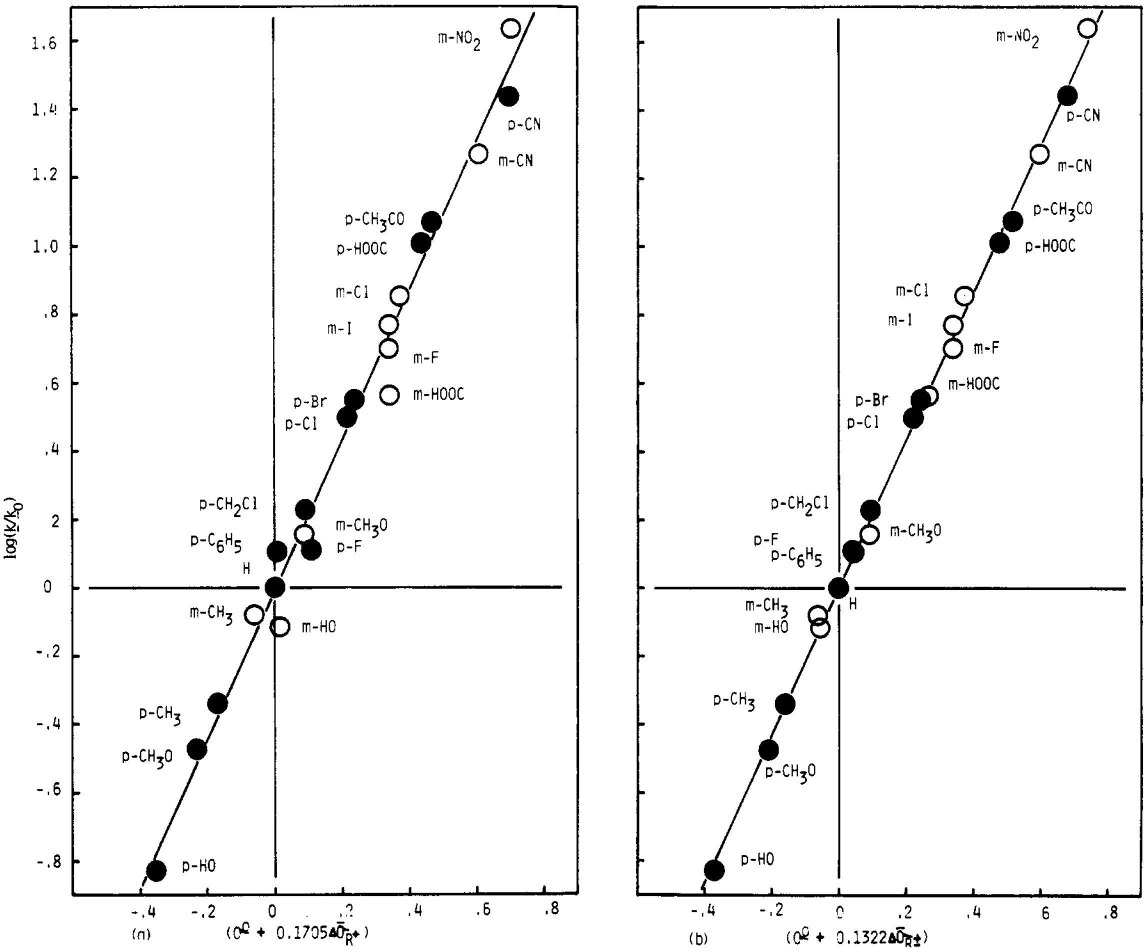

Figure 3. Yukawa–Tsuno plot for the reduction of meta- and para-substituted nitrobenzenes with $SnCl_2$ in 90% EtOH at 30 °C: (a) $\log (k/k_0) = 2.197\sigma^0 + 0.3746\Delta\bar{\sigma}_{R^+} - 0.0152$, $\rho = 2.1973$, $r^+ = 0.1705$, $R = 0.9953$, $S = 0.0664$, $n = 21$; (b) $\log (k/k_0) = 2.151\sigma^0 + 0.2844\Delta\bar{\sigma}_{R^+} + 0.0003$, $\rho = 2.1513$, $r^+ = r^- = r^\pm = 0.1322$, $R = 0.9989$, $S = 0.032$, $n = 21$.

groups accelerate the reduction (positive ρ) as expected from the nucleophilic attack of $SnCl_3^-$.

The rate constants for meta- and para-substituted nitrobenzenes were correlated with σ values of pK-W, (Cor for p-C_6H_5 and m-HOOC, Corr for p-CH_2Cl, Est for p-HOOC, because their pK-W values were unavailable)[15] (see Table II, footnotes *a–d*). A large deviation from the line for m-HO and m-HOOC or m-CH_3CO was observed, which may be ascribed to an interaction of these groups with the solvent. Analogous examples of this sort of solvation effect have been reported on the ionization of substituted benzoic acids[21] and on the solvent dependence of the σ values for HO group in aqueous ethanol.[19] A satisfactory plot was obtained, when σ values in parentheses were used for m-HO, m-CH_3CO, m-HOOC, and p-HO (Table II, footnotes *e–h*). The plot satisfies the equation $\log (k/k_0) = 2.081\sigma + 0.0184$, with $S = 0.0534$ (Table III). The ρ values (2.081), which is much larger than that at 90 °C (av ρ = 1.248), was reported also in the case of ten para- and meta-substituted nitrobenzenes.[6]

The Yukawa–Tsuno equation (eq 7)[22] was applied to k values in eq 5, where $\bar{\sigma}_{R^+} = \sigma^+ - \sigma^0$ and $\bar{\sigma}_{R^-} = \sigma^- - \sigma^0$:

$$\log (k/k_0) = \rho(\sigma^0 + \gamma^\pm\Delta\bar{\sigma}_{R^\pm}) = \rho(\sigma^0 + \gamma^+\Delta\bar{\sigma}_{R^+}) = \rho(\sigma^0 + \gamma^-\Delta\bar{\sigma}_{R^-}) \quad (7)$$

Using σ^0 values of Stat (Aver for m- and p-HOOC, Taft for p-CH_2Cl because of unavailability of these Stat's σ^0 values)(cf. Table II, footnotes *i–k*) and σ^+ values of Brown–Okamoto (Taft for p-CH_3CO because the Brown–Okamoto value is unavailable)(cf. Table II, footnotes *l* and *m*), the following equation was obtained by a binary regression method: $\log (k/k_0) = 2.197(\sigma^0 + 0.1705\Delta\bar{\sigma}_{R^+}) - 0.0152$, with $\gamma^+ = 0.1705$ (parameter of the importance of direct conjugation of the substituent with the reaction center) and $S = 0.0664$ (Table III). Equation 7 gives a plot shown in Figure 3a, where a rather large deviation was again observed with solvating groups such as m- and p-HO, m-HOOC, m-NO_2, p-F, and m- and p-CN (Figure 3a). A better fit to the line was obtained with alternative σ^0 values given in parentheses for these groups in Table II (cf. footnotes *n* and *p*). The plot satisfies the equation $\log (k/k_0) = 2.179(\sigma^0 + 0.1469\Delta\bar{\sigma}_{R^+}) + 0.0130$, with $S = 0.0337$ (Table III).

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(15) (a) Chapman, N. B.; Shorter, J. "Correlation Analysis in Chemistry, Recent Advances"; Plenum: New York, 1978. (b) Chapman, N. B.; Shorter, J. "Advances in Linear Free Energy Relationships"; Plenum: New York, 1972.

(16) Matsui, T.; Ko, H. C.; Hepler, L. G. *Can. J. Chem.* **1974**, *52*, 2906.

(17) Hoefnagel, A. J.; Wepster, B. M. *J. Am. Chem. Soc.* **1973**, *95*, 5357.

(18) Exner, O. *Collect. Czech. Chem. Commun.* **1966**, *31*, 65.

(19) Jaffé, H. H. *Chem. Rev.* **1953**, *53*, 191.

(20) Thamer, B. J.; Voigt, A. F. *J. Phys. Chem.* **1952**, *56*, 225.

(21) Bright, W. L.; Briscoe, H. T. *J. Phys. Chem.* **1933**, *37*, 787.

(22) (a) Yukawa, Y.; Tsuno, Y.; Sawada, M. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 1198. (b) Yukawa, Y.; Tsuno, Y.; Sawada, M. *Ibid.* **1966**, *39*, 2274.

(23) Sjöström, M.; Wold, S. *Chem. Scr.* **1976**, *9*, 200.

(24) Taft, R. W.; Price, E.; Fox, I. R.; Lewis, I. C.; Anderson, K. K.; Davis, G. T. *J. Am. Chem. Soc.* **1963**, *85*, 709, 3146.

(25) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, *80*, 4979.

Table III. Statistical Treatments on the Application of Relative Rates (k/k_0) for the $SnCl_2$ Reduction of Nitrobenzenes to Some Substituent Effect Equations:[a]

Hammett eq: $\log (k/k_0) = \rho\sigma + \alpha$

Yukawa-Tsuno eq: $\log (k/k_0) = \rho(\sigma^0 + \gamma^{\pm} \Delta\bar{\sigma}_R{}^{\pm}) + \alpha$ (7)

Taft eq: $\log (k/k_0)_i = \rho_I{}^i\sigma_I + \rho_R{}^i\sigma_R{}^0 + \alpha$ (8)

equation		ρ	$\rho_I{}^i$	$\rho_R{}^i$	α	R	S	n
Hammett	uncorr	2.090			−0.0136	0.9853	0.1106	24
	corr[b]	2.081			+0.0184	0.9966	0.0534	24
Yukawa-Tsuno	uncorr	2.197			−0.0152	0.9953	0.0664	21
	corr[b]	2.151			+0.0003	0.9989	0.0320	21
Taft	uncorr m		1.983	0.891	−0.0089	0.9802	0.1204	12
	p		2.061	2.646	+0.0457	0.9844	0.1298	13
	corr[b] m		2.005	0.796	−0.0152	0.9845	0.1066	12
	p		2.098	2.323	+0.0258	0.9961	0.0655	13

[a] ρ, reaction constant; R, correlation coefficient expressing linearity; S, standard deviation from the regression line; n, number of compounds involved in the calculation of ρ. [b] Corrected for solvation of the solvent.

Table IV. Example of Rate Constant Calculation by Eq 11 and 12 for $SnCl_2$ Reduction of Nitrobenzene in 90% (v/v) EtOH at 30 °C[a]

t, s	$a - x$, M	x, M	$3b - x$, M	$10^2k'$, M^{-1} s^{-1}	$b - x/3$, M	$(c - 7x/3)^{0.5}$, M	10^2k, $M^{-1.5}$ s^{-1}
0	0.1455	0.0000	0.1500		0.0500	1.2047	
900	0.1353	0.0102	0.1398	0.1674	0.0466	1.1947	0.1395
1800	0.1266	0.0189	0.1311	0.1655	0.0437	1.1862	0.1385
3600	0.1120	0.0335	0.1165	0.1655	0.0388	1.1718	0.1394
5400	0.1000	0.0455	0.1045	0.1673	0.0348	1.1598	0.1419
7200	0.0911	0.0544	0.0956	0.1644	0.0319	1.1508	0.1401
9000	0.0829	0.0626	0.0874	0.1660	0.0291	1.1424	0.1421
10800	0.0762	0.0693	0.0807	0.1662	0.0269	1.1356	0.1429
				av: 0.1660			av: 0.1406

[a] Initial concentration $[SnCl_2] = a = 0.1455$ M, $[PhNO_2] = b = 0.0500$ M, and $[HCl]_{st} = c = 1.4512$ M.

Further, the rate constants are also correlated with σ^0 (values in parenthesis in Table II) and $\bar{\sigma}_{R\pm}$ (i.e., $\sigma^- - \sigma^0$ for p-CN, p-CH_3CO, p-HOOC, or p-C_6H_5 and $\sigma^+ - \sigma^0$ for other groups) in eq 7. For σ^- values, see footnotes q, r, and h in Table II. A satisfactory plot was obtained (Figure 3b), that fits the equation: $\log (k/k_0) = 2.151(\sigma^0 + 0.1322\bar{\sigma}_{R\pm} + 0.0003$, with $S = 0.0320$, suggesting a better fit of eq 7 than Hammett equation (Table III). As is apparent from γ^+ (= 0.1705 or 0.1469) or $\gamma^{\pm}$ (= 0.1322), the direct conjugative interaction or substituents with the reaction center is very small.

By assuming σ^0 values for m- and p-C_2H_5O and m-CH_3CO groups in eq 7, the corresponding σ^+ or $\Delta\bar{\sigma}_{R^+}$ values were calculated and are shown in Table II (cf. footnotes s and t), since σ^0 or σ^+ values for m- and p-C_2H_5O were unavailable and σ^0 for m-CH_3CO may be too large in the reaction.

Moreover, Taft's dual-substituent-parameter equation (eq 8)[26] for meta and para substrates was applied to k values in eq 5. Equation 8 expresses a linear combination

$$\log (k/k_0)_i = \rho_I{}^i\sigma_I + \rho_R{}^i\sigma^0{}_R \quad (8)$$

of inductive effects ($\rho_I{}^i\sigma_I$) and resonance effects ($\rho_R{}^i\sigma^0{}_R$) in meta and para substituents at position i. The susceptibility constants $\rho_I{}^i$ and $\rho_R{}^i$ define the blend of inductive and resonance effects characteristic of the influence of substituents in the position i, the blending constant λ^i being defined as $\rho_R{}^i/\rho_I{}^i$. The σ_I values were derived from pK-Ac except for C_2H_5O which uses pK and HOOC which uses pK-BCO, because their pK-Ac values were unavailable. The $\sigma^0{}_R$ values were derived from ←Stat (IR for C_2H_5O, Cor for HOOC and C_6H_5, ^{19}F NMR for HO and CH_2Cl because of unavailability of these ←Stat's $\sigma^0{}_R$ values) (Table II, footnotes u–z). The following two equations were obtained by a binary regression method: $\log (k/k_0)_m = 1.983\sigma_I + 0.8905\sigma^0{}_R - 0.0089$, with $S = 0.1204$, and $\log (k/k_0)_p = 2.061\sigma_I + 2.646\sigma^0{}_R + 0.0457$, with $S = 0.1298$ (Table III).

As is apparent from Table III, $\rho_I{}^m - \rho_I{}^p$ and $\rho_R{}^m - \rho_R{}^p/3$ in Taft equation 8,[15,26] where $\lambda^m/\lambda^p = \rho_R{}^m\rho_I{}^p/\rho_I{}^m\rho_R{}^p$ (= 0.35), approximates the literature value of ca. 0.4.

A large deviation from the line plotted was also observed with a solvating group such as m- and p-HO, p-HOOC, and p-F. A better fit was obtained with $\sigma^0{}_R$ (Table II, footnote ‡) shown in parentheses, which fits equations $\log (k/k_0)_m = 2.005\sigma_I + 0.796\sigma^0{}_R - 0.0152$, with $S = 0.1066$, and $\log (k/k_0)_p = 2.098\sigma_I + 2.323\sigma^0{}_R + 0.0258$, with $S = 0.0655$ (Table III), where λ^m/λ^p (0.36) $\simeq$ ca. 0.4.[26] The susceptibility constants were $\rho_I{}^m$ (ca 2.0) $\simeq$ $\rho_I{}^p$ (ca. 2.1) for the inductive effect and $\rho_R{}^m$ (ca. 0.9 or 0.8) $\simeq$ $\rho_R{}^p$ (ca. 2.7 or 2.3)/3 for the resonance effect.

In conclusion, in view of the S and R values, Hammett, Yukawa–Tsuno, and Taft equations give similar fit to a linear relationship by taking into account the solvation of some hydrogen-bonding groups such as F, OH, COOH, and

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(26) (a) Taft, R. W.; Brownlee, R. T. C.; Ehrenson, S. "Progress in Organic Chemistry"; Wiley: New York, 1973; Vol. 10. (b) Taft, R. W.; Topsom, R. D., ref 26a, 1976; Vol. 12.

(27) Bekkum, H. van; Verkade, P. E.; Wepster, B. M. *Recl. Trav. Chim. Pays-Bas* **1959**, *78*, 815.

(28) Litvinenko, L. M. *Bull. Acad. Sci. USSR, Div. Chem. Sci.* (*Engl. Transl.*) **1962**, 1737, 1653.

(29) Cohen, L. A.; Jones, W. M. *J. Am. Chem. Soc.* **1963**, *85*, 3397.

(30) Charton, M. *J. Org. Chem.* **1964**, *29*, 1222.

(31) Minamida, I.; Ikeda, Y.; Uneyama, K.; Tagaki, W.; Oae, S. *Tetrahedron* **1968**, *24*, 5293.

(32) Baker, F. W.; Parish, R. C.; Stock, L. M. *J. Am. Chem. Soc.* **1967**, *89*, 5677.

(33) Brownlee, R. T. C.; Hutchinson, R. E. J.; Katritzky, A. R.; Tidwell, T. T.; Topsom, R. D. *J. Am. Chem. Soc.* **1968**, *90*, 1757.

COR. All these equations give a good fit. The exception can be made to fit, if appropriate σ values corrected for solvation effects are taken into account. The best fit is the Yukawa-Tsuno equation (eq 7), but the difference of R values between these values is small (Table III).

Experimental Section

Materials. Inorganic and organic reagents used were all of the highest commercial grade and used without further purification. A solution of HCl in ethanol–water (90:10 v/v) was prepared by mixing 35% aqueous HCl or gaseous HCl with appropriate amount of 99% ethanol and water. The concentration was confirmed by alkalimetry.

Kinetics. A 90% (v/v) ethanolic solution (25 mL) containing an appropriate amount of HCl and nitro compound (2.5 mmol) and another 90% (v/v) ethanolic solution (25 mL) containing HCl (same amount) and $SnCl_2$ (7.5 mmol) were held at constant temperature (30 ± 0.1 °C). The two solutions were mixed to start the reaction, and aliquots were pipetted out at appropriate intervals of time. The concentration of $SnCl_2$ was measured by introduction of the aliquots into a 0.1 N I_2 solution containing KI followed by titration with 0.1 N $Na_2S_2O_3$. The reduction was quenched by introduction of aliquots into the iodine solution. For the estimation of HCl concentration, an aliquot sample at the beginning of experiment was introduced into aqueous sodium citrate[7] to subtract the amount of HCl produced by the hydrolysis of $SnCl_2$, and then the solution was titrated with 0.5 N NaOH with phenolphthalein as an indicator.

The HCl-catalyzed $SnCl_2$ reduction of nitro compounds ($ArNO_2$) obeys the stoichiometric equation 9:[5]

$$ArNO_2 + 3SnCl_2 + 7HCl \rightarrow ArNH_2{\cdot}HCl + 3SnCl_4 + 2H_2O \qquad (9)$$

Assuming that the initial concentration of $SnCl_2$ is a, that of $ArNO_2$ b, that of HCl c, and consumed concentration of $SnCl_2$ at time t x, $[ArNO_2]$ at time t is expressed at $[b - x/3]$ on the basis of eq 9. Hence

$$v = -d[SnCl_2]/dt = dx/dt = k'[a - x][b - x/3] \qquad (10)$$

$$k' = \frac{6.909}{t[3b - a]} \log \frac{a[3b - x]}{3b[a - x]} \qquad (11)$$

A typical calculation of rate data for nitrobenzene is shown in Table IV as an example.

If [HCl] at time t is expressed as $(c - 7x/3)^{0.5}$ on the basis of eq 9, then

$$dx/dt = k[a - x][b - x/3][c - 7x/3]^{0.5} \qquad (12)$$

Microcomputer-calculated k values for the integration of eq 12 are shown in Table IV (right column). The average k value calculated by eq 5 ($10^2k = 0.1378$ in Table II) is ca. 2% smaller than that by eq 12 ($10^2k = 0.1406$ in Table IV) for nitrobenzene.

The conversion of the reaction was ca. 30–50% under the duration of the kinetic experiments. A conversion over 50% would substantially decrease the acidity due to the formation of anilines, even if a large excess of HCl were used. As is well-known,[34] the reaction is a clean reaction, producing anilines alone; hence the kinetics were studied at these lower conversions.

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Registry No. p-$HOC_6H_4NO_2$, 100-02-7; p-$CH_3OC_6H_4NO_2$, 100-17-4; p-$C_2H_5OC_6H_4NO_2$, 100-29-8; p-$CH_3C_6H_4NO_2$, 99-99-0; m-$HOC_6H_4NO_2$, 554-84-7; m-$CH_3C_6H_4NO_2$, 99-08-1; $PhNO_2$, 98-95-3; p-$C_6H_5C_6H_4NO_2$, 92-93-3; p-$FC_6H_4NO_2$, 350-46-9; m-$C_2H_5OC_6H_4NO_2$, 621-52-3; m-$CH_3OC_6H_4NO_2$, 555-03-3; p-$ClCH_2C_6H_4NO_2$, 100-14-1; p-$ClC_6H_4NO_2$, 100-00-5; p-$BrC_6H_4NO_2$, 586-78-7; m-$HOOCC_6H_4NO_2$, 121-92-6; m-$CH_3COC_6H_4NO_2$, 121-89-1; m-$FC_6H_4NO_2$, 402-67-5; m-$IC_6H_4NO_2$, 645-00-1; m-$ClC_6H_4NO_2$, 121-73-3; p-$HOOCC_6H_4NO_2$, 62-23-7; p-$CH_3COC_6H_4NO_2$, 100-19-6; m-$NCC_6H_4NO_2$, 619-24-9; p-$NCC_6H_4NO_2$, 619-72-7; m-$NO_2C_6H_4NO_2$, 99-65-0; $SnCl_2$, 7772-99-8.

Supplementary Material Available: The Hammett and Taft plots of the reduction of meta- and para-substituted nitrobenzenes with $SnCl_2$ (3 pages). Order information is given on any current masthead page.

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[34] (a) Gattermann, L.; Wieland, H. "Die Praxis des Organischen Chemikers", 25th ed.; Walter de Gruyter: Berlin, Germany, 1925; p 170. (b) Ogata, Y. "Theories of Organic Reactions", 3rd ed.; Maruzen: Tokyo, 1975, p 461.

Improved Chiral Derivatizing Agents for the Chromatographic Resolution of Racemic Primary Amines

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Several 4- and/or 5-aryl-substituted 2-oxazolidones have been prepared and studied as chiral derivatizing agents (CDA) for the chromatographic resolution of chiral primary amines via diastereomeric allophanates. The diastereomeric allophanates derived from either racemic primary amines and *cis*-4,5-diphenyl-2-oxazolidone-3-carbamyl chloride or racemic isocyanates and *cis*-4,5-diphenyl-2-oxazolidone show sufficient NMR chemical shift differences and chromatographic separability that this heterocyclic system should prove to be a very useful CDA for the chromatographic resolution and determination of the absolute configuration of a variety of chiral primary amines. The diastereomeric allophanates are readily hydrolyzed to return both chiral components of the allophanates in excellent yield. Both solution and adsorbed conformations of these allophanates are discussed in reference to the determination of the absolute configuration of the allophanates (and hence of the chiral primary amine) from the senses of NMR nonequivalence between and chromatographic elution order of the diastereomers.

As part of an ongoing effort to develop improved chiral derivatizing agents (CDAs) for use in determinations of enantiomeric purity, absolute configuration, and preparative resolutions of racemates, we have been concerned with the origins of the chromatographic separability noted for the diastereomers of numerous acyclic type 1 carba-