(5), 121 (47), 91 (17), 89 (60), 63 (27), and 62 (12). (c) **4-(4-Methoxyphenyl)-1-(trimethylsilyl)-1,3-butadiyne (11).** (4-Methoxyphenyl)acetylene was coupled to (trimethylsilyl)acetylene by using method A to give **11**: TLC (3% ethyl ether/hexane) 0.33; ^{1}H NMR ($CDCl_3$) 0.21 (s, 9 H), 3.80 (s, 3 H), 6.81 (d, 2 H, J = 9.0 Hz), and 7.41 (d, 2 H, J = 9.0 Hz); HRMS exact mass calculated for $C_{14}H_{16}SiO$ (M^+) 228.0970, found 228.0978.

8-*tert*-Butyl-1,3-bis(trimethylsilyl)spiro[6.5]deca-1,3,7-triene (22): from 4-*tert*-butyl-1-cyclohexene triflate (**19**), (trimethylsilyl)acetylene, and method A with LiCl (3 equiv) gave **22** in 49% yield; ^{1}H NMR ($CDCl_3$) 0.15 (s, 18 H), 0.90 (s, 9 H), 1.35 (m, 2 H), 1.95 (m, 1 H), 2.35 (m, 1 H), 2.50–2.90 (m, 2 H), 6.25 (s, 1 H), 6.30 (br s, 1 H), and 6.70 (m, 1 H); ^{13}C NMR ($CDCl_3$) −1.50, 27.1, 28.1, 29.5, 33.2, 33.6, 49.7, 132.9, 134.2, 136.8, 142.8, 142.9, and 147.6; HRMS exact mass calculated for $C_{20}H_{37}Si_2$ (MH^+) 333.2434, found 333.2424.

3,5-Bis(trimethylsilyl)biphenyl (23) and 3-Phenyl-1-(trimethylsilyl)-but-3-en-1-yne (24): from α-bromostyrene, (trimethylsilyl)acetylene, and method B gave **23** (2%) and **24** (2%); **23**, ^{1}H NMR ($CDCl_3$) 0.31 (s, 18 H), 7.35 (t, 1 H, J = 7.3 Hz), 7.45 (t, 2 H, J = 7.3 Hz), 7.59 (d, 2 H, J = 7.1 Hz), 7.66 (s, 1 H), and 7.69 (s, 2 H); ^{13}C NMR ($CDCl_3$) −1.3, 29.5, 77.2, 127.3, 127.6, 128.9, 133.1, 137.3, 140.0, 140.2, and 142.3; HRMS exact mass calculated for $C_{18}H_{26}Si_2$ (M^+) 298.1573, found 298.1572. **24**, ^{1}H NMR ($CDCl_3$) 0.25 (s, 9 H), 5.71 (br s, 1 H), 5.93 (br s, 1 H), 7.35 (m, 3 H), and 7.65 (m, 2 H); HRMS exact mass calcaulated for $C_{13}H_{16}Si$ 200.1021, found 200.1021.

Acknowledgment. The authors thank Professor Larry E. Overman of the University of California, Irvine and one of the referees for insightful comments and Beth Meyer for her secretarial assistance.

Single-Electron Transfer in Deacylation of Ethyl Dinitrobenzoates

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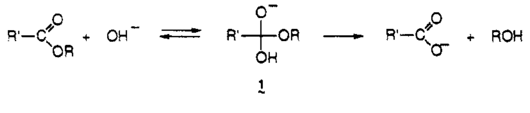
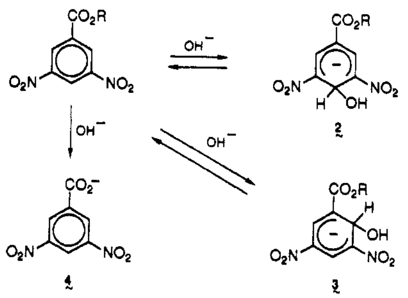
Abstract: Reactions of OH^- with ethyl 2,4- and 3,5-dinitrobenzoate (2,4-DNB and 3,5-DNB) in $DMSO/H_2O$ 1:1 (v/v) involve single-electron transfer from OH^- into the antibonding orbital of the substrate to form a charge transfer complex of $\dot{O}H$ and the radical anion. This complex collapses into a tetrahedral intermediate that gives products. Nonproductive Meisenheimer complexes form and gradually disappear. The rate and equilibrium constants of the various reaction steps can be calculated by using relaxation theory. The charge transfer complexes lead to hydrogen exchange of both substrates and products in DMSO-d_6/D_2O/OD^- and ^{1}H signals of the esters broaden during reaction. Exchange of the carboxylate ions is slow. The 2- and 4-Meisenheimer complexes of OD^- and 3,5-DNB are detected by ^{1}H NMR spectroscopy. Semiempirical MO calculations with AM1 parameters predict that formation of charge transfer and Meisenheimer complexes, and of the tetrahedral intermediate, is enthalpically favored in the absence of solvent interactions and hydration of OH^- is a significant barrier to reaction.

Nucleophilic attack on carboxylic esters at the acyl center in aqueous or polar media is generally assumed to generate a tetrahedral intermediate (**1**) that may partition between return to reactants and formation of products. The initial addition is written as a single step, as shown for reaction of OH^- (Scheme I).[2]

Scheme I



Scheme II



This scheme explains many features of the reactions, including structural effects and the second-order kinetic form in dilute OH^-, and there is extensive evidence for partitioning of tetrahedral intermediates.[2] This general scheme has been applied to a variety of acyl transfers. There is evidence for concerted bond making and breaking, based largely on linear free energy relations (LFER), that relate free energy of activation to basicities of entering and leaving groups.[3] Nucleophilicity is often correlated with basicity, and rates of deacylation follow basicities of nucleophiles that have a common reactive center. However, Ritchie[4] has concluded that nucleophilicity in deacylation follows N_+ values, provided that partitioning of tetrahedral intermediates is taken into account, and N_+ values correlate with oxidation potentials of the nucleophiles.[4d] Buncel, Shaik, and co-workers[5] showed that activation free energies for a variety of acyl transfers correlate with vertical ionization potentials of nucleophiles. These observations cast doubt on the general validity of LFER based on basicities but agree with descriptions of nucleophilic reactions as involving single electron transfer from nucleophile to electrophile.[6]

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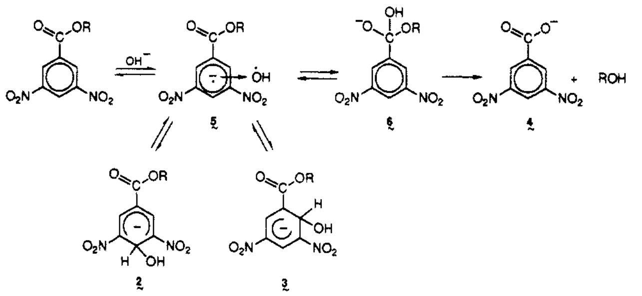
Scheme III



The saponification of substituted benzoate esters is well studied, but there are complications for reactions of dinitrobenzoates.[7] Crampton and co-workers[7a] showed that reaction of a 3,5-dinitrobenzoate ester was accompanied by formation of Meisenheimer complexes and explained their results in terms of Scheme II. Structures of similar Meisenheimer complexes have been examined by flow NMR spectroscopy.[7d] In Scheme II attack of OH^- gives, in a fast process, an unstable 4-Meisenheimer complex (**2**) in excess over a more stable 2-Meisenheimer complex (**3**), and they equilibrate in a second slower step, and eventually an irreversible reaction leads to the benzoate ion product (**4**). These reactions are typical of attack upon 3,5-dinitrobenzoate esters by such nucleophiles as MeO^-,[7a–c] $MeCOCH_2^-$,[7a,d] SO_3^{2-},[7a] or CN^-.[7e] Derivatives of 2,4-dinitrobenzoic acid seem to behave similarly, because the ethyl ester reacts with $MeCOCH_2^-$ [8a] to form a mixture of more stable 5-Meisenheimer and less stable 3-Meisenheimer complexes, and MeO^- adds to 2,4-dinitrobenzoate ion to give Meisenheimer complexes.[8b]

We have suggested that additions and substitutions of OH^- with di- and trinitroarenes and their derivatives in aqueous media occur by initial single-electron transfer from OH^- to the lowest antibonding orbital of the nitroarene to form an intermediate. This intermediate was written as a charge transfer complex of $\dot{O}H$ with a radical anion of the arene, with charge delocalized into the electron-withdrawing substituents of the arene, and it collapses to addition products.[9] This mechanism was consistent with kinetic evidence,[9a–c,e] exchange of arene hydrogens, and ^1H NMR line broadening [9d] during reactions of OD^- with di- and trinitroarenes and their derivatives. It is also consistent with MO calculations of enthalpies of charge transfer and Meisenheimer complexes.[9f]

On this hypothesis conversion of a dinitrobenzoate ester into Meisenheimer complex and finally into carboxylate ion could involve a common intermediate, the charge transfer complex (**5**), as shown in the simplest form in Scheme III. The charge in **5** will be partially delocalized into the carboxyl group and collapse could give the tetrahedral intermediate (**6**).

We examined the multistep kinetics of reactions of OH^- with ethyl 2,4- and 3,5-dinitrobenzoate (2,4-DNB and 3,5-DNB) in $DMSO/H_2O$ 1:1 (v/v) and treated the experimental values by a computer simulation based on relaxation theory.[9b] We also used NMR spectroscopy to examine exchange of arene hydrogens with D_2O in the course of overall substitution and the possibility of ^1H line broadening and related the results to MO calculations of reaction enthalpies on the basis of the AM1 semiempirical method.[9f,10]

Table I. Relaxations for Reaction of Ethyl 2,4-Dinitrobenzoate[a]

$[OH^-]$, M	τ_1^{-1}, s^{-1} 320 (dec)[c]	τ_2^{-1}, s^{-1} 520 (inc)[c]	τ_2^{-1}, s^{-1} 330 (inc)[c]	τ_3^{-1}, s^{-1} 520 (dec)[c]	τ_3^{-1}, s^{-1} 320 (inc)[c]	τ_3^{-1}, s^{-1} 330–360 (dec)[c]
0.1	250[b]	8.98		0.489	0.580	
0.2	275	8.39[b]		0.787	0.885	
0.3	275	8.73		1.07	1.42	
0.4	265[b]	8.90[b]		1.74	1.77	
0.5	309	9.37[b]			1.91	
0.6	277	9.88[b]			1.86	
0.7	260	10.2[b]	10.89		1.86	1.97
0.8	260	12.3	11.42	1.97	1.74	1.96
0.9	290	12.9	12.07	1.61	1.62	1.56
1.0	310	12.6[b]	13.9	1.56	1.56	1.48
1.2				1.34		
1.4				1.09		
1.6				0.86		
1.8				0.78		
2.0				0.65		0.73

[a] Reaction with OH^- in $DMSO/H_2O$ 1:1 v/v at 25.0 °C. [b] Mean of two independent values. [c] λ, nm.

Results

Kinetics. Ethyl 2,4-Dinitrobenzoate. We observed three relaxations in the reaction of 2,4-DNB with OH^-. All relaxations were followed on a stopped-flow spectrometer over the range of 0.05 to 1.0 M KOH, but the slowest relaxation could be followed in up to 2 M KOH on a diode array spectrophotometer (Table I).

The fastest relaxation, τ_1, followed at 320 nm, represented disappearance of substrate and equilibration with the charge transfer complex. The second relaxation, τ_2, followed as increases in absorbance at 330 or 520 nm, represents formation of a Meisenheimer complex, or an equilibrium mixture of 3- and 5-Meisenheimer complexes. These complexes could not be characterized by their UV-visible spectra, because they disappear as rapidly as carboxylate ion is formed. However, similar complexes absorb in the same spectral region.[8] The 3- and 5-Meisenheimer complexes of 2,4-dinitrobenzoate ion obtained by reaction of the acid with KOH in $DMSO/H_2O$ 99:1 (v/v), absorb at 650 and at 550 nm respectively,[8b] and those of methyl 2,4-dinitrobenzoate with acetonate anion absorb at 695 and 560 nm, respectively.[8a] We did not observe a relaxation corresponding to equilibration of two isomeric Meisenheimer complexes. They may be formed from the charge transfer complex in a ratio close to the equilibrium composition, but more probably the 5-Meisenheimer complex predominates under our reaction conditions. As shown later, MO calculations predict that the 5-Meisenheimer complex is more stable than the 3-complex so the latter may be present only in low concentrations, as in reactions of 2,4-dinitrohalobenzenes.[11] Disappearance of Meisenheimer complex(es) and formation of 2,4-dinitrobenzoate ion represents the final relaxation, measured as absorbance decrease at 330–360 or 520 or increase at 320 nm.

Ethyl 3,5-Dinitrobenzoate. We observed five relaxations in the reaction of 3,5-DNB with OH^- by stopped flow and diode array spectroscopy (Table II).

The first relaxation, τ_1, was followed as a decrease of absorbance at 290 nm, corresponding to disappearance of the substrate, and as increases of absorbance at 510 and 560 nm, in the spectral range where charge-transfer complexes of substituted di- and trinitroarenes generally absorb. Derivatives of 3,5-dinitrobenzoic acid, i.e., arylalkylamides, form intramolecular charge-transfer complexes provided that the alkyl group between the aryl group and the amidic nitrogen is long enough to permit the interaction. These complexes absorb in the range 450–500 nm.[12]

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Table II. Relaxations for Reaction of Ethyl 3,5-Dinitrobenzoate[a]

	τ_1^{-1}, s^{-1}			τ_2^{-1}, s^{-1}		τ_3^{-1}, s^{-1}	τ_4^{-1}, s^{-1}	τ_5^{-1}, s^{-1}	
[OH$^-$]	510 (inc)[c]	560 (inc)[c]	290 (dec)[c]	560 (inc)[c]	290 (inc)[c]	510 (inc)[c]	560 (dec)[c]	290 (inc)[c]	510 (dec)[c]
0.0125				6.68		3.01		0.19	0.17
0.025		260		8.90		3.40		0.39	0.34
0.05		283		9.04		4.86		0.85	0.70
0.1	253	241		12.8	12.6	6.36		1.64	1.27
0.2	231	262		12.4	10.2	9.91		2.00	1.74
0.3	246	247	249	16.1	14.3	11.3	5.1[b]	1.96	1.83
0.4			224	19.4	17.2	12.3		1.68	1.76
0.5				18.9		18.3	5.8		1.53
0.6	226			18.5					
0.7	261	256		27.6	26.1	22.9		1.21	1.21
0.8	308			27.4	27.0	23.2	6.1		1.22
0.9	313			27.9	28.8	27.7			1.03
1.0	294		276	32.0	32.0	27.4	5.8	0.85	0.95
1.2									0.74
1.4									0.58
1.6									0.46
1.8									0.42
2.0									0.33

[a] Reaction with OH$^-$ in DMSO/H_2O 1:1 v/v at 25.0 °C. [b] Mean of two independent values. [c] λ, nm.

Table III. Hydrogen Exchange[a]

substrate, M	DMSO-d_6/ D_2O, v/v	[OD$^-$], M	time, min	pos[b]	exchange, % substr	exchange, % product
2,4-$(NO_2)_2C_6H_3CO_2K$						
0.092	75:25	0.30	5	3	85	-
0.092	75:25	0.04	5	3	5	-
2,4-$(NO_2)_2C_6H_3CO_2Et$						
0.10	75:25	0.01	15	3	33	22[c]
0.10	75:25	0.02	15	3	58	41[c]
0.10	75:25	0.04	10	3	81	56[c]
0.08	70:30	0.40	-	3		81
3,5-$(NO_2)_2C_6H_3CO_2K$						
0.08	75:25	0.03	15	4	4	-
3,5-$(NO_2)_2C_6H_3CO_2Et$						
0.10	81:19	0.02	80	4	34	18
0.05	83:17	0.03	15	4	66	46

[a] At 25.0 °C. [b] Position of exchange. [c] Similar results were obtained after 45 min.

The second relaxation, τ_2, followed as absorbance increases at 290 and 560 nm, represents formation of a mixture of 4- and 2-Meisenheimer complexes. This kinetically controlled mixture partially equilibrates in the third relaxation, τ_3, followed as an increase of absorbance at 510 nm. Relaxations τ_2 and τ_3 are not easily separated and become very similar at high [OH$^-$] (Table II). Examination of the reaction of methyl 3,5-dinitrobenzoate with OH$^-$ in DMSO/H_2O 70:30 (v/v) by NMR spectroscopy in a flow system showed that the kinetically controlled mixture contains 49% and 51% 4- and 2-Meisenheimer complex, respectively. This mixture is converted into the thermodynamically controlled mixture of 25% and 75% 4- and 2-isomer,[7d] respectively. Formation of the kinetically controlled mixture and its subsequent equilibration had also been followed by UV-visible spectroscopy.[7a] The 4- and 2-Meisenheimer complexes absorb at 560 nm and 510 nm, respectively. There are slight differences in the wavelengths observed by Crampton and Greenhalgh[7a] and in our work, probably because we used more aqueous media.

The relatively slow decreases of absorbance at 510–560 nm and increase at 290 nm correspond to disappearance of Meisenheimer complexes and formation of 3,5-dinitrobenzoate ion (**4**) and involve two processes which are not easily separated. The first, τ_4, has a relaxation 2–5 times faster than the second, τ_5, with no significant dependence on [OH$^-$]. Values of τ_5^{-1} increase, reach a maximum, and then decrease with increasing concentration of OH$^-$. Crampton and Greenhalgh[7a] assigned a relaxation with similar rates to the second one that we observe (τ_5), conversion of a mixture of Meisenheimer complexes into the benzoate ion. However, they did not study the dependence of this relaxation upon [OH$^-$], and we consider that decrease of τ_5^{-1} with [OH$^-$] (Table II) is incompatible with their assignment. We therefore assign the fourth relaxation, τ_4, to formation of product and disappearance of monohydroxy Meisenheimer complexes and the final relaxation, τ_5, to formation of product and disappearance of a dianionic Meisenheimer complex. This final relaxation is slow enough to be followed on a diode array spectrophotometer in up to 2 M OH$^-$ where formation of relatively long-lived double Meisenheimer complexes is to be expected. Di- and trinitroarenes form double Meisenheimer complexes in DMSO/H_2O 1:1 (v/v) at high [OH$^-$] and formation of a final substitution product is then inhibited by high [OH$^-$].[8,9]

It is more difficult to separate the subsequent steps of reactions of the esters than of di- and trinitroarenes[9b–e] because conversions of esters into tetrahedral intermediates and carboxylate ions do not give the large absorbance changes seen with formation of aryloxide ions. Fortunately relaxation theory permits kinetic analysis even when complex reactions cannot be monitored at λ_{max} of one of the components.[13]

As stated earlier,[9] there is no guarantee that the set of calculated rate constants is unique for a given reaction scheme, or that this scheme is the only one allowing the fitting of experimental data. Any optimization procedure may lead to local minima, that may appear to be satisfactory, but may not be the complete answer to the real problem. However, our general scheme fits kinetic data for a wide variety of reactions.

Hydrogen Exchange. In some overall nucleophilic aromatic substitutions, in DMSO-d_6/D_2O with substrate in excess over OD$^-$, there is extensive exchange of arene hydrogen in the reaction product and in unreacted substrate, even though neither Meisenheimer complexes, nor aryloxide ions, exchange hydrogens under these conditions.[9d] This exchange suggests that addition of OD$^-$

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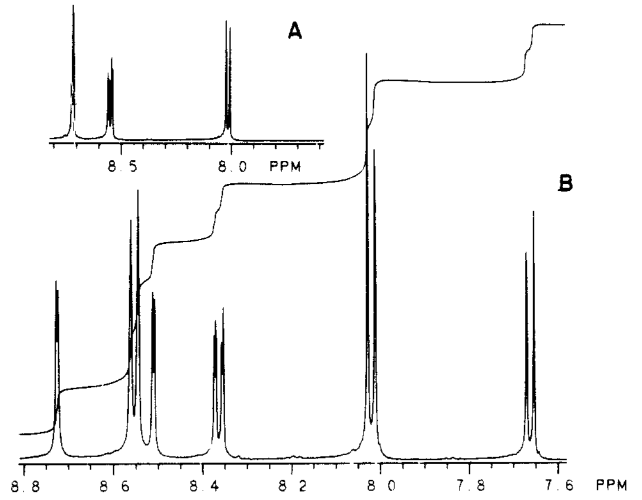

Figure 1. NMR spectrum of 0.1 M 2,4-DNB in DMSO-d_6/D_2O 75:25 (v/v) at 25 °C: A, before addition of OD^-; B, at complete reaction with 0.02 M KOD.

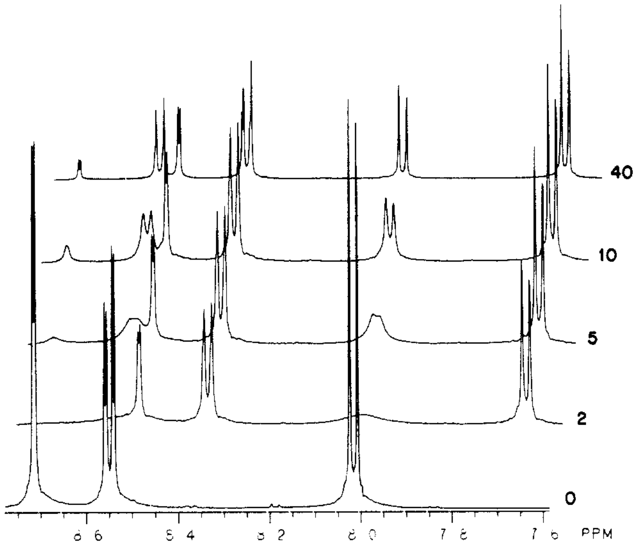

Figure 2. NMR spectrum of 0.1 M 2,4-DNB in DMSO-d_6/D_2O 75:25 (v/v) at 25 °C with 0.04 M KOD as a function of time (minutes).

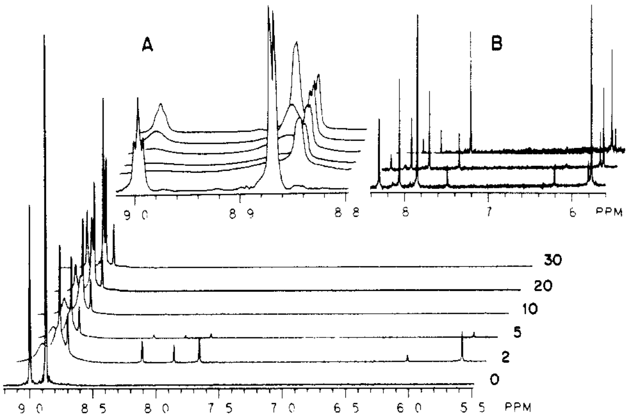

Figure 3. NMR spectrum of 0.1 M 3,5-DNB in DMSO-d_6/D_2O 81:19 (v/v) at 25 °C with 0.02 M KOD as a function of time (minutes). Insert A shows the expanded spectra of ester and carboxylate product. Insert B shows the same NMR spectrum of 0.1 M 3,5-DNB after further addition of 0.09 M KOD with 2-min intervals between scans.

Table IV. Reaction Enthalpies for Formation of Intermediates in Reaction of Ethyl 2,4-Dinitrobenzoate^a

species	ΔH_f	ΔH_r
2,4-DNB	−73.6^b	
CTC$^-$ (**8**)	102.2	−28.7^c
3-MC$^-$	−157.9	−55.6^d
5-MC$^-$ (**10**)	−164.2	−61.9^d
3,5-MC$^-$	−185.4	12.5^e
int (**12**)	−139.6	−37.3^d

^{a}In kcal mol^{-1}. ^{b}Based on ΔH_f = −33.7 kcal mol^{-1} for OH^-.[15] ^{c}From ester and OH^-. ^{d}From charge-transfer complex (**8**). ^{e}From 5-MC$^-$ (**10**) and OH^-.

to give Meisenheimer complex is not a single-step process, but involves an intermediate that can exchange its arene hydrogens. We applied this test to deacylation of ethyl dinitrobenzoates with OD^- in DMSO-d_6/D_2O.

Exchange of the esters, as of nitroarenes,[9d] occurs preferentially at the position between the nitro groups (Table III). The overall reactions of these esters with OD^- are too fast for us to follow this exchange kinetically, so we usually took ester in excess over OD^- and examined the NMR spectra of unreacted ester and dinitrobenzoate ion. Concentrations of OD^- decrease rapidly in the course of reaction so it is difficult to relate rates of exchange and overall reaction. Figure 1 shows the NMR spectrum in the aromatic region of 2,4-DNB (A, insert) before addition of OD^- and (B) after complete reaction. There is extensive exchange in both unreacted ester and dinitrobenzoate ion (Table III) which increases with increasing conversion of ester into carboxylate ion as initial [OD^-] is increased. Exchanges of carboxylate ions are relatively slow under the reaction conditions (Table III). Exchange is at C-3 of 2,4-DNB and C-4 of 3,5-DNB, and we saw no exchange at the other positions.

The ^1H NMR signals of the unreacted esters broaden in the course of reaction (Figures 2 and 3), but those of the carboxylate ion products and mesitoate ion, where present, were sharp. There is, however, broadening of the ^1H signals of 3,5-dinitrobenzoate ion at higher [OD^-], and it is discussed later. Signals of the unreacted esters become sharp as all the OD^- is consumed, and reaction stops. This behavior is very similar to that observed in reactions of dinitrobenzene derivatives.[9d,11b] We did not see NMR signals of Meisenheimer complexes of 2,4-DNB, even though we used high substrate concentrations. However, we saw weak signals of Meisenheimer complexes of 3,5-DNB (Figure 3). These signals are assigned by analogy with assignments for Meisenheimer complexes of methyl 3,5-dinitrobenzoate and MeO^-.[7a-d] Insert B shows signals of Meisenheimer complexes of ester and carboxylate ion. The first-formed 4-complex of ester has a signal at 8.07 ppm (H-2,5) and at 6.20 ppm (H-4), and the more stable 2-complex has signals at 8.30 ppm (H-4), 7.85 ppm (H-6), and 5.75 ppm (H-2). These signals gradually disappear and those of the Meisenheimer complexes of the carboxylate ion appear at 7.5 and 5.8 ppm (insert B). These signals were also seen on addition of excess KOD to the carboxylic acid. In our experiments ^1H signals at position 4 of 3,5-DNB and its derivatives are reduced due to exchange (Table III). Addition of excess KOD to 3,5-dinitrobenzoic acid gives line-broadened signals of the carboxylate ion and weak, but sharp signals of a Meisenheimer complex.

MO Calculations. We showed that MO calculations, by the AM1 semiempirical procedure,[10] predict that nitroarenes with more than one nitro group react with OH^- to form charge-transfer complexes with considerable radical character at the nitroarene moiety.[9f] Similar conclusions have come from other calculations.[14] These complexes collapse to form, initially, Meisenheimer complexes at the carbon atom with the lowest electron density and eventually there is equilibration to form the most stable Meisenheimer complexes. Although there are large systematic errors, due to neglect of correlation and thermal and solvation energies, AM1 calculations correctly predict relative stabilities of Meisenheimer complexes.[9f]

Calculated formation and reaction enthalpies of intermediates from their precursors are shown in Tables IV and V for reactions of methyl 2,4- and 3,5-dinitrobenzoate with OH^-. We carried

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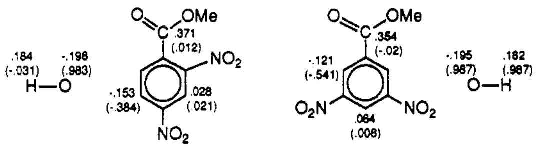
(14) Dotterer, S. K.; Harris, R. L. *J. Org. Chem.* **1988**, *53*, 777.

Table V. Reaction Enthalpies for Formation of Intermediates in Reaction of Ethyl 3,5-Dinitrobenzoate[a]

species	ΔH_f	ΔH_r
3,5-DNB	−79.3[b]	
CTC⁻ (**16**)	−105.2	−25.9[c]
4-MC⁻ (**18**)	−170.5	−65.3[d]
2-MC⁻ (**19**)	−170.2	−65.0[d]
2,4-MC²⁻	−196	7.9[e]
int (**21**)	−142.3	−37.2[d]

[a] In kcal mol⁻¹. [b] From ester and OH⁻. [d] From charge-transfer complex (**16**). [e] From 2-MC⁻ (**19**) and OH⁻.



2,4-DNB **3,5-DNB**

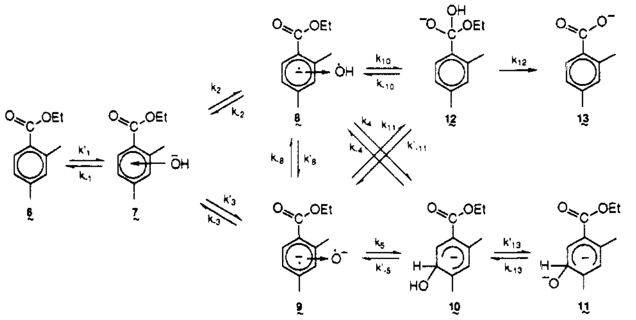
Figure 4. Charge and spin densities (in parentheses) of charge transfer complexes of methyl 2,4- and 3,5-dinitrobenzoate with OH⁻.

out the calculation for methyl esters because inclusion of the ethyl group significantly complicates the calculation and methyl and ethyl esters are chemically very similar. We added −33.7 kcal mol⁻¹ to the formation enthalpy of the substrates to allow for the experimental formation enthalpy of OH⁻ in the gas phase.[15] The differences between formation enthalpies represent the reaction enthalpy of the respective processes. We also added −33.7 kcal mol⁻¹ to the enthalpies of the monohydroxy Meisenheimer complexes in considering their conversion into dihydroxy Meisenheimer complex, and we included the 3- and 3,5-Meisenheimer complexes of 2,4-DNB in the calculation, even though we have no kinetic evidence for their formation. Treatment of the charge transfer complexes was based on the assumption that OH is located at ca. 2.3 Å above the center of the aromatic ring.[16] This geometry corresponds to an energy minimum in charge transfer complexes of 1,3,5-trinitrobenzene and OH⁻.[9f] This geometry is probably not strictly correct for the esters because their symmetries differ from that of 1,2,3-trinitrobenzene and the calculations will then underestimate stabilities of the charge transfer complexes. For charge transfer complexes of both methyl dinitrobenzoates, the degree of electron transfer from OH⁻ to the substrate is ca. 0.98, and there is almost unit spin density on OH, as with 1,3,5-trinitrobenzene. Charges and spin densities at the reactive centers of the charge transfer complexes are shown in Figure 4. Formation enthalpies of charge transfer complexes are lower than those of substrate and OH⁻.

The Meisenheimer complexes have much lower formation enthalpies than charge transfer complexes, and our calculations predict that they should readily form. For the 2,4-dinitrobenzoate ester the 5-Meisenheimer complex has a lower enthalpy than the 3-complex. This result is consistent with absence of a relaxation corresponding to equilibration of initially formed monohydroxy Meisenheimer complex, i.e., the 3-Meisenheimer complex, if formed, is in very low concentration, or is converted rapidly into the more stable 5-Meisenheimer complex (Table I). However, for the 3,5-ester, the 4- and 2-Meisenheimer complexes have similar calculated formation enthalpies, in agreement with observation of a relaxation (τ_3) corresponding to their equilibration (Table II).

This evidence on relative stabilities of Meisenheimer complexes is consistent with NMR evidence and empirical values of relative free energies.[7,17] The tetrahedral intermediates have formation enthalpies lower than the corresponding charge transfer complexes but higher than the Meisenheimer complexes. However, conversion of the tetrahedral intermediates into carboxylate ion is irreversible, and MO calculations of relative enthalpies neglect solvation. Hydration of anionic tetrahedral intermediates should be very important in hydroxylic solvents, because of charge localization, and compensates for differences in gas phase enthalpies between these intermediates and Meisenheimer complexes.

Scheme IV[a]



[a] — denotes NO₂; $k'_1 = k_1[\mathrm{OH}^-]$; $k'_3 = k_3[\mathrm{OH}^-]$; $k'_{-5} = k_{-5}[\mathrm{OH}^-]$; $k'_{-11} = k_{-11}[\mathrm{OH}^-]$; $k'_8 = k_8[\mathrm{OH}^-]$; $k'_{13} = k_{13}[\mathrm{OH}^-]$.

The dihydroxy Meisenheimer complexes have formation enthalpies similar to the sum of enthalpies of monohydroxy complexes and OH⁻ (Table IV and V), so that their formation in concentrated OH⁻ is understandable.

Discussion

Kinetic Schemes. The existence of fast relaxations, which cannot be ascribed to any intermediates in classical schemes of ester hydrolysis (Scheme I), observations of hydrogen exchange and line broadening of esters in the course of reaction (Figures 1–3, Table III), and MO calculations (Tables IV and V) demand modification of accepted mechanisms. We must consider at least one additional intermediate in conversions of esters into Meisenheimer complexes and tetrahedral intermediates (Scheme III).

Several relaxations were observed in aromatic nucleophilic substitutions.[8] The fastest was ascribed to conversion of a transient complex of substrate and OH⁻ into a charge transfer complex, which was converted into aryloxide ion, or into one or more unproductive Meisenheimer complexes. Complexes reverted relatively slowly to the charge transfer complex to form more aryloxide ion. For some reactions it was necessary to include deprotonation of the charge transfer complex in the overall kinetic scheme to allow simulation of the dependence of τ^{-1} on [OH⁻].

We follow similar schemes in fitting variations of τ^{-1} with [OH⁻] for reactions of ethyl dinitrobenzoates, except that we assume that charge transfer complexes can also collapse to tetrahedral intermediates, as shown in the simplest form in Scheme III. It is important to recognize that charge in the charge transfer complex will be delocalized partially into the carboxyl group. We do not include extensive protonation of the anionic tetrahedral intermediates in our model because of the high pH of the reaction solutions and acid dissociation constants of gem-diols with electron-withdrawing substituents.[18] We include tetrahedral intermediates in our simulation, on the basis of extensive kinetic and isotopic evidence for their intermediacy in deacylation.[19]

The overall reactions of 2,4-DNB are shown in Scheme IV.

We ascribe the fastest relaxation to formation of charge-transfer complexes (**8** and **9**) from a π-complex (**7**) whose existence is assumed on the basis of the conclusions of Caldin and co-workers regarding very rapid formation of complexes of nucleophiles and activated arenes.[20] An alternative structure is that of a sol-

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(15) *Handbook of Chemistry and Physics*; Weast, R. G., Astlee, M. J., Eds.; CRC Press: Boca Raton, 1984.

(16) The calculated energy minimum is shallow and is not very sensitive to distance and spin density on OH is maximum at 2.2–2.3 Å.[9f]

(17) Fendler, J. H.; Hinze, W. L.; Jan-Liu, L. *J. Chem. Soc., Perkin Trans. 2* **1975**, 1768.

(18) (a) Bell, R. P.; McTigue, P. T. *J. Chem. Soc.* **1960**, 2983. (b) Stewart, R.; Van der Linden, R. *Can. J. Chem.* **1960**, *38*, 399.

(19) (a) Lowry, T. H.; Ricardson, K. S.; *Mechanism and Theory in Organic Chemistry*, 3rd ed.; Harper and Row: New York, 1987; Chapter 8. (b) Jencks, W. P. *Catalysis in Chemistry and Enzymology*; McGraw Hill: New York, 1969; Chapter 2. (c) Bruice, T. C.; Benkovic, S. Bioorganic Mechanisms; Benjamin: New York, 1966; Chapter 1.

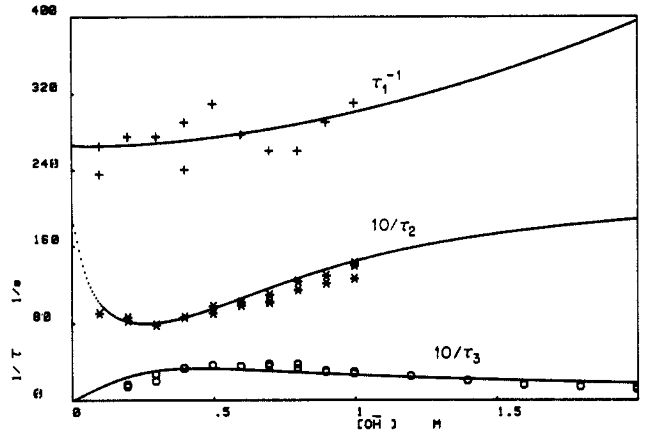


Figure 5. Observed and predicted values of τ^{-1} for reaction of 2,4-DNB with OH^-.

Table VI. Individual Rate Constants for Ester Reactions[a]

	2,4-$(NO_2)_2C_6H_3CO_2Et$	3,5-$(NO_2)_2C_6H_3CO_2Et$[b]	$(NO_2)_3C_6H_2Cl$[c]
k_2, s^{-1}	327	607	260
k_{-2}, s^{-1}	177	202	322
k_3, $M^{-1}\ s^{-1}$	350	1120	320
k_{-3}, s^{-1}	173	133	169
k_4, s^{-1}	22.7	3.52	206
k_{-4}, s^{-1}	25.8	4.42	0.65
k_5, s^{-1}	60.9	6.36	210
k_{-5}, $M^{-1}\ s^{-1}$	72.1	22.3	1.54
k_6, s^{-1}	–	4.44	
k_{-6}, s^{-1}	–	7.35	
k_{10}, s^{-1}	69.2	67.5	
k_{-10}, s^{-1}	8.42	11.1	
k_{11}, s^{-1}	7.46	*b*	
k_{-11}, $M^{-1}\ s^{-1}$	0.94	*b*	
k_{12}, s^{-1}	14.1	37.9	
k_{14}, $M^{-1}\ s^{-1}$	–	20.8	
k_{-14}, s^{-1}	–	3.77	

[a] In DMSO/H_2O 1:1 (v/v) at 25.0 °C. [b] k_7,k_{-7} (**17** ⇄ **19**), k_9,k_{-9} (**18** ⇄ **20**), and k_{11},k_{-11} (**17** ⇄ **21**) have very small values with no kinetic significance for reaction of 3,5-DNB. [c] For TNCB.[9c]

vent-separated encounter complex which could generate a charge-transfer complex with loss of intervening solvent.[21] The second relaxation corresponds to formation of an equilibrium mixture of 5-Meisenheimer complex (**10**) and its deprotonated complex (**11**). We did not include a dihydroxy Meisenheimer complex in the treatment because we saw no relaxation corresponding to its slow appearance or disappearance. Such a species could be present, but not observed, if its interconversion with **10** is a fast equilibrium or gives little change of absorbance. It is therefore possible that the postulated fast relaxation **10** ⇄ **11** involves formation of a dihydroxy Meisenheimer complex, rather than deprotonation, and we cannot distinguish kinetically between these processes. The third relaxation, τ_3, represents formation of product **13** via tetrahedral intermediate (**12**). The numbering of the reactions in Scheme VI corresponds, as far as possible, to that applied to reactions of trinitrobenzene and its derivatives.[9c]

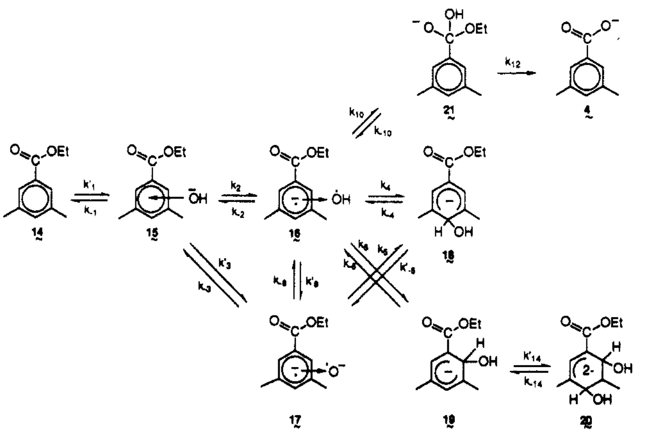
Figure 5 shows the predicted dependence of τ^{-1} upon $[OH^-]$, and the lines are calculated from the rate and equilibrium constants in Tables VI and VII. Some of the reactions in Scheme VI are rapid equilibria (k_1, k_{-1}, k_8, k_{-8}, k_{13}, and k_{-13}), and only equilibrium constants can then be calculated. The simulation procedure has been described.[9b,c]

Table VII. Individual Equilibrium Constants[a]

	2,4-$(NO_2)_2C_6H_3CO_2Et$	3,5-$(NO_2)_2C_6H_3CO_2Et$	$(NO_2)_3C_6H_2Cl$[b]
K_1, M^{-1}	0.121	0.116	1.65
K_2	1.84	3.00	0.81
K_3, M^{-1}	1.91	8.42	1.89
K_4	0.878	0.796	319
K_5, M	0.845	0.285	136
K_6	–	0.604	
K_7, M	–	0.215	
K_8, M^{-1}	1.04	2.80	10.8
K_9, M^{-1}	–	4.17	
K_{10}	8.21	6.08	
K_{11}, M	7.91	2.17	
K_{13}, M^{-1}	19.3	–	275
K_{14}, M^{-1}	–	5.52	

[a] In DMSO/H_2O 1:1 (v/v) at 25.0 °C. [b] For TNCB.[9c]

Scheme V[a]



[a] — denotes NO_2; $k'_2 = k_1[OH^-]$; $k'_3 = k_3[OH^-]$; $k'_{-5} = k_{-5}[OH^-]$; $k'_8 = k_8[OH^-]$; $k'_{14} = k_{14}[OH^-]$.

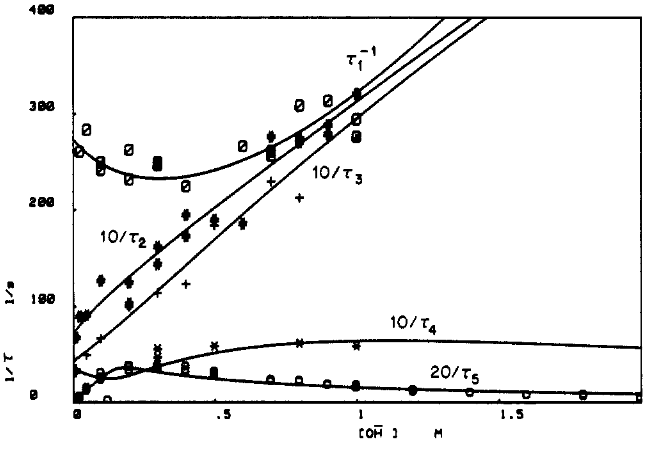


Figure 6. Observed and predicted values of τ^{-1} for reaction of 3,5-DNB with OH^-.

In reactions of 3,5-DNB the fastest relaxation, following precedent, is ascribed to conversion of π-complex or encounter complex (**15**) (cf. refs 20 and 21) into charge-transfer complexes (**16**, **17**) (Scheme V). The next two relaxations are assigned to formation of kinetically and thermodynamically controlled mixtures of Meisenheimer complexes (**18**, **19**, and **20**).[7] The slowest two relaxations should be due to disappearance of Meisenheimer complexes and formation of carboxylate ion (**4**) via charge transfer complexes (**16** and **17**) and tetrahedral intermediate (**19**). We do not include a deprotonated Meisenheimer complex in Scheme V because, for reaction of the 3,5-, but not the 2,4- ester, we see a slow relaxation that we ascribe to interconversion of mono- and dihydroxy Meisenheimer complexes. We cannot exclude deprotonation of Meisenheimer complexes, but it does not appear to have kinetic significance.

Variations of τ^{-1} with $[OH^-]$ (Figure 6) can be fitted to the reactions shown in Scheme V, and the lines represent calculated

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(20) (a) Ainscough, J. B.; Caldin, E. F. *J. Chem. Soc.* **1956**, 2528; 2540. (b) Allen, C. R.; Brook, A. J.; Caldin, E. F. *Ibid.* **1961**, 2171.

(21) (a) Hine, J. *J. Am. Chem. Soc.* **1971**, *93*, 3701. (b) Richard, J. P.; Jencks, W. P. *Ibid.* **1984**, 106, 1373. (c) Ritchie, C. D. *Physical Organic Chemistry*, 2nd ed.; Marcel Dekker: New York, 1990; Chapter 4.

Table VIII. Calculated and Observed Reciprocal Relaxation Times for Reaction of Ethyl 2,4-Dinitrobenzoate

	obsd[a]	calcd[b]
τ_1^{-1}, s^{-1}	310	353 (**8**),[c] 364 (**9**)[c]
τ_2^{-1}, s^{-1}	14.1	17.8 (**8**),[d] 17.9 (**9**),[d] 16.6 (**10**)[c]
τ_3^{-1}, s^{-1}	1.5	1.2 (**13**)[c]

[a] Mean values in 1 M OH^- (Table I). [b] Calculated from Figure 4A by following the species indicated in parentheses (Scheme IVA). [c] Appearance. [d] Disappearance.

Table IX. Calculated and Observed Reciprocal Relaxation Times for Reaction of Ethyl 3,5-Dinitrobenzoate

	obsd[a]	calcd[d]
	In 0.1 M OH^-	
τ_1^{-1}, s^{-1}	247	228 (**16**),[c] 217 (**17**)[c]
τ_2^{-1}, s^{-1}	12.7	10.5 (**18**),[c] 10.5 (**17**)[c]
τ_3^{-1}, s^{-1}	6.6	7.7 (**19**)[c]
τ_5^{-1}, s^{-1}	1.4	1.3 (**18**),[d] 1.6 (**19**),[d] 1.4 (**21**)[d] 1.4 (**14**),[d] 1.4 (**4**)[c]
	In 1 M OH^-	
τ_1^{-1}, s^{-1}	285	345 (**16**),[c] 333 (**17**)[c]
τ_2^{-1}, s^{-1}	32	41 (**18**)[c]
τ_3^{-1}, s^{-1}	27.4	31 (**19**)[c]
τ_4^{-1}, s^{-1}	5.8	7.6 (**17**),[d] 5.4 (**18**),[d] 7.1 (**20**),[d] 6.1 (**21**)[d]
τ_5^{-1}, s^{-1}	1.0	1.0 (**4**)[c]

[a] Mean values (Table II); τ_4 could not be followed in 0.1 M OH^-. [b] Calculated from Figure 4 parts B and C by following the species indicated in parentheses (Scheme V). [c] Appearance. [d] Disappearance.

values based on rate and equilibrium constants from Tables VI and VII.

We show in Scheme V those reactions for which significant rate constants can be calculated by simulation. Some steps are relatively slow and do not affect the simulation and consequently we do not include them. However, this observation does not mean that these reactions are not on the path to Meisenheimer complex or overall product, it simply means that their inclusion does not improve the simulation. From Scheme V it appears that the deprotonated charge transfer complex (**17**), although formed, plays a less important role than complex (**16**) in formation of Meisenheimer complexes and final product.

We used numerical integration[22] and rate and equilibrium constants in Table VI and VII to predict variations of concentrations of reactants, intermediates and products with time.[9c] Examples are shown in Figure 7, and from variations of these concentrations with time we recalculated values of τ^{-1} that are in reasonable agreement with observed values (Tables VIII and IX). This agreement strengthens our assignment of the relaxations and the quality of the computer simulations. We could not observe relaxation τ_4 in the reaction of 3,5-DNB in 0.1 M OH^- because its amplitude was too low. Values of τ_2^{-1} and τ_3^{-1} are very similar for this reaction in 1 M OH^- (Table IX) probably because equilibriation of the 2- and 4-Meisenheimer complexes (**19** and **18**) becomes fast under these conditions.

It is useful to compare rate and equilibrium constants for the ester reactions with those of 2,4,6-trinitrochlorobenzene (TNCB). The equilibrium constants (Table VII) indicate that formation of the initial transient complex is more favorable with TNCB than with the esters,[9c] consistent with electron withdrawal by the three nitro groups, and overall equilibrium constants for conversions of substrates into charge complexes are more favorable for TNCB than for the esters. Equilibrium contants for deprotonation of CTC^- and formation of Meisenheimer complexes follow the sequence: TNCB[9c] > 3,5-DNB > 2,4-DNB. Equilibrium constants for deprotonation of the charge transfer complexes (K_8) are consistent with $pK_a = 11.8$ for deprotonation of $\dot{O}H$.[23] Dependence of these equilibrium constants upon substrate structure are as expected from qualitative models of electronic effects.[24]

Structural effects upon rate constants of individual steps are consistent with qualitative models of electronic effects, because nitro groups have larger -I and -M effects than carbethoxy groups,

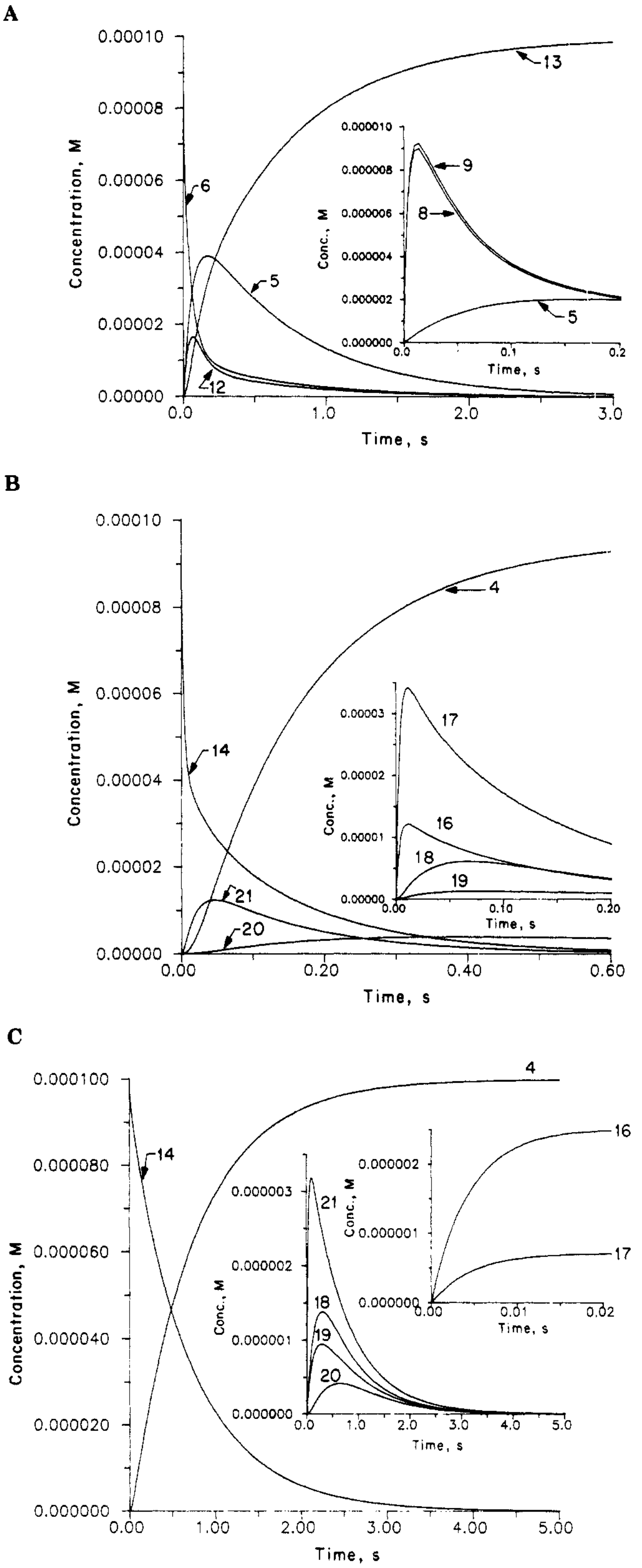

Figure 7. Predicted variations of concentrations of esters, intermediates and product with time (s): A, 2,4-DNB and 1 M OH^-; B, 3,5-DNB and 0.1 M OH^-; C, 3,5-DNB and 1 M OH^-. The numbers relate to Schemes IV and V (10^{-4} M ester).

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(22) McKinney, R. J.; Weigert, F. G. *Quantum Chemistry Program Exchange*, QCMP022.

(23) Bard, A. J.; Parson, P.; Jordan, J. *Standard Potentials in Aqueous Solution*; Marcel Dekker: New York, 1985; p 59.

(24) Reference 2a; Chapter 3.

and electron withdrawal should be greater with 1,3,5- than with 1,2,4-substituents.[24,25]

Overall Mechanism. The previously accepted Scheme I for nucleophilic addition/elimination reactions of carboxylic esters does not explain our results, and they are also inconsistent with concerted deacylation. We have evidence for at least one other intermediate, whose appearance can be monitored spectrophotometrically and which gives hydrogen exchange and NMR line broadening of the substrate. The relaxations ascribed to this intermediate are slower than those for trinitrobenzene derivatives[9b,c] and slightly slower than for reactions of dinitronaphthalene derivatives.[9e] They are well within the range of stopped-flow spectroscopy, so that the accuracy of determinations of τ_1^{-1} is better than for the nitroarenes. Hydrogen exchange and NMR line broadening during reactions of ethyl dinitrobenzoates are indicative of the radicaloid character of the charge-transfer complexes, as with reactions of nitroarenes. Line broadening of unreacted substrate was ascribed to transient interactions between unreacted substrate, with its electron-withdrawing groups and anionic charge-transfer complexes.[9d] Consistently these anionic complexes do not interact with Meisenheimer complexes, because of coulombic repulsions and signals of these species are always sharp. Line broadening increases as charge-transfer complexes build up in concentration, so much so that signals of unreacted 3,5-DNB disappear as sharp lines and gradually reappear as concentrations of ester and complex decrease (Figure 3A). Molecular orbital calculations were useful for reactions of nitroarenes and suggest that a single electron transfer from OH^- to di- and trinitroarenes[9f] and their halogeno,[11b] cyano,[9f] or carboxy derivatives is possible, at least in the absence of solvent effects. The magnitude of the calculated reaction enthalpies suggests that partial dehydration of OH^- is a key component of the barrier to reaction.[4,9] The MO calculations predict that conversions of complexes **8** and **16** into Meisenheimer complexes (Scheme IV and V) is enthalpically very favorable. However, these processes involve significant solvent reorganizations which will increase the energy barriers to these reactions.

We considered the possibility that the species responsible for exchange and line broadening are not on the overall reaction path, although this possibility is excluded for reaction of some trinitroarene derivatives.[9d] This problem is general in elucidation of mechanisms of many multistep reactions where overall reactions are accompanied by isotopic exchange or changes in stereochemistry, but the simplest explanations are typically accepted.[26] The electron donated into the antibonding orbital of the dinitrobenzoates is partially delocalized into the carboxyl residue (Figure 4), so if we accept that the charge-transfer complexes can collapse to give Meisenheimer complexes (Schemes IV and V) we must also assume that they can collapse to give tetrahedral intermediates (**12** and **21**) which give the final reaction products.

The kinetic simulations do not provide the essential arguments for single-electron-transfer processes in these nucleophilic reactions. The essential arguments are the ability of the model to explain all the kinetic, NMR, and exchange results and be consistent with MO calculations.

Mechanisms of multistep reactions are often treated kinetically by examining reaction rates under a variety of limiting conditions, for example in dilute and concentrated OH^- for nucleophilic substitutions. This approach may be misleading if some reaction steps are misidentified, and physical evidence on the existence of intermediates is of key importance. To this extent, mechanistic assignments based solely on kinetic evidence in limiting conditions are fraught with uncertainty.

These deacylations are complex, and consequently uncertainties in simulation are possible. However, some conclusions can be drawn from examination of equilibrium and rate constants (Tables VI and VII). Equilibrium constants for formation of π- (or encounter) complexes and charge-transfer complexes are relatively small, so these intermediates will probably not be observed in dilute OH^- or in solvents with high water content, because water, by solvating OH^-, inhibits their formation. In the gas-phase loss of the first water molecule from OH^- is enthalpically disfavored by ca. 23 kcal mol^{-1}, but loss of subsequent water molecules is less unfavorable.[27] These complexes will probably be steady-state intermediates in dilute aqueous OH^- where reaction is overall second order. As expected, electron-attracting substituents at 1,3,5-positions are more effective in favoring formation of these complexes than are those at 1,2,4-positions. Deprotonated charge-transfer complexes (**9** or **17**), although formed in a favorable equilibrium, may not be effective intermediates in subsequent additions and substitutions if the subsequent step, collapse to the tetrahedral intermediate, is determined mainly by electrostatic interactions.[9f] The anion radical moiety has extensive negative charge, so it should react less readily with the negatively charged radical, $\dot{O}^-$, than with neutral $\dot{O}H$, especially when there is less delocalization of the negative charge into electron-withdrawing substituents. This situation seems to apply to the 3,5-methyl ester for which the AM1 calculation gives a −0.78 charge on the arene carbon atoms of the charge-transfer complex and the same calculation gives a −0.76 charge for the 2,4-methyl ester. We did not optimize the geometry of the charge-transfer complexes with respect to relative positions of substrate and OH and the symmetrical disposition of $\dot{O}H$ over the center of the benzene ring is probably less correct in 1,2,4-derivatives than in the more symmetrical 1,3,5-derivatives. However, these uncertainties do not negate the use of MO results, because our estimated enthalpies of charge-transfer complexes will, if anything, be higher than those optimized for unsymmetrical structures.

Meisenheimer complexes of the 1,3,5-ester are favored over those of the 1,2,4-ester, as predicted by rules of relative stabilities[17] and classical electronic theory.[24,25] The MO calculations (Schemes IV and V) support this conclusion and are consistent with kinetically estimated equilibrium constants (Table VII). Observation of ^{1}H NMR signals of Meisenheimer complexes of 3,5-DNB (Figure 3) but not of 2,4-DNB, also supports these conclusions. There are marked differences between the conditions of the kinetic and NMR experiments so the two sets of data can only be compared qualitatively. All the evidence shows that extent of formation of unproductive Meisenheimer complexes is much lower in deacylation than in reactions of trinitrobenzene derivatives.[7-9,11a]

The tetrahedral intermediate of 2,4-DNB is more stable than that of 3,5-DNB, on the basis of the equilibrium constants (Table VII) and related MO calculations (Table IV and V). Electronic effects of nitro groups should increase the positive charge density at a forming carboxyl group due to the mesomeric effect of 2,4-nitro groups on the adjacent aromatic carbon. However, formation enthalpies of these intermediates are not very different, on the basis of AM1 calculations.

Decomposition of tetrahedral intermediate to carboxylate ion is faster for the 3,5- than for the 2,4-dinitro derivative (Table VI). This observation is understandable because formation of 2,4-dinitrobenzoate ion, **13**, should be sterically hindered due to interference between the carboxyl and nitro groups, which tend to be coplanar with the phenyl group.

General Conclusions

The difference between our model of nucleophilic substitution on carboxylic derivatives and that of Buncel, Shaik, et al.,[5] is that we consider the charge-transfer complex as an intermediate formed by electron transfer between nucleophile and electrophile rather than as merely an important component of the transition state. The existence of a charge-transfer complex will depend on the presence of strongly electron-withdrawing groups[9f] and in their absence it will probably merely be a component of the transition state.[5] We do not consider that free radicals are intermediates in aqueous media because electron transfer can generate complexes (**8** and **16**) that subsequently collapse to addition products. However, if this collapse is disfavored, due to substrate structure

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(25) Reference 9; Chapter 2.

(26) Reference 19a; Chapter 4.

(27) Marcus, Y. *Ion Solvation*; Wiley Interscience: New York, 1985; Chapter 2.

or the nature of the solvent, the complex may dissociate with generation of free radicals.[9] We believe that the conventional distinction between "ionic" (heterolytic) and "radical" (homolytic) reactions is artificial and a barrier to the understanding of chemical reactivity, in that an initial single electron transfer is involved in both processes.[6] This step may be followed by collapse leading to products ascribed to heterolytic processes, or dissociation leading to products ascribed to homolytic processes, or to free radicals. The rates of these subsequent steps will depend critically upon reactant structure and the medium. In many "ionic" reactions steps following the initial electron transfer may be so rapid that existence of intermediates akin to **8** and **9**, and **16** and **17** (Schemes IV and V) will be moot. For example, charge transfer (and Meisenheimer) complexes will be in very low concentration in deacylation in aqueous media of substrates that do not have strongly electron-withdrawing substituents. In these reactions overall kinetics will be second order so there will be no apparent reason to postulate step-wise mechanisms. However, even in these reactions linear free energy relations based on single-electron-transfer processes, e.g., vertical ionization potentials, will be more useful than those based on two-electron equilibria, e.g., basicity or acidity,[4d,5] if reagents of different structures are involved. There is now considerable evidence that many reactions that have been written as two-electron transfers are better described in terms of single-electron transfers.[5,6,28]

Experimental Section

Materials. Ethyl 3,5-dinitrobenzoate was a commercial sample (Lancaster) and ethyl 2,4-dinitrobenzoate was prepared from the acid (Lancaster) via the acid chloride.[29] Dimethyl sulfoxide (DMSO) (Aldrich) was freshly distilled.

Kinetics. Rate measurements were made at 25.0 °C with a Durrum stopped-flow spectrophotometer for the faster and with HP diode array spectrophotometers for the slower reactions.[9] First-order rate constants were calculated by using a nonlinear fit of experimental data, or by log-linear least-squares calculations. The values of τ^{-1} for stopped-flow kinetics were means from 3–5 runs, and where possible we followed relaxations at more than one wavelength.

NMR Spectra. Spectra were recorded on a GE-500 spectrometer (500 MHz). Overall reactions were so fast that exchange was generally examined at the end of the reaction with substrate in excess over OD^-, although we saw line broadening in the course of reaction.

Kinetic Simulations. Simulations were made with a Hewlett-Packard 310 micro computer by using a program described earlier.[9b] Assignments of structures of Meisenheimer complexes were based on existing data,[7] and we saw no evidence for formation of Meisenheimer complexes with OH^- ipso to the carbethoxy group, consistent with MO calculations (not shown). Values of rate and equilibrium constants for formation of Meisenheimer complexes are the least reliable, because these complexes do not build up in concentration as much as in reactions of the di- and trinitroarenes, so fits to the simulation depend less critically upon the related rate constants.[9c,e]

The computer simulation of τ^{-1} values for reaction of 2,4-DNB predicts that Meisenheimer complex builds up at high $[OH^-]$, and from our rate and equilibrium constants (Tables VI and VII) we can predict the concentration dependence of this complex with time (Figure 7A). We carried out an experiment with 10^{-4} M ester and 2 M KOH in $DMSO/H_2O$ 1:1 (v/v) at 25.0 °C and obtained repetitive scans on an HP 8451 A spectrophotometer. In the first scan, the absorbance at 520 nm was 0.08 which for an extinction coefficient of 10^4 corresponds to 8×10^{-6} M Meisenheimer complex. The numerical integration for reaction under these conditions predicts concentrations of Meisenheimer complex of 1.5×10^{-5} and 8×10^{-6} M at 1.5 and 2 s, respectively, after mixing. The dead time of mixing in a conventional spectrophotometer is 1-2 s, so our results agree qualitatively with the simulation, and the color of the Meisenheimer complex is such that its fading can be observed visually over several seconds.

We tested our kinetic simulation by estimating variations of concentrations of reactants, intermediates, and products by numerical integration on the basis of rate and equilibrium constants in Tables VI and VII. The results are shown in Figure 7 and these concentration/time variations can be used to recalculate values of τ^{-1} (Table VIII and IX). There is reasonable agreement between observed and calculated values although for τ_2 and τ_3 in reaction of 3,5-DNB it is difficult to separate the relaxations at high $[OH^-]$.

Hydrogen Exchange. The extent and position of exchange were determined by integration of the ^1H signals of product and unreacted substrate. Extents of exchange were calculated from integrated peak areas of the ^1H signals of the arene and ethyl residues or of the mesitoate ion, when present. We used less aqueous media for these than for the kinetic experiments for reasons of solubility and potassium mesitoate was generally present as reference.[9d] We did not observe NMR spectra of Meisenheimer intermediates of 2,4-DNB under our reaction conditions because of the fast overall reaction, but we saw weak signals of Meisenheimer complexes of 3,5-DNB (Figure 3). Evidence on exchange of arene hydrogen at position 3 in the reaction of 2,4-DNB with an insufficiency of OD^- is presented in Figures 1 and 2. There was little exchange at position 5 within the limits of the peak area integrations. Evidence for exchange, and line broadening, in the reaction of 3,5-DNB is shown in Figure 3. The chemical shifts of the arene hydrogens of 3,5-DNB and 3,5-dinitrobenzoate ion are very similar, so peak separations were less than with 2,4-DNB. There is a small amount of exchange of the dinitrobenzoate ions (Table III) and we saw very weak signals of Meisenheimer complexes of 3,5-dinitrobenzoate ion (Figure 3) and the solutions were red.

Theoretical Calculations. MO calculations were carried out on a Vax 1/780 computer, with the AM1 model from the AMPAC program QCPE 506. All calculations were made by using the unrestricted Hartree-Fock scheme and were based on experimental geometries of related compounds.[30] The calculations include a correction of 10.1 kcal mol^{-1} per nitro group to allow for interoxygen repulsions[9f] (cf. ref 31). Geometries were fully optimized, except that we assumed coplanarity of atoms in the phenyl group and directly bonded substituents and for the charge transfer complexes, $\dot{O}H$ was located at 2.3 Å above the center of the phenyl group as for 1,3,5-trinitrobenzene.[9f] This assumption is least satisfactory for methyl 2,4-dinitrobenzoate because of its unsymmetrical structure.

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