# Mechanistic Features of $S_NAr$ Reactions of Neutral and Cationic Metal-complexed Halogenobenzenes with Methoxide

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Summary  Rate studies have shown that the activation of halogenobenzenes towards replacement of halide by methoxide in methanol increases through the series of $\pi$-attached residues $(OC)_3Cr < (OC)_3Mo << (\eta^5\text{-}C_5H_5)\text{-}Fe^+ < (OC)_3Mn^+$, with the fluorobenzene complexes more reactive than the chlorobenzene analogues; evidence has been obtained that the cationic complexes readily form ion-pairs with methoxide, resulting in a reduction in their reactivity towards nucleophilic substitution.

Although halogenobenzenes are inert to $S_NAr$ reactions under normal conditions,[1] their $\pi$-complexes with transition metal–ligand residues undergo ready nucleophilic displacement of halide. Kinetic studies have established that $\pi$-attachment of a $Cr(CO)_3$ residue activates fluoro- and chloro-benzene towards nucleophilic substitution to an extent similar in magnitude to the effect of a $p$-nitro substituent,[2] and that $\pi$-complexation with an $(\eta^5\text{-}C_5H_5)Fe^+$ residue exerts an even more marked effect.[3]

Since ($\eta^6$-arene)metal complexes are available in a wide diversity of structural types,[4] and in view of the current interest in the mechanistic details of $S_NAr$ reactions,[5] we report some results of a kinetic study of replacement by methoxide of halide in a series of neutral and cationic complexes (1—4a,b) of fluoro- and chloro-benzene. Reaction rates were followed by u.v.–visible spectroscopy for methanol solutions of the substrates (ca. $5 \times 10^{-4}$ M) containing predetermined concentrations of sodium methoxide in excess, such that the observed reactions (1—4a or b) → (1—4c) obeyed a pseudo-first-order kinetic expression.
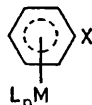


| (1) | $L_nM = (OC)_3Cr$ | a; X = F |
| (2) | $L_nM = (OC)_3Mo$ | b; X = Cl |
| (3) | $L_nM = (\eta^5\text{-}C_5H_5)Fe^+$ | c; X = OMe |
| (4) | $L_nM = (OC)_3Mn^+$ | |

Table. Rate constants[a]

| Substrate | [MeO$^-$]/M | $k_{obs.}[\text{MeO}^-]^{-1}/\text{s}^{-1}\,\text{l mol}^{-1}$ |
|---|---|---|
| (1a) | 0·1—1·0[b] | $1·31 \times 10^{-2}$ |
| (1b) | 0·5—3·0[b] | $2·70 \times 10^{-5}$ |
| (2a) | 0·1—1·0[b] | $3·80 \times 10^{-2}$ |
| (3a)[c] | $4·88 \times 10^{-3}$ | 3·13 |
| | $9·76 \times 10^{-3}$ | 1·44 |
| | $4·88 \times 10^{-2}$ | 0·60 |
| | $9·76 \times 10^{-2}$ | 0·34 |
| | 0·195 | 0·155 |
| | 0·39 | 0·098 |
| (3b)[c] | $4·88 \times 10^{-3}$ | 1·86 |
| | $9·76 \times 10^{-3}$ | 1·03 |
| | $4·88 \times 10^{-2}$ | 0·51 |
| | $9·76 \times 10^{-2}$ | 0·28 |
| | 0·195 | 0·24 |
| | 0·39 | 0·11 |
| (4b)[c] | $5·70 \times 10^{-3}$ | 12·1 |
| | $9·60 \times 10^{-3}$ | 7·82 |
| | $4·80 \times 10^{-2}$ | 3·06 |
| | $9·60 \times 10^{-2}$ | 0·56 |
| | 0·29 | 0·15 |

a For reactions in MeOH at 44·5 °C, following u.v.–visible absorbance changes; $k_{obs.}$ values were calculated from good first-order rate plots (correlation coefficients > 0·998); for the cationic complexes, a selection only of determined rate constants is given.  b $k_{obs.}$ [MeO$^-$]$^{-1}$ Values were constant through this range.  c As (PF$_6^-$) salt.

Rates of reactions of the halogenobenzenechromium complexes (1a,b)[6] and the molybdenum complex (2a)[7] were linearly dependent upon methoxide concentration over the ranges used; these ranges and the second-order rate constants $\{k_{obs}[\text{MeO}^-]^{-1}\}$ are in the Table.  In agreement with earlier work, [2a,c] we found that fluorobenzene complex (1a) is much more reactive (ca. 2000 times) towards methoxide than is the chlorobenzene complex (1b), in accordance with a mechanism in which the nucleophilic addition step is rate-limiting and the concentration of the anionic Meisenheimer-type intermediate does not build up during the reaction.† For a given methoxide concentration, reaction rates were modestly retarded in the presence

† For related reactions of (1a) with sodium ethoxide in ethanol, $k_{obs}.[\text{EtO}^-]^{-1} = 2·05 \times 10^{-2}\,\text{s}^{-1}\,\text{l mol}^{-1}$ through the range of nucleophile concentrations 0·25—1·0 M.

of inorganic salts (LiCl and NaClO$_4$; 0·1—0·5 M) but substantially accelerated when the methanol solvent was diluted with tetrahydrofuran (THF) or 1,4-dioxan. The molybdenum complex (2a) was slightly more reactive towards displacement of fluoride than was chromium complex (1a).

The cationic sandwich complexes (3a,b),[8] as (PF$_6^-$) salts, were likewise converted into the cationic anisole complex (3c) on reaction with methoxide, but the reactions showed quite different kinetic features from those of the chromium complexes (1a,b). Although, for a given methoxide concentration in the range 10$^{-3}$—10$^{-1}$ M, the fluorobenzene complex (3a) was more reactive than the chlorobenzene analogue (3b), the difference in reactivity was small (< two-fold) and the latter was in fact slightly more reactive at higher nucleophile concentrations. Consequently, although $\pi$-attachment of an ($\eta^5$-C$_5$H$_5$)Fe$^+$ residue activates both halogenobenzenes to a degree greater than that resulting from Cr(CO)$_3$ complexation, the magnitude of the increase in reactivity is much greater for chlorobenzene than for fluorobenzene. More strikingly, values of $k_{obs}$. [MeO$^-$]$^{-1}$ (Table) for reactions of the cationic complexes decreased sharply with increasing methoxide concentration up to ca. 0·1 M and then levelled off to approach a constant value at higher nucleophile concentrations.
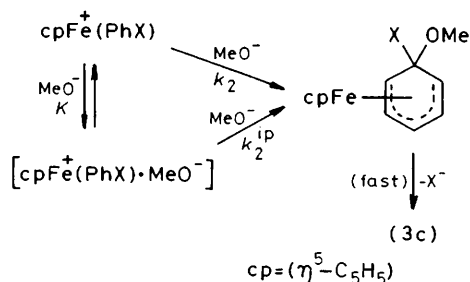


SCHEME

Although alternative interpretations are possible, these results are best accommodated by the assumption that methoxide readily forms tight ion-pairs with the cations (3a,b), and that the product (3c) results from reactions of methoxide with both the 'free' cation and the ion-pair, with the latter much less reactive (Scheme). For this Scheme, the rate expression (1) can be derived, where $k_{obs}$., $k_2$, and

$$\frac{k_{obs}.}{[MeO^-]} = \frac{k_2^{ip}K[MeO^-] + k_2}{K[MeO^-] + 1} \qquad (1)$$

$k^{ip}$ are respectively the observed pseudo-first-order rate constant and the second-order rate constants for reactions of methoxide with the 'free' cation and the ion-pair, and $K$ is the equilibrium constant for ion-pairing. The characteristic 'dog-leg' plots of $k_{obs}$. [MeO$^-$]$^{-1}$ against [MeO$^-$] are well fitted by this expression with values for $k_2$, $k_2^{ip}$, and $K$ of 4·0 s$^{-1}$ l mol$^{-1}$, 0·04 s$^{-1}$ l mol$^{-1}$, and 124 l mol$^{-1}$ respectively for (3a), and 2·7 s$^{-1}$ l mol$^{-1}$, 0·20 s$^{-1}$ l mol$^{-1}$, and 138 l mol$^{-1}$, respectively, for (3b).

The rate-modifying influence of ion-pairing has also been found for reactions of the cationic manganese complex (4b), with methoxide[9] for which values of 24·5 s$^{-1}$ l mol$^{-1}$, 0·04 s$^{-1}$ l mol$^{-1}$, and 143 l mol$^{-1}$ respectively have been estimated for $k_2$, $k_2^{ip}$, and $K$. Since this substrate (in both 'free' and ion-paired forms) is very much more reactive towards methoxide than (3b) (Table), we were able to detect‡ formation of the intermediate (neutral) Meisenheimer-like adduct and its conversion into the product (4c).

‡ The time dependence of the absorption at 265 nm reveals two distinct steps for reaction of (4b) in 0·005—0·1 M NaOMe–MeOH.

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