Kinetics and Mechanism of Thalliation of Aromatic Compounds in Trifluoroacetic acid

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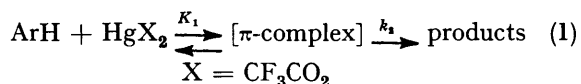
A detailed kinetic study of aromatic thalliation in trifluoroacetic acid is reported. Owing to impurities present in the commonly used reagent, thallium(III) trifluoroacetate, which cause irreproducible reaction rates, thallium(III) triacetate sesquihydrate was used as the thalliating agent. The results obtained from u.v. data were analysed in terms of a rapidly formed π-complex followed by its rate-determining conversion into products. The overall second-order rate constant showed a better Hammett correlation with σ^+ than σ values yielding a ρ^+ value of −8.3 which indicates greater charge development during the reaction than the corresponding mercuriation process. The stability of the intermediate π-complex however shows a greater sensitivity towards substituent effects than that of the mercury complexes. The overall free energies of activation of thalliation and mercuriation are very similar but significant variations occur in their component parameters, notably the entropy of formation of the π-complex is more negative for thallium than for mercury. The overall primary kinetic isotope effect of 4.3 is lower than that for mercuriation but the reverse is true for the conversion of the π-complex into products.

THE synthetically important process of thalliation has been the subject of a number of kinetic studies.[1-3] Rates have usually been determined by competitive methods using thallium(III) trifluoroacetate as the thalliating agent in solvent trifluoroacetic acid.[4,5] An n.m.r. study was recently completed in these laboratories which indicated that thalliation was much slower than the corresponding mercuriation reactions.[6]

We report a detailed kinetic investigation examining the nature and purity of the electrophilic reagent, and using substituent and isotope effects to elucidate mechanistic details.

RESULTS AND DISCUSSION

In a recent kinetic study of aromatic mercuriation conducted in these laboratories, evidence for the mechanism in equation (1) was presented.[7] The conditions [ArH]

$$\text{ArH} + \text{HgX}_2 \underset{}{\overset{K_1}{\rightleftharpoons}} [\pi\text{-complex}] \xrightarrow{k_2} \text{products} \quad (1)$$
$$X = CF_3CO_2$$

≫ [HgX₂] were chosen to obviate polymercuriation and also to simplify the kinetic equations describing process (1). This led to the reciprocal relationship of pseudo-first-order rate constant (k_1^{obs}) to [ArH] as given in equation (2). Using this equation, K_1 and

$$1/k_1^{obs.} = 1/k_2K_1\cdot 1/[\text{ArH}] + 1/k_2 \quad (2)$$

k_2 were separable yielding much useful information on the rate-determining step and on the nature of the intermediate π-complex. Accordingly, a similar study was initiated for the corresponding thalliation reactions using in the first instance thallium(III) trifluoroacetate. Preliminary examinations of the reaction using u.v. scans showed indeed that the same general behaviour was apparent. Mixing solutions of benzene and thallium(III) salt in solvent CF₃CO₂H produced a rapid increase in absorbance in the region 300—350 nm followed by a slower decrease. However, these preliminary experiments revealed that the reaction

rates were very much faster than those found using n.m.r. methods.[6] No evidence of any radicals was found from e.s.r. measurements on reaction solutions. Table 1 lists the data. The value of K_1k_2 which is equal to the observable second-order rate constant (k_2^{obs}) is some ten times that found by the n.m.r. method which employed equimolar (0.3M) conditions. Moreover, although rate

TABLE 1

Pseudo-first-order rate constants (k_1^{obs}) for the reaction of benzene with recrystallised thallium(III) trifluoroacetate (0.02M) in trifluoroacetic acid at 25°

[Benzene]/M	[Benzene]⁻¹/ M⁻¹	10³ k_1^{obs}/s⁻¹	$(k_1^{obs})^{-1}$ ᵃ/s
0.205	4.88	3.11	321.5
0.205	4.88	3.24	308.6
0.205	4.88	3.19	313.5
0.222	4.50	3.48	287.4
0.222	4.50	3.36	297.6
0.239	4.19	3.64	274.7
0.239	4.19	3.68	271.7

ᵃ Correlation coefficient $r = 0.968$, $k_2K_1 = 0.0167$ l mol⁻¹ s⁻¹, $k_2 = 0.0447$ s⁻¹, and $K_1 = 0.37$ l mol⁻¹.

constants were reproducible for a given batch of thallium-(III) salt, variations occurred from batch to batch. In most work using thallium trifluoroacetate, this reagent has been used without analysis of its thallium(III) content. The exception was the work of Deacon et al.[8] on dithalliation of anisole and related compounds, in which ca. 5% of the thallium was in the thallium(I) state (suppliers ROC/RIC). Accordingly, we have analysed both commercial (Aldrich Chemicals) and recrystallised material using three procedures (two for Tlᴵᴵᴵᴵ and one for Tlᴵ: see Experimental section). The results appear in Table 2. It is clear that thallium(III) trifluoroacetate contains very significant quantities of thallium(I) salt, which is not removed on recrystallisation. An alternative thallium(III) salt was therefore sought which could be obtained in a purer form. Thallium(III) triacetate sesquihydrate analysed very satisfactorily and was found to give reproducible reaction rates of similar magnitude to those for the trifluoro-

TABLE 2

Thallium analyses (%) for various thallium salts

Thallium salt	Method I [a]	Method II [b]	Method III [c]	Theoretical value
Tl(OCOCF$_3$)$_3$ [d]	29.9 ± 0.8		20.4 ± 0.4	37.61
Tl(OCOCF$_3$)$_3$ [e]	33.5 ± 0.3		15.9 ± 0.1	37.61
Tl(OCOCH$_3$)$_3$·1½H$_2$O [d]	48.3 ± 0.3		0	50.03
Tl(OCOCH$_3$)$_3$·1½H$_2$O [e]	50.2 ± 0.3	50.1 ± 0.7	0	50.03
TlOCOCH$_3$			78.0	77.6

[a] EDTA method.[12] [b] Cerium(IV) sulphate method.[13] [c] Potassium iodate method.[14] [d] Commercial sample. [e] Recrystallised sample.

acetate. Additionally, k_2^{obs} as determined at 28.4° by n.m.r. measurements (2.3 ± 0.1 × 10^{-2} l mol^{-1} s^{-1}) was in excellent agreement with that obtained from the more accurate u.v. data employing equation (2) for substrate benzene (2.19 ± 0.01 × 10^{-2} l mol^{-1} s^{-1}, Table 3).

TABLE 3

Pseudo-first-order rate constants (k_1^{obs}) for the reaction of benzene with thallium(III) triacetate sesquihydrate (0.02M) in trifluoroacetic acid at 28.4°

[Benzene]/M	[Benzene]$^{-1}$/ M^{-1}	10^3 k_1^{obs}/s^{-1}	(k_1^{obs})$^{-1}$ [a]/s
0.204	4.91	3.18	314.1
0.204	4.91	3.18	314.1
0.222	4.50	3.40	293.8
0.222	4.50	3.40	293.8
0.241	4.16	3.58	279.1
0.241	4.16	3.57	279.7
0.259	3.86	3.77	265.0
0.259	3.86	3.77	265.0
0.278	3.60	3.92	255.1
0.278	3.60	3.92	255.1
0.296	3.38	4.09	244.6
0.296	3.38	4.11	243.4
0.314	3.18	4.26	234.5
0.314	3.18	4.26	234.5
0.333	3.00	4.43	225.5
0.333	3.00	4.43	225.5
0.351	2.84	4.55	219.7
0.351	2.84	4.54	220.5
0.370	2.70	4.72	212.0
0.370	2.70	4.70	212.7

[a] Correlation coefficient $r = 0.9997$, $k_2 K_1 = 2.19 ± 0.01 × 10^{-2}$ l mol^{-1} s^{-1}, $k_2 = 1.12 ± 0.02 × 10^{-2}$ s^{-1}, $K_1 = 1.96 ± 0.03$ l mol^{-1}.

Having established the reliability of the method, the rates of a series of substituted benzenes were determined, and K_1 and k_2 separated as before. The results appear in Table 4.

The overall relative rates (k_2^{obs}) are fairly similar to those obtained by Olah[4] with the exception of t-butyl-benzene [k(Bu^t)/k(H) = 81.5 in our work, 200 in Olah's study].

The reaction is clearly fairly selective both in substrate and in regiospecificity commensurate with a reagent of moderate electrophilicity. Using Olah's values * for

* One might expect a somewhat different regiospecificity for thallium(III) acetate compared with thallium(III) trifluoroacetate. However it is probable that ligand exchange occurs in CF$_3$CO$_2$H as for Hg(OAc)$_2$ in the same solvent. Thus the thalliating species is likely to be similar [viz. Tl(OCOCH$_3$)$_n$(OCOCF$_3$)$_{3-n}$]. We have some evidence of this exchange from conductivity measurements which will be presented at a future date. The regiospecificity is so pronounced in any case (usually >95% $para$ thalliation) that the p_f values are unlikely to vary greatly with the nature of the thalliating species.

product ratios in thalliation and our values for k_2^{obs}, partial rate factors were determined and plots of log p_f versus Hammett σ values made. Our data correlated somewhat better with σ$^+$ (r 0.966, 0.991 without the fluorine substituent) than σ values (r 0.975, 0.963 without F), and yielded a ρ value of -8.3 close to the value obtained using Olah's data (-8.5). Yukawa–Tsuno plots gave ρ -8.6 for γ 0.6. The data clearly indicate substantially greater charge development during the reaction compared with mercuriation. However, the intermediate complex shows a greater sensitivity to substituents than is the case with mercuriation (cf. K_{rel} values for toluene of 5.7 and 1.2, respectively) which would indicate rather greater charge transfer in what is still basically a π- rather than a σ-complex. Hammett plots of log K_1^X/K_1^H show reasonable correlations with both σ and σ$^+$ ($r = 0.961$, 0.959, respectively) with a ρ value of $ca.$ -3. Hammett plots of k_2 with σ$^+$ values gives only a moderate correlation (r 0.945, ρ -5.2) largely as the result again of the fluoro-substituent. If this point is omitted the correlation is excellent (r 0.994) with a ρ value of -5.3 which is more negative than that found for mercuriation (-4.0). Thus greater charge development is apparent in both phases of the reaction.†

(A)
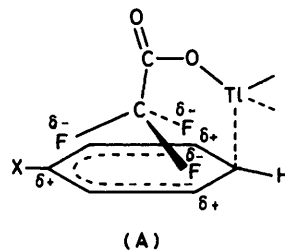
The Arrhenius parameters for this reaction are again revealing, the data for benzene appearing in Table 5, and the parameters themselves, together with those for mercuriation, in Table 6. Although the overall free energies of activation for both mercuriation and thalliation are almost identical, there are some interesting variations in the component parameters. In particular, the entropy of formation of the intermediate, $\Delta S_1°$, is

† The anomaly of the fluorine substituent is puzzling and derives in part from a much lower K_1 value than expected. Since the intermediate complexes show some degree of charge separation, a more localised structure is envisaged with some σ-character. This implies that K_1 as well as k_2 is associated with positional selectivity. Quantum mechanical calculations show that C–F dipoles can stabilise σ-intermediates,[9] so that structure (A) for the complex is plausible. The strong direct field effect of the fluorine would destabilise such a structure.

TABLE 4

Values of k_2^{obs} ($= K_1k_2$), k_2, and K_1 for the thalliation of various aromatic derivatives in CF_3CO_2H at 25.0° together with K_1 (relative to benzene) for both thalliation and mercuriation

Compound	$10^2 k_2^{obs}$/l mol^{-1} s^{-1}	$10^2 k_2$/s^{-1}	K_1/l mol^{-1}	Tl K_{rel}	Hg K_{rel}[a]	λ[b]
Benzene	1.95 ± 0.04	1.04 ± 0.05	1.9 ± 0.1	1.0	1.0	350
Benzene[c]	0.45 ± 0.01	0.166 ± 0.008	2.7 ± 0.2			350
Toluene	108 ± 4	10.1 ± 0.9	10.7 ± 1.3	5.7	1.2	350
Ethylbenzene	150 ± 1	10.5 ± 0.1	14.3 ± 0.3	7.6		350
t-Butylbenzene	159 ± 3	12.3 ± 0.4	12.9 ± 0.7	6.9		350
Fluorobenzene	0.208 ± 0.003	0.176 ± 0.008	1.18 ± 0.07	0.63	0.122	315
Chlorobenzene	0.0515 ± 0.0004	0.0733 ± 0.003	0.70 ± 0.03	0.37	0.098	320
Bromobenzene	0.0418 ± 0.0004	0.0469 ± 0.0018	0.89 ± 0.04	0.47		315

[a] Ref. 7. [b] Analytical wavelengths (nm). [c] [$^2H_6$]Benzene in CF_3CO_2D.

TABLE 5

Values of k_2^{obs}, k_2, and K_1 for the thalliation of benzene in CF_3CO_2H at various temperatures

T/°C	$10^2 k_2^{obs}$/l mol^{-1} s^{-1}	$10^2 k_2$/s^{-1}	K_1/l mol^{-1}	r[a]	N[b]
25.0	1.97 ± 0.05	1.03 ± 0.05	1.9 ± 0.1	0.9960	19
28.4	2.19 ± 0.01	1.12 ± 0.01	1.96 ± 0.03	0.9997	20
31.0	3.00 ± 0.04	1.29 ± 0.03	2.3 ± 0.1	0.9987	15
35.0	3.23 ± 0.04	1.82 ± 0.04	1.78 ± 0.06	0.9989	18
40.0	4.46 ± 0.15	3.16 ± 0.27	1.41 ± 0.17	0.9919	17

[a] r = correlation coefficient for reciprocal plots. [b] Number of points.

significantly more negative for thalliation. This is consistent with the increase in charge transfer in the intermediate noted above, giving rise to a more tightly bound species. The overall stability of the intermediate is lower than that for mercuriation due in large part to

the proton is half transferred to the base in solution $(CF_3CO_2^-?)$. The lower value for mercuriation must be due therefore to more advanced proton transfer with concomitant reductions in the charge on the aromatic nucleus. The nature of the thalliating agent is not known with certainty, but it is reasonable to suppose that ligand exchange between acetate and trifluoroacetate occurs [cf. $Hg(OAc)_2$ in CF_3CO_2H in ref. 7] particularly in view of the similarity in rates of reaction using $Tl(OCOCF_3)_3$ and $Tl(OCOCH_3)_3 \cdot 1.5H_2O$. The number of such ligand exchanges is however not yet known.

Added water appears to slow down the reaction. Equimolar solutions of water and thallium(III) salt (0.02M) cause a 50% decrease in rate. Addition of water during a run results in a dramatic decrease in the absorbance due to the intermediate indicating that water

TABLE 6

Activation parameters ΔG_n^m, ΔH_n^m, and ΔS_n^m for thalliation and mercuriation of benzene

	ΔG_2^{obs}/kcal mol^{-1}	$\Delta G_2^{\ddagger}$/kcal mol^{-1}	ΔG_1°/kcal mol^{-1}	ΔH_2^{obs}/kcal mol^{-1}	$\Delta H_2^{\ddagger}$/kcal mol^{-1}	ΔH_1°/kcal mol^{-1}	ΔS_2^{obs}/cal mol^{-1} K^{-1}	$\Delta S_2^{\ddagger}$/cal mol^{-1} K^{-1}	ΔS_1°/cal mol^{-1} K^{-1}
Tl	$+19.8$	$+20.2$	-0.4	$+9.5$	$+13.5$	-4.0	-34.4	-22.5	-11.9
Hg[a]	$+19.0$	$+20.4$	-1.4	$+13.5$	$+15.2$	-1.7	-20.3	-19.1	-1.2

[a] Ref. 7.

this unfavourable entropy term. Finally, isotope effects were measured for benzene on each of the component rate and equilibrium constants. The results appear in Table 7, again with values obtained for mercuriation for comparison. Isotope effects on K_1 should be reasonably close to unity as is found.

competes with the aromatic solute for the thalliating agent.

TABLE 7

Isotope effects for thalliation and mercuriation of benzene in CF_3CO_2H at 25°

	isotope effect on		
	k_2^{obs}/l mol^{-1} s^{-1}	k_2/s^{-1}	K_1/l mol^{-1}
Thalliation	4.3 ± 0.3	6.2 ± 0.6	0.7 ± 0.2
Mercuriation	5.6[a]	3.7	1.5
Mercuriation	6.0[b]		

[a] Ref. 7. [b] Ref. 10.

The overall kinetic isotope effect of 4.3 agrees quite well with previous values (3.7, ref. 2), and is lower than values obtained for mercuriation (5.6, ref. 7; 6.0, ref. 10). However, the isotope effect on the slow step is significantly greater for thalliation, approaching the situation where ly greater for thalliation, approaching the situation where

EXPERIMENTAL

Trifluoroacetic acid was heated with a small quantity of P_2O_5 and fractionated, rejecting the first 30% of the total distillate. The deuteriated acid was prepared as previously described.[7] Thallium(III) trifluoroacetate was obtained from Aldrich Chemicals and recrystallised from a small quantity of trifluoroacetic acid prior to use. Thallium(III) triacetate sesquihydrate was either purchased from Aldrich Chemicals and recrystallised from glacial acetic acid or synthesised from thallium(III) oxide and acetic acid.[11] All aromatic substrates were redistilled prior to use.

Analytical Techniques.—The thallium(I) and thallium(III) contents of the thallium salts used were determined using the following methods.

Method I (Tl^{III}). This involves the titration of Tl^{3+} with EDTA in an acetate buffer (pH 4.5),[12] using Xylenol Orange as an indicator. Tl$^+$ does not react under these conditions.

Method II (Tl^{III}). Tl^{3+} was reduced to Tl$^+$ with an excess of iron(II) ammonium sulphate. The excess of Fe^{2+}

was back titrated with standard ceric ammonium sulphate using phenanthroline as the indicator.[13]

Method III (Tl[I]). The following procedure was adopted for analyses of Tl+ contents in thallium salts.[14] The thallium(I) salt was oxidised to the thallium(III) state by potassium iodate in concentrated HCl–chloroform mixtures. The end point occurred on the disappearance of the violet colour in the organic phase. The results of the analyses appear in Table 2.

TABLE 8

Data for the evaluation of the second-order rate constants (k_2[obs]) for the thalliation of benzene (0.2M) by thallium-(III) triacetate sesquihydrate (0.2M) at 28.4° in CF_3CO_2H

t/min	I [a]	x/a	$\dfrac{x}{a - x}$ [b]	$10^2\, k_2$[obs]/ 1 mol^{-1} s^{-1} [c]
0	122			
10	95	0.221	0.284	2.4
18	80	0.344	0.524	2.4
28	70	0.427	0.745	2.2
38	57.5	0.529	1.12	2.5
48	52.5	0.570	1.33	2.3
60	46.5	0.619	1.62	2.3
4 300	8	0.934		

[a] Integral of aromatic signal at δ 7.00 in arbitrary units. [b] Correlation coefficient r 0.998. [c] k_2[obs] average = 2.35 ± 0.10 × 10^{-2} 1 mol^{-1} s^{-1}.

Kinetic Techniques.—The method used was identical with that used previously for mercuriation,[7] data being analysed by regression analysis for the reciprocal plots using equation (2). Pseudo-first-order plots showed excellent linearity up to 60% reaction ($r > 0.999$). Thereafter some curvature was noted though its cause has not yet been identified.

Guggenheim plots yielded rate constants in good agreement with the simple first-order plots of data up to 60% reaction. As a check on the u.v. method the reaction was studied by n.m.r. using the methods applied previously.[6] In this instance the rate was determined by monitoring the decrease in the aromatic signal. Contrary to the findings of the previous study using thallium(III) trifluoroacetate,[6] the reaction proceeded almost to completion using Tl(OAc)$_3$·1$\frac{1}{2}$ H_2O. Table 8 lists the data.

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