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Correlation of the rates of solvolysis of *tert*-butyl chlorothioformate and observations concerning the reaction mechanism

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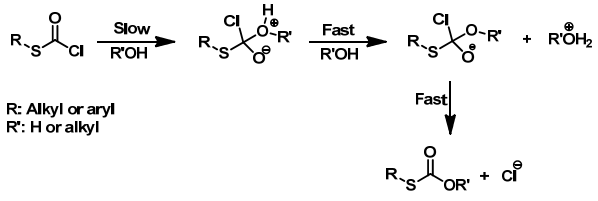
ABSTRACT

The "parent" tertiary alkyl chloroformate, *tert*-butyl chloroformate, is unstable, but the *tert*-butyl chlorothioformate (1) is of increased stability and a kinetic investigation of the solvolyses is presented. Analyses in terms of simple and extended Grunwald-Winstein equations are carried out. The original one-term equation satisfactorily correlates the data with sensitivity towards changes in solvent ionizing power of 0.73±0.03. When the two-term equation is applied, the sensitivity towards changes in solvent nucleophilicity of 0.13±0.09 is associated with a high (0.17) probability that the term that it governs is not statistically significant.

1. Introduction

There have been extensive studies of the solvolyses of chloroformate esters [1]. Recent studies have included the application of linear free energy relationships (LFERs), such as the Grunwald-Winstein (G-W) equation [2-4], which consider the influence of changes in solvent composition on the rates of solvolysis reactions. In the present study, we consider the solvolyses of a tertiary alkyl chlorothioformate (*t*-BuSCOCl, **1**). It has previously been shown [5-9] for chloroformates that the replacement of the alkoxy oxygen by sulfur leads to a move, away from an addition-elimination mechanism (Scheme 1) towards one of several possible ionization mechanisms (Scheme 2).

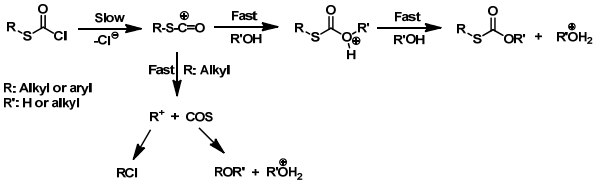


Scheme 1

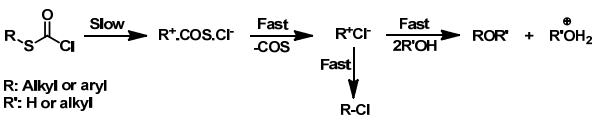
The original Grunwald-Winstein (G-W) equation employed *tert*-butyl chloride as the standard substrate and 80% ethanol as the standard solvent (Equation 1).

$$\log (k/k_o) = mY + c \quad (1)$$

In Equation 1, k, and k_o are the specific rates of solvolysis (first-order rate coefficients) in the solvent under consideration and in the standard solvent respectively, m is a measure of the sensitivity of the specific rate of solvolysis towards changes in solvent ionizing power (Y). The Y values are based on the specific rates of solvolysis of the standard substrate with m set at unity and c at zero [2]. Subsequently, it was realized that the solvolyses of 1-adamantyl or 2-adamantyl derivatives (1-AdX or 2-AdX), incorporating the adamantane cage attached to a leaving group X, minimized the extent of nucleophilic assistance to the ionization process [10-12]. Discussions of the development of Y scales and values for a wide variety of Y_X scales have previously been presented [4,13].



(a) Unimolecular Solvolyses



(b) Unimolecular Solvolysis-Decomposition

Scheme 2

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While there was some success in applying the original form of the equation to bimolecular solvolyses for a series of aqueous-organic solvent compositions for a given organic component [3], it was realized that for an application involving a single LFER for solvolyses in a series of aqueous-organic mixtures an extended approach would be required, and this led to the addition of a second term to give the original (extended) two-term G-W equation [Equation 2].

$$\log (k/k_o) = lN + mY + c \quad (2)$$

The additional term involves the sensitivity l to changes in solvent nucleophilicity N. Initially this scale was set up using methyl *p*-toluenesulfonate (tosylate) as the standard substrate (l = 1; c = 0) [14], but there was no rigid way to arrive at the required m value for the process [15]. Use of an initially positively charged leaving group, leaving as a neutral molecule, minimizes the need to consider leaving-group influences [15,16] and the S-methyldibenzothiophenium ion is usually chosen as the standard substrate, to yield the N_T scale [16]. The development and uses of this scale has been reviewed [4,17].

Studies involving the application of the G-W equation to chloroformate esters have included the methyl ester [18], examples of primary alkyl esters such as ethyl [6], propyl [19], isobutyl [9], neopentyl [20], and *n*-octyl [21], examples of secondary alkyl esters such as isopropyl [22,23] and 2-adamantyl [24], phenyl [25], and substituted phenyl esters [26,27]. There has been only one study in terms of the G-W equation of a tertiary alkyl chloroformate. The simplest, *tert*-butyl chloroformate, decomposes rapidly above 10 °C and the major products are isobutylene, hydrogen chloride, and carbon dioxide [28]. The *tert*-pentyl chloroformate has been reported to be only slightly more stable [29]. The 1-adamantyl chloroformate has been extensively studied in terms not only of solvolysis (accompanied by decomposition) [30-33] but also in terms of decomposition in relatively inert solvents [32-34]. In aqueous-organic solvents, the reaction proceeds by an ionization mechanism [30,31] and, in the solvents commonly used for solvolysis studies, only in 100% ethanol was a very small amount (less than 1%) of the mixed carbonate detected, which could result either from addition-elimination (association-dissociation), as shown in Scheme 1, or by ionization to chloride and carboxylium ions, followed by solvent capture (Scheme 2a). In the other solvents, all of the products were consistent with a solvolysis-decomposition mechanism. For chloride and ether formation, this would be as in Scheme 2b. Alcohol formation could result for either the Scheme 2b pathway or *via* loss of carbon dioxide from an initially formed half carbonate (ROCOOH).

The increased stability of the neat substance [35] could be due in part to it being a solid and in part due to alkene formation, which would put a double bond at a bridgehead, being highly unfavorable (Bredt's rule) relative to the dominant alkene-formation pathway involved in the *tert*-butyl chloroformate decomposition.

The much slower reaction of 1-adamantyl fluoroformate [36] suggests that ionization is not to $1\text{-Ad}^+(\text{OCOX})^-$, where the substrate with the more electronegative fluorine for X would be expected to contain the superior leaving group.

The substrate of the present investigation *tert*-butyl chlorothioformate (**1**) is commercially available but it was found to be rather unstable, even when stored in a cold room. Such storage allowed use for several weeks but eventually a new sample was required. Compound **1** has been used in the preparation of herbicides, pesticides and antifungal agents and, in particular, in the derivatization of 5-fluorouracil (2,4-dihydroxy-5-fluoropyrimidine)to give promising antitumor agents [37].

2. Experimental

The *tert*-butyl chlorothioformate (96%, Sigma-Aldrich) was used as received. Solvents were purified as described previously [26]. Kinetic measurements were made conductometrically using a rapid response technique [38]. Runs were carried out in duplicate with at least 70 readings taken at suitable intervals over approximately three half-lives and infinity readings were taken after ten half-lives. The values were used to calculate an average value, accompanied by the associated standard deviation. Simple and multiple regression analyses were carried out using the Excel 2010 package from the Microsoft Corporation.

3. Results and discussion

The specific rates of solvolysis of **1** in nineteen solvents, at 25.0 °C are reported in Table 1, together with the applicable N_T [16,17] and Y_{Cl} [13,39-42] values. Values at three elevated temperatures in 100% and 80% ethanol and at three reduced temperatures in 97% and 90% 2,2,2-trifluoroethanol (TFE) were also obtained. For each solvent, these three values were combined with the value at 25.0 °C from Table 1 for a treatment in terms of the Eyring equation to arrive at values for the enthalpy and entropy of activation, accompanied by the standard errors (Table 2). The major change in going from ethanol or 80% ethanol to the two aqueous-TFE solvents is a reduction of 4-6 k cal/mole in the enthalpies of activation. The entropy values of -17 and -12 cal mol^{-1} K^{-1} for the ethanol and 80% ethanol bracket the values of -14 and -15 cal mol^{-1} K^{-1} for the aqueous-TFE solvents. Entropies of this magnitude are on the border between values of -14 to -9 cal mol^{-1} K^{-1} proposed for S_N1 reactions of alkyl chlorides and values of -23 to -19 cal mol^{-1} K^{-1} for the corresponding S_N2 reactions [43].

Table 1. Specific rates of solvolysis (k) of *tert*-butyl chlorothioformate (**1**), in several pure and binary solvents at 25.0 °C, and literature values of N_T and Y_{Cl} for the solvents.

Solvent [a]	10^4 k_1, s^{-1}, [b]	N_T [c]	Y_{Cl} [d]
100% EtOH	0.0777 ± 0.0003	0.37	-2.50
90% EtOH	0.612 ± 0.002	0.16	-0.90
80% EtOH	4.04 ± 0.02	0.00	0.00
70% EtOH	17.5 ± 0.2	-0.20	0.78
100% MeOH	0.743 ± 0.003[e]	0.17	-1.20
90% MeOH	3.75 ± 0.02	-0.01	-0.20
80% MeOH	15.9 ± 0.02	-0.06	0.67
90% Acetone	0.0341 ± 0.0003	-0.35	-2.39
80% Acetone	0.605 ± 0.004	-0.37	-0.80
70 % Acetone	4.94 ± 0.03	-0.42	0.17
60 % Acetone	27.5 ± 0.2	-0.52	1.00
97% TFE (w/w)	373 ± 3	-3.30	2.83
90% TFE (w/w)	320 ± 1	-2.55	2.85
80T-20E[f]	48.7 ± 0.7	-1.76	1.89
60T-40E[f]	5.54 ± 0.05	-0.94	0.63
40T-60E[f]	0.853 ± 0.002	-0.34	-0.48
20T-80E[f]	0.171 ± 0.001	0.08	-1.42
70%HFIP (w/w)	4387 ± 61	-2.94	3.83
50%HFIP (w/w)	702 ± 12	-2.49	3.80

[a] On a volume-volume basis at 25.0 °C unless otherwise indicated.
[b] With associated standard deviations.
[c] From ref. [17].
[d] From refs. [13,40-42].
[e] Also a value of 0.533 ± 0.002 in 100% MeOD corresponding to a k_{MeOH}/k_{MeOD} value of 1.39 ± 0.01.
[f] T-E are TFE-EtOH mixtures.

For methanolysis, the specific rate was determined in both MeOH and MeOD, allowing a solvent deuterium isotope effect (k_H/k_D) of 1.39 to be determined (Table 1), This value is similar to the value of 1.26 for the methanoysis of *tert*-butyl fluoroformate, which is believed to follow a unimolecular pathway. Values for chloroformate esters have usually been close to two for reactions believed to go by the addition-elimination pathway with, for example, values of 2.17 for *n*-propyl chloroformate [19] and 1.87 for 2-adamantyl chloroformate [24]. When all of the hydrogens of one of three

methyl groups of *tert*-butyl chloroformate are replaced by chlorine (2,2,2-trichloro-1,1-dimethylethyl chloroformate), the substrate is quite stable and the k_{MeOH}/k_{MeOD} ratio of 2.14 indicates an addition-elimination pathway for the methanolysis of this trisubstituted-*tert*-alkyl chloroformate [44].

Table 2. Specific rates of solvolysis (k) of **1** in 100% and 80% ethanol and in 97% and 90% TFE (w/w) at temperatures other than 25.0 °C and the enthalpies ($\Delta H^{\neq}$) and entropies ($\Delta S^{\neq}$) of activation.

Solvent	Temp, °C	$10^4 k_1$, s^{-1} [a]	$\Delta H^{\neq}_{298}$ (kcal/mole) [b,c]	$\Delta S^{\neq}_{298}$ (eu) [b,c]
100% EtOH	42.0	0.444 ± 0.002	19.2 ± 0.5	-17.4 ± 1.6
	50.0	0.975 ± 0.001		
	55.0	1.71 ± 0.01		
80% EtOH	30.0	6.56 ± 0.03	18.5 ± 0.4	-12.2 ± 1.4
	35.0	11.4 ± 0.3		
	40.0	18.6 ± 0.2		
97% TFE (w/w)	2.0	44.7 ± 0.7	15.4 ± 0.7	-13.7 ± 2.6
	0.0	34.5 ± 0.4		
	-5.0	17.1 ± 0.2		
90% TFE (w/w)	2.0	53.9 ± 0.6	13.3 ± 1.0	-14.5 ± 3.6
	0.0	42.3 ± 0.8		
	-5.0	20.9 ± 0.5		

[a] With associated standard deviations.
[b] Based on four temperatures (also including the 25.0 °C value from Table 1).
[c] With associated standard error.

The rate data of Table 1 have been analyzed in terms of both the simple (Equation 1) and extended (Equation 2) forms of the G-W equation. The correlation values; sensitivities towards solvent nucleophilicity and solvent ionizing power, intercept (residual) values, simple and multiple correlation coefficients, and *F*-test values are presented in Table 3, where the values for **1** are compared with values for a selection of solvolyses of other haloformates from the literature. The analyses of **1** are carried out both with and without the TFE-ethanol data points. Frequently the TFE-ethanol values deviate from the correlations in pure solvents and aqueous binary solvents [45] but in the present instance, as can be seen from the values in Table 3 and from Figures 1 and 2, the four TFE-ethanol solvolyses conform to the values for the other 15 solvolyses studied.

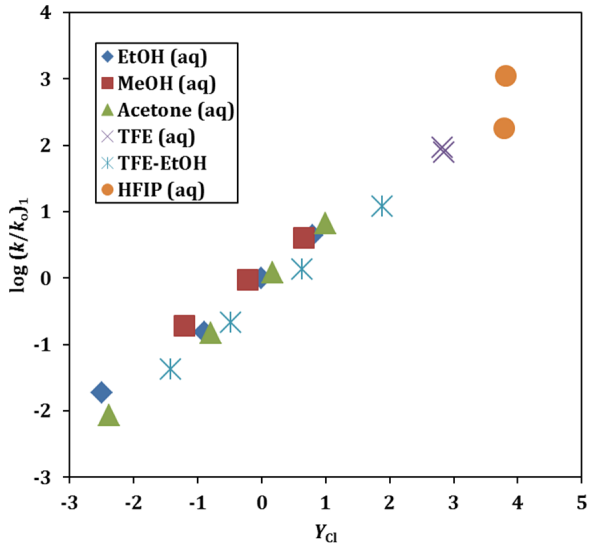

Figure 1. The plot of log (k/k_o) for *tert*-butyl chlorothioformate (**1**) against Y_{Cl} in the nineteen solvents of this study; slope of 0.73 ± 0.03.

A further observation is that there is, at best, only a marginal improvement observed when the values obtained using Equation 2 are compared to those obtained using Equation 1. Indeed the four correlation coefficients, Equation 1 or Equation 2 coupled with 19 or 15 solvents, vary only from 0.998 to 0.991.

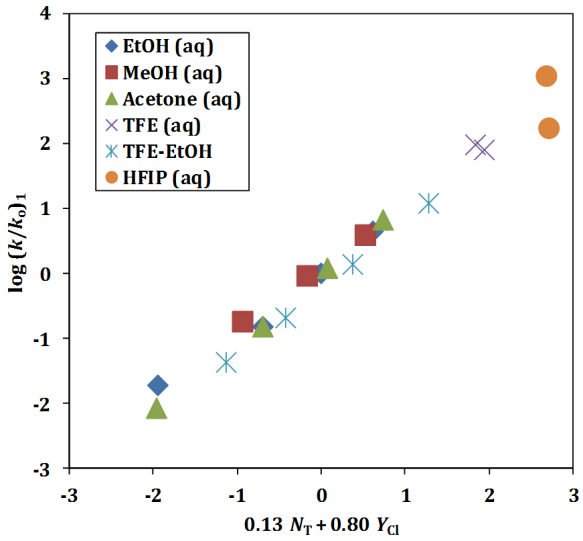

Figure 2. The plot of log (k/k_o) for *tert*-butyl chlorothioformate (**1**) against 0.13 N_T + 0.80 Y_{Cl} in the nineteen pure and binary solvents studied.

Accordingly, the *F*-test values on moving to Equation 2 are about halved and the probabilities that the *lN* term is not statistically significant are very high at 0.17 for 19 solvents and 0.22 for 15 solvents. One can draw the conclusions that the specific rates of solvolysis of **1** are satisfactorily correlated using Equation 1 and that there is no justification from the analyses for applying Equation 2. However, one cannot rule out a *small* sensitivity towards changes in solvent nucleophilicity.

Other data in Table 3 are for 1-adamantyl chloroformate (1-AdOCOCl) [30,31], 2-adamantyl chloroformate (2-AdOCOCl) [24], isopropyl chloroformate (*i*-PrOCOCl) [22,23], methyl chloroformate (MeOCOCl) [18], and phenyl chloroformate (PhOCOCl) [25]. Methyl chlorothioformate (MeSCOCl) [7], ethyl chlorothioformate (EtSCOCl)[6], *iso*-butyl chlorothioformate (*i*-BuSCOCl) [9], the secondary *iso*-propyl chlorothioformate (*i*-PrSCOCl) [8], and two tertiary fluoroformates, *tert*-butyl fluoroformate (*t*-BuOCOF) [46] and 1-adamantyl fluoroformate (1-AdOCOF)[36] are additional substrates for which the analyses of their rates of solvolysis are presented within the table. It is of interest that in the presence of antimony pentafluoride as a solution in SO_2 or SO_2ClF, methyl and ethyl chlorothioformates give alkylthiocarbonyl cations but the corresponding chloroformate (or halosulfite) esters react with loss of carbon dioxide (or sulfur dioxide), to give alkyl fluoroantimonates (for chlorides a rapid exchange with excess antimony pentafluoride occurs). Although the conditions are very different to solvolysis conditions, these findings [47] do indicate that halothioformates will have an increased tendency, relative to haloformates, to follow Scheme 2a rather than Scheme 2b. Support for this view comes from the observation [48] that calculated bond dissociation energies suggest that a direct cleavage of the CO-Cl bond in a chlorothioformate would be a relatively favorable process.

A comparison of the rates of solvolysis of MeSCOCl, EtSCOCl, *i*-BuSCOCl, *i*-PrSCOCl, and *t*-BuSCOCl in Table 4 shows a very similar ethanolysis rate order of $k_{MeSCOCl} \approx k_{EtSCOCl} \approx k_{i\text{-}BuSCOCl} \approx k_{i\text{-}PrSCOCl} \approx k_{t\text{-}BuSCOCl}$. On the other hand, the methanolysis rate of the tertiary alkyl thioester is three times faster that it's secondary or primary counterparts. In the highly ionizing fluoroalcohols [TFE or 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP)], the reactivity order $k_{MeSCOCl} < k_{EtSCOCl} \approx k_{i\text{-}BuSCOCl} < k_{i\text{-}PrSCOCl} << k_{t\text{-}BuSCOCl}$ observed, is now greatly influenced by the alkyl group structure.

Table 3. Correlation of the specific rates of reaction of several chloro- and chlorothioformate esters and *tert*-butyl- and 1-adamantyl fluoroformate using the simple and extended forms[a] of the Grunwald-Winstein equation (Equation 1 and Equation 2).

Substrate	n[b]	l[c,d]	m[c]	c[c]	l/m	R[e]	F[f]	Mechanism[g]
t-BuSCOCl (**1**)	19	-	0.73 ± 0.03	-0.10 ± 0.05	-	0.988	686	I
	19	0.13 ± 0.09 (0.17)	0.80 ± 0.06	-0.03 ± 0.07	0.16	0.989	365	I
	15	-	0.72 ± 0.03	-0.04 ± 0.06	-	0.990	647	I
	15	0.12 ± 0.09 (0.22)	0.78 ± 0.06	0.02 ± 0.07	0.15	0.991	341	I
1-AdOCOCl[h]	15	-	0.47 ± 0.03	0.03 ± 0.05	-	0.985	-	I
	11[i]	0.08 ± 0.20 (0.71)	0.59 ± 0.05	0.06 ± 0.08	0.14	0.985	179	I
2-AdOCOCl[j]	19	-	0.47 ± 0.03	-0.11 ± 0.19	-	0.970	-	I
	19	0.03 ± 0.07 (0.70)	0.48 ± 0.04	-0.10 ± 0.19	0.06	0.971	130	I
i-PrOCOCl[k]	9	1.35 ± 0.22	0.40 ± 0.05	0.18 ± 0.07	3.38	0.960	35	A-E
	16	0.28 ± 0.04	0.59 ± 0.04	-0.32 ± 0.06	0.47	0.982	176	I
MeOCOCl[l]	19	1.59 ± 0.09	0.58 ± 0.05	0.16 ± 0.07	2.74	0.977	171	A-E
PhOCOCl[m]	49	1.66 ± 0.05	0.56 ± 0.03	0.15 ± 0.07	2.96	0.980	568	A-E
MeSCOCl[n]	12	1.48 ± 0.18	0.44 ±0.06	0.08 ± 0.08	3.36	0.949	40	A-E
	8	0.79 ± 0.06	0.85 ± 0.07	-0.27 ± 0.08	0.92	0.987	95	I
EtSCOCl[o]	19	0.66 ± 0.08	0.93 ± 0.07	-0.16 ± 0.11	0.71	0.961	96	I
i-PrSCOCl[p]	19	0.38 ± 0.11	0.72 ± 0.09	-0.28 ± 0.10	0.53	0.961	97	I
i-BuSCOCl[q]	15	0.42 ± 0.13	0.73 ± 0.09	-0.37 ± 0.13	0.58	0.961	73	I
t-BuOCOF[r]	17	0.41 ± 0.05	0.65 ± 0.03	0.02 ± 0.04	0.63	0.989	301	I
1-AdOCOF[s]	16	-	0.70 ± 0.01	-0.02 ± 0.05	-	0.999	-	I
$Cl_3CC(CH_3)_2OCOCl$[t]	33	1.42 ± 0.09	0.39 ± 0.05	0.16 ± 0.08	3.64	0.945	-	A-E

[a] Which form used is clear from the presence or absence of an *l* value.
[b] *n* is the number of solvents.
[c] With associated standard error.
[d] Accompanied by the probabilities that the lN_T term is not statistically significant when value is greater than 0.001.
[e] Simple or multiple correlation coefficient.
[f] *F*-test value.
[g] Ionization (I) or Addition-Elimination (A-E).
[h] Values taken from ref. [22,23,30,31].
[i] See ref. [23] for the 11 solvents involved.
[j] With omission of the four data points for 100 and 90% EtOH and MeOH.
[k] From ref. [23].
[l] From ref. [18].
[m] From ref. [49].
[n] From ref. [7].
[o] From ref. [6].
[p] From ref. [8].
[q] From ref. [9].
[r] From ref. [46].
[s] From ref. [36].
[t] From ref. [44].

Table 4. A comparison of the rates of solvolysis of MeSCOCl, EtSCOCl, *i*-BuSCOCl, *i*-PrSCOCl, and *t*-BuSCOCl in selected common solvents at 25.0 °C.

Solvent (%)	MeSCOCl 10^5k, s^{-1} [a]	EtSCOCl 10^5k, s^{-1} [b]	*i*-BuSCOCl 10^5k, s^{-1} [c]	*i*-PrSCOCl 10^5k, s^{-1} [d]	*t*-BuSCOCl 10^5k, s^{-1} [e]
100% MeOH	2.00	2.15	2.27	1.99	7.43
100% EtOH	0.884	0.430	1.01	1.21	0.777
80% EtOH	2.44	2.68	2.99	13.7	40.4
97% TFE	0.986	5.98	6.01	49.8	3730
90% TFE	1.92	10.2	11.7	69.5	3200
70% HFIP	13.9	81.3	78.4	659	43870

[a] Ref [7].
[b] Rates are reported at 24.2 °C in Ref. [6].
[c] Ref. [9].
[d] Ref. [8].
[e] Table 1.

The analysis for **1** in all of the 19 solvents of the study using Equation 1 leads to an *m* value of 0.73±0.03. Using Equation 2 values are obtained of 0.13±0.09 for *l* and 0.80±0.06 for *m*. These values are very little changed for analyses carried out with the omission of the four data points for TFE-ethanol (T-E) solvents. The *l*/*m* ratio of 0.16 observed using Equation 2 is low in comparison to those obtained for the corresponding primary and secondary alkyl thioesters. A dual mechanism was proposed for the solvolysis of MeSCOCl [7]. In 12 of the more nucleophilic solvents, an *l* value of 1.48±0.18 and an *m* value of 0.44±0.06 were obtained. The *l*/*m* ratio of 3.36 is consistent with the proposal of a dominant addition-elimination mechanism for MeSCOCl in these solvents. In the remaining eight highly ionizing solvents studied an *l*/*m* ratio of 0.92 was obtained. This value is similar to the *l*/*m* ratios (0.53-0.71) obtained for EtSCOCl, *i*-PrSCOCl, and *i*-BuSCOCl. These values were considered [6-9] to reflect an ionization mechanism (Scheme 2a) involving loss of chloride ion to give a carboxylium ion with appreciable stabilization by nucleophilic solvation. Phenyl chlorothioformate, which would solvolyze in the usual solvents employed in G-W equation studies without involvement of the phenyl cation shows very similar behavior to the solvolyses of the methyl, primary and secondary alkyl thioesters, with the *l* and *m* values observed being 0.62±0.08 and 0.92±0.11, respectively [5]. In this correlation, the data points in 100% methanol and 100% and 90% ethanol were not included in the analyses because of the presence of an addition-elimination component. The corresponding values obtained for phenyl chloroformate, *l* value of 1.66±0.05 and *m* value of 0.56±0.03 including all of the 49 available solvolyses [49], can be taken as being typical for the addition- elimination pathway, with the addition step rate-determining. For example, for 50 of 51 solvolyses of isopropenyl chloroformate [CH_2=C(CH_3)OCOCl] (97% HFIP specific rate value omitted), very similar values of 1.54±0.03 and 0.54±0.03, respectively, were obtained [50] and it was shown that the solvolyses of phenyl chloroformate was a very good similarity model to use in a linear free energy comparison with the specific rates of solvolysis of isopropenyl chloroformate, with a value of 0.95±0.02 for the slope and a correlation coefficient of 0.991.

As examples of compounds involving a proposed concerted decomposition-ionization process in the rate-determining step,

we can look to adamantyl derivatives. These are used as either 1-adamantyl or 2-adamantyl derivatives to set up scales of solvent ionizing power and, hence, when Y_X values are used, by definition the *l* values for solvolyses involving adamantyl cation formation will be zero. It can be seen within Table 3 that the *l* values for adamantyl chloroformate solvolysis are negligible. The low *m* values of 0.47 to 0.59 observed for the pathway involving ionization requires that the concurrent decomposition reduces the need for electrophilic assistance at the chloride-ion leaving group and, thinking in terms of the influence upon the reaction coordinate, an earlier transition state is involved. A similar process is believed to operate for 1-adamantyl fluoroformate (Table 3) but, due to the stronger C-F bond being heterolyzed, there is an increased need for electrophilic assistance from the solvent and a larger *m* value of 0.70±0.01 is observed for reactions in fluoroalcohol (HFIP, TFE) containing solvents.

The *l* and *m* values associated with *tert*-butyl fluoroformate solvolyses in 17 solvents of 0.41 and 0.65, respectively, (Table 3) are similar to the values of 0.30 and 0.76 for *tert*-butyl chloride solvolyses [17,40] and a pathway with nucleophilic solvation of an incipient *tert*-butyl cation could be quite similar to the ionization process involved in the solvolyses of the chloride but with a fluoroformate anion as the leaving group. However, the ionization process for solvolyses of **1** is unlikely to involve a simple ionization to a carbocation and chloroformate anion in the rate determining step (RDS), because, as discussed in the introduction, the considerably slower reaction of a fluoroformate relative to the corresponding chloroformate argues in favor of a mechanism with some degree of fission of the carbon-chlorine bond in the RDS. Further, estimates [51] have indicated very large rate ratios for solvolyses of *tert*-butyl and isopropyl chlorides (or bromides) with values of about 10^6 in 97% HFIP and 10^4 in 80% ethanol. The present ratio for solvolyses of **1** and the isopropyl equivalent of 67 in 70% HFIP (Table 4) is much lower and suggest a reduced alkyl group-sulfur bond fission at the transition state of the RDS.

Unfortunately, there does not appear to be any estimates available for *tert*-butyl to isopropyl solvolytic rate ratios involved in the RDS ionization to a carboxylium ion and a chloride ion. A likely mechanistic candidate leading to the modest value for the ratio obtained in 70% HFIP involves a rate-determining solvolysis-decomposition involving expulsion of COS and formation of R^+ and Cl^- counterions (Scheme 2b). Such a mechanism can be considered as a hybrid of the two schemes considered immediately above with a relatively large contribution from the ionization to R^+ component for *tert*-butyl fluoroformate and appreciable contributions from both this component and the component involving ionization to $RSCO^+$ for *tert*-butyl chlorothioformate solvolyses.

It was mentioned earlier that the magnitude of the deuterium isotope effect for 2,2,2-trichloro-1,1-dimethylethyl chloroformate (β,β,β-trichloro-*tert*-butyl chloroformate) suggested a changeover from ionization to addition-elimination on introduction of the three electron-withdrawing chlorine atoms. This was given strong support by a G-W equation treatment [44] leading (Table 3) to an *l* value of 1.42±0.09 and an *m* value of 0.39±0.05.

4. Conclusions

The increased stability of *tert*-butyl chlorothioformate (**1**) relative to the corresponding chloroformate may well be related to the observation [47] for alkyl thioesters and esters that treatment with antimony pentafluoride in SO_2 or SO_2ClF result in the formation of carboxylium ions for methyl or ethyl chlorothioformate but a loss of carbon dioxide (and chloride/fluoride exchange) leads to methyl or ethyl hexafluoroantimonate for the chloroformate.

For the solvolyses of the 19 solvents of this study, including eight with fluoroalcohol content, a treatment in terms of the one-term Grunwald-Winstein equation using Y_{Cl} values leads to a good correlation (R = 0.988) with an *m* value (sensitivity towards changes in solvent ionizing power) of 0.73±0.03. There is only negligible improvement when the two-term [Equation 2] G-W equation is applied (R = 0.989) and the *l* value (sensitivity to changes in solvent nucleophilicity) is 0.13±0.09, associated with a high (0.17) probability that the lN_T term is not statistically significant. There is no evidence, even in pure ethanol and methanol, for the incursion of the addition-elimination pathway. For such a pathway (Scheme 1), the *l* value is considerably larger and it is at a magnitude of 1.66 (±0.05) for phenyl chloroformate solvolysis: a value generally taken as typical for an addition-elimination pathway.

Typical values for the pathway shown in Scheme 2b are the essentially zero *l* values observed for 1-adamantyl and 2-adamantyl chloroformate solvolyses. The ionization solvolyses of MeSCOCl, EtSCOCl, *i*-BuSCOCl, and *i*-PrSCOCl involve an *l*/*m* range of 0.53-0.92. It is believed that this magnitude of *l*/*m* ratios reflects a pathway of the Scheme 2a type, with the formation of the carboxylium ion assisted by an appreciable nucleophilic solvation. In contrast, the corresponding *tert*-butyl ester (**1**) follows the Scheme 2b variant of the ionization process. The vanishingly low *l* value is probably a consequence of a concerted ionization-fragmentation having an appreciable internal driving force and a lower demand for assistance from nucleophilic solvation.

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