The Reduction of 2,2,2-Trichloroacetanilide by Vanadium(II)

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The reduction of 2,2,2-trichloroacetanilide by $VCl_2(py)_4$ yields only 2,2-dichloroacetanilide and V(III), in contrast to the reductions of aralkyl halides, RX, studied previously which selectively formed coupling products, R_2. In the presence of small concentrations of water, the reaction rate in THF is first order in oxidant and V(II) and is accelerated by electron-withdrawing substituents. However, the rate decreases with decreasing water concentration and the rate law becomes complex under anhydrous condions. The yield of 2,2-dichloroacetanilide is unaffected by the presence or absence of water, but it increases with oxidant concentration and is higher than predicted by the stoichiometry

$$PhNHCOCCl_3 + 2V(II) + H^+ \longrightarrow PhNHCOCHCl_2 + 2V(III) + Cl^-$$

indicating the occurrence of unknown secondary reactions.

The selective reductive coupling of aralkyl halides by vanadium(II), and in particular by the complex $VCl_2(py)_4$, was previously reported by one of us.[1] We have now extended this investigation to the reduction of 2,2,2-trichloroacetanilides and have discovered marked differences between the two series of reactions.

Experimental Section

Unless otherwise noted, experimental techniques, preparations, and purifications used were as described previously.[1,2]

Materials. 2,2,2-Trichloroacetanilide and its ring-substituted derivatives were prepared by reaction of trichloroacetyl chloride with the corresponding aniline.[3] 2,2-Dichloroacetanilide was prepared by the method of McVie.[4] All compounds were recrystallized and their purities checked by melting point and elemental analysis.

Results

Product Analysis. 2,2,2-Trichloroacetanilide oxidizes $VCl_2(py)_4$ to V(III) species only. This was demonstrated by polarographic measurements[1] over a wide range of conditions (Table I) and also by the colors of the final solutions which, as in the case of oxidation of $VCl_2(py)_4$ by aralkyl halides, were diagnostic: yellow in the presence of water and pink in its absence.[1] (In contrast, reactions which convert $VCl_2(py)_4$ to V(IV) species, *e.g.*, oxidation by air or nitrobenzene, yield apple green final solutions.) Gas chromatography,[1] mass spectroscopy, and thin layer chromatography (silica gel G, benzene eluent) indicated that the only organic reduction product is 2,2-dichloroacetanilide, whether reaction is carried out in benzene or THF solvent. Product yields measured by gas chromatography as described previously[1,2] are shown in Table I. The presence or absence of trace water had no effect on the nature or yield of the product. There is no appreciable further reduction of 2,2-dichloroacetanilide under these conditions.

Reaction Kinetics. Rates were measured by following the decrease in V(II) concentration at 480 nm as described previously.[1] In tetrahydrofuran (THF) solution containing a small quantity of water, the oxidation of $VCl_2(py)_4$ by 2,2,2-trichloroacetanilide followed eq 1 over at least three

$$-d[VCl_2(py)_4]/dt = k_2[VCl_2(py)_4][PhNHCOCCl_3] \quad (1)$$

half-lives (correlation coefficients >0.9993) (Table II). ΔH^* and ΔS^* were 16.4 kcal mol^{-1} and −2.7 eu, respectively (Table III). 2,2,2-Trichloroacetanilides substituted on the ring or the nitrogen atom also followed eq 1 over at least two half-lives, and electron-attracting substituents increased the reaction rate while electron-releasing substituents decreased it (Table IV), although this effect was relatively small. The range of substituents permissible was limited by their oxidation or complexing of the V(II).[1] Oxidation by N-methyl-2,2,2-trichloroacetanilide was less than a tenth as fast as that by 2,2,2-trichloroacetanilide although it followed the same rate law (Table IV).

Table I
Product Yields from Reduction of $PhNHCOCCl_3$ by $VCl_2(py_4)$[a]

10^3 initial $[VCl_2(py)_4]$, (A)	10^2 initial $[PhNHCOCCl_3]$, M	10^3 $[PhNHCOCHCl_2]$ produced, M (B)	B/A	K[b]
		A. No Water		
7.6	0.84	3.9	0.51	0.003
7.9	1.01	4.3	0.54	0.03
7.9	1.68	5.3	0.67	0.18
7.6	2.52	4.2	0.55	0.02
7.9	3.36	5.2	0.65	0.07
7.6	5.0	5.1	0.67	0.06
7.9	6.7	6.0	0.76	0.10
7.6	8.4	6.5	0.85	0.19
7.6	12.6	6.7	0.87	0.15
		B. $[H_2O] = 0.010\ M$		
7.6	0.84	4.4	0.58	0.10
7.6	2.52	5.3	0.69	0.13
7.6	5.0	5.8	0.75	0.13
7.6	8.4	6.4	0.84	0.17
7.6	12.6	6.6	0.86	0.14

[a] THF solution, 22°. V(III) was the only inorganic oxidation product over the concentration ranges studied. [b] From eq 13.

In contrast to the oxidation of $VCl_2(py)_4$ by aralkyl halides, when the presence or absence of water had little effect,[1] the rate of oxidation of $VCl_2(py)_4$ by 2,2,2-trichloroacetanilides was increased somewhat by increasing water concentration (Table V) (although there is no effect on the products), and eq 1 holds only at appreciable water concentrations (above about $3 \times 10^{-4}\ M$; the kinetic results given above are for $[H_2O] = 5 \times 10^{-4}\ M$). In anhydrous THF, the reaction is approximately first order in V(II) only at low oxidant concentrations; at higher oxidant concentrations it approaches toward second order in V(II). Nonlinear regression analysis[5] shows a good fit to expressions such as

Table II
Oxidation of $VCl_2(py)_4$ by $PhNHCOCCl_3$[a]

10^2 [PhNH-COCCl$_3$], M	$10^2 k'$, sec^{-1} [b]	k_2, M^{-1} sec^{-1} [c]
3.36	3.11	0.93
1.68	1.69	1.01
0.60	0.61	1.02
0.46	0.48	1.05
0.228	0.220	0.96
0.114	0.117	1.03

[a] 20°, THF solvent containing 5.0 × 10^{-4} M H_2O; initial $[VCl_2(py)_4]$ = 3.5 × 10^{-4} M. [b] $k' = -\mathrm{d}\ln[VCl_2(py)_4]/\mathrm{d}t$. [c] $k_2 = k'/[PhNHCOCCl_3]$. Regression line through the origin gives k_2 = 0.945 M^{-1} sec^{-1} (standard deviation 0.016, correlation coefficient 0.9993).

Table III
Activation Parameters for the Oxidation of $VCl_2(py)_4$ by $PhNHCOCCl_3$[a]

Temp, °C	k_2, M^{-1} sec^{-1} [b]	Temp, °C	k_2, M^{-1} sec^{-1} [b]
1.6	0.130	30.0	2.46
6.0	0.200	34.9	3.83
10.5	0.345	39.8	5.60
15.4	0.631	44.7	9.26
20.0	0.945	49.6	12.7
25.0	1.54		

[a] Initial $[VCl_2(py)_4]$ = 3.3 × 10^{-4} M. THF solvent containing 5.0 × 10^{-4} M H_2O. [b] Activation parameters calculated from regression of ln k_2 upon 10^3 T_{abs} °K^{-1} are ΔH^* = 16.4 kcal mol^{-1} ($S_{\Delta H^*}$ = 0.12); ΔS^* = −2.7 eu at 25.6° ($S_{\Delta S^*}$ = 0.41); ΔG^* = 17.2 kcal mol^{-1} at 25.6°, ($S_{\Delta G^*}$ = 0.17); correlation coefficient = 0.9998. (Compare for the reduction of $PhCCl_3$: ΔH^* = 17.3 kcal mol^{-1}. ($S_{\Delta H^*}$ = 0.38); ΔS^* = −3.5 eu ($S_{\Delta S^*}$ = 1.21.)

Table IV
Rates of Oxidation of $VCl_2(py)_4$ by Substituted 2,2,2-Trichloroacetanilides[a]

Substituent		k_2, M^{-1} sec^{-1}	Standard error of k_2	σ-value[c,d]
4-CN	53165-95-0	2.17	0.042	1.00
4-CF_3	2107-36-0	1.81	0.012	0.74
4-EtOOC	53165-96-1	1.41	0.029	0.68
3-CF_3	1939-29-3	1.37	0.047	0.41
3-Cl	3004-73-7	1.21	0.006	0.37
4-Cl	2877-13-6	1.20	0.031	0.23
3-CH_3O	4257-82-3	0.97	0.023	0.11
H	2563-97-5	0.95	0.016	0.00
3-CH_3	2563-96-4	0.97	0.013	−0.07
4-CH_3	2564-09-2	0.81	0.016	−0.17
4-CH_3O	4257-81-2	0.80	0.006	−0.27
4-$NHCOCCl_3$	4257-74-3	1.58[b]	0.050[b]	
(N–CH_3)		(0.081)	(0.0026)	

[a] 20.0°; THF solvent containing 5.0 × 10^{-4} M water; initial $[VCl_2(py)_4]$ *ca.* 3.4 × 10^{-4} M. [b] Per $-NHCOCCl_3$ group. [c] H. H. Jaffé, *Chem. Rev.*, 53, 191 (1953); P. R. Wells, "Linear Free Energy Relationships," Academic Press, London, 1968, Chapter 2. [d] ρ-derived by unweighted linear least squares (correlation coefficient 0.978) is 0.34 (standard error 0.024). There is only poor correlation between log k_2 and Hammett σ values.

Table V
Effect of Water on Rate of Oxidation of $VCl_2(py)_4$ by 2,2,2-Trichloroacetanilides[a]

	k_2, M^{-1} sec^{-1} [b]		
$10^4[H_2O]$, M	$PhNHCOCCl_3$	p-$ClC_6H_4NHCOCCl_3$	p-$MeC_6H_4NHCOCCl_3$
0.00	0.57	0.83	0.55
0.16	0.62		
0.63	0.74	0.99	0.64
1.59	0.70	1.10	0.66
3.18	0.96		0.72
6.35	0.97	1.36	0.81
15.9	1.19	1.55	0.88

[a] 20°; THF solvent; initial $[VCl_2(py)_4]$ *ca.* 3.5 × 10^{-4} M. [b] At low $[H_2O]$, this is calculated assuming eq 1 from reactions performed at low [oxidant], when the rate is approximately first order in [V(II)].

$$-\mathrm{d}[VCl_2(py)_4]/\mathrm{d}t = k[VCl_2(py)_4]^{1.8}[PhNHCOCCl_3]^{1.5} \qquad (2)$$

but such equations are difficult to interpret mechanistically. Similar substituent effects are also observed in anhydrous solution as in anhydrous solutions.

Discussion

The oxidation of $VCl_2(py)_4$ with 2,2,2-trichloroacetanilides differs strikingly from the oxidation with aralkyl halides reported previously.[1] The reaction with aralkyl halides gives high yields of coupling products even in the presence of proton or hydrogen atom sources.

$$2RHal + 2V(II) \longrightarrow R_2 + 2V(III) + 2Hal^- \qquad (3)$$

In contrast, reduction of 2,2,2-trichloroacetanilides gives only the 2,2-dichloroacetanilide even in dry solutions.

$$PhNHCOCCl_3 + 2V(II) + H^+ \longrightarrow PhNHCOCHCl_2 + 2V(III) + Cl^- \qquad (4)$$

Reaction paths such as (4) are followed in many reductions of organic halo compounds by transition metal compounds,[1] often concurrently with the formation of coupling products. There appear to have been no studies on the reduction of 2,2,2-trichloroacetanilides by other low-valent transition-metal compounds, although with regard to halogen α to a carbonyl group, Cr(II) reduces trichloroacetaldehyde and trichloroacetic acid to acetaldehyde and acetic acid respectively in aqueous methanol[6] and p-bromophenyl dibromomethyl ketone to a mixture of p-bromoacetophenone and 1,2-bis(p-bromobenzoyl)ethane in aqueous dimethylformamide.[7]

The product yields (Table I) show that the reaction stoichiometry is not constant. The ratio ([$PhNHCOCHCl_2$] produced/[$VCl_2(py)_4$] consumed) decreases at lower $PhNHCOCCl_3$ concentrations and extrapolates to 0.5 (the value corresponding to eq 4) only at zero oxidant concentration. Despite this apparent change in stoichiometry, only V(III) was obtained in the oxidation products in all concentration ranges studied. This suggests that there are secondary reactions involving $PnNHCOCCl_3$ (see below).

The reduction of 2,2,2-trichloroacetanilides by $VCl_2(py)_4$ follows the same rate law as the reduction of aralkyl halides despite the difference in reaction path. However, the present reactions are much faster, owing to a lower ΔH^* (Table III; the ΔH^* values for $PhCCl_3$ and $PhNHCOCCl_3$ are significantly different at the 2% level, while the ΔS^* values are statistically indistinguishable). This indicates that the electronic effect of the adjacent carbonyl group is important. Similar rate enhancement by carbonyl groups is observed in reductions of halo compounds by Cr(II)[7] and cobaloximes[8] and in the faster reduction of NH_2COCH_2Hal than of CH_3Hal by pentacyanocobalt(II).[9]

Consistent with this, electron-withdrawing substituents increase the rate of reduction of 2,2,2-trichloroacetanilides while electron-donating substituents decrease it, similar to the case of the aralkyl halides,[1] although the effect is much smaller in the present case. The much larger effect observed when a methyl group is substituted on the side chain nitrogen atom rather than on the ring (Table IV) may also reflect a greater increase in electron density at the reaction center, although steric effects could be important.

Two distinct types of mechanism are possible for the reactions in hydrous solution, analogous to those proposed previously for aralkyl halides.[1] A one-electron transfer

$$PhNHCOCCl_3 + V(II) \xrightarrow{k_5} PhNHCOCCl_2\cdot + V(III) + Cl^- \quad (5)$$

could be followed immediately by

$$PhNHCOCCl_2\cdot + V(II) \xrightarrow{k_6} [PhNHCOCCl_2\text{–}V(III)] \quad (6)$$

and then

$$[PhNHCOCCl_2\text{–}V(III)] + H^+ \longrightarrow PhNHCOCHCl_2 + V(III) \quad (7)$$

The electron transfer (eq 5) could be either inner or outer sphere, consistent with the small negative ΔS^*, but in contrast to the case of the aralkyl halides it could be assisted by complexing of vanadium with the nitrogen or carbonyl group forming a halogen-bridged five-membered cyclic transition state. However, there is no evidence for such complex formation.

Alternatively, an organovanadium(IV) intermediate might result from an inner-sphere redox step

$$PhNHCOCCl_3 + V(II) \xrightarrow{k_8} [PhNHCOCCl_2\text{–}V(IV)] + Cl^- \quad (8)$$

followed by

$$[PhNHCOCCl_2\text{–}V(IV)] + V(II) \xrightarrow{k_9} [PhNHCOCCl_2\text{–}V(III)] + V(III) \quad (9)$$

Direct insertion of the metal into the C–Cl bond *via* attack at the carbon center is unlikely, as discussed previously.[1]

The positive ρ^- shows that the organic moiety gains some anionic character on attainment of the transition state, as might be expected for both paths in (5) and (8). The measured value of ρ^- (0.34) is much lower than that for reactions such as $ArNHCOMe + MeO^- \rightarrow ArNH_2$ (2.15)[10] or than the ρ value for reduction of benzotrichloride by $VCl_2(py)_4$ (1.2).[1] This may be due to less development of negative character at the reaction center in the transition state, or to the longer distance through which the effect must be transmitted.

The reason for the difference in products between these reactions and the reduction of aralkyl halides is uncertain, but one possibility is that the organic moiety in the $PhNHCOCCl_2\text{–}V(III)$ species has much more anionic character than in the $PhCCl_2\text{–}V(III)$ species because of the electronegativity of the C=O group, and hence is more easily cleaved by protons. Alternatively, attack of a further molecule of $PhNHCOCCl_3$ on the $[PhNHCOCCl_2\text{–}V(III)]$ intermediate might be too slow to allow the formation of coupled products.

The reason for the increase in the ratio ($[PnNHCOCHCl_2]$ produced/($[VCl_2(py)_4]$ consumed) above the value of 0.5 (corresponding to eq 4) with increasing $PhNHCOCCl_3$ concentration is not known. The vanadium oxidation product formed is V(III) over all the concentration ranges studied, and the change in stoichiometry is not due to generation of V(IV) or V(V). A possibility is that reaction with the substrate by radicals liberated in step 5

$$PhNHCOCCl_2\cdot + PhNHCOCCl_3 \xrightarrow{k_{10}} PhNHCOCHCl_2 + Ph\dot{N}COCCl_3 \quad (10)$$

competes with reaction 6 in their subsequent removal. However, this step would caise the observed variation in stoichiometry only if it be assumed that the pathway for removal of $Ph\dot{N}COCCl_3$ does not involve oxidation of another V(II). While this route appears unlikely, it may be more feasible than the alternative of reaction 8 followed by

$$[PhNHCOCCl_2\text{–}V(IV)] + PhNHCOCCl_3 \longrightarrow PhNHCOCHCl_2 + [PhN(COCCl_3)\text{–}V(IV)] \quad (11)$$

when it must be assumed that the resultant V(IV) complex is resistant to reduction. A scheme involving only eq 5, 6, 7, and 10 and assuming stationary state conditions for $[PhNHCOCCl_2\cdot]$ and $[PhNHCOCCl_2\text{–}V(III)]$ would lead to

$$-dV/dt = k_5VA[1 + k_6V/(k_6V + k_{10}A)] \quad (12)$$

and

$$[PhNHCOCHCl_2] = V_0/2 + (kA/4)\ln[(2V_0/kA) + 1] \quad (13)$$

where $V = [VCl_2(py)_4]$, $V_0 =$ initial $[VCl_2(py)_4]$, $A = [PhNHCOCCl_3]$, and $k = k_{10}/k_6$. Equation 13 is solved for k for each reaction in Table I, but the values found are larger than would be expected (considering that k_6 is likely to be about $10^8\ M^{-1}\ sec^{-1}$[1] and k_{10} would be many orders of magnitude less[11]) and are not constant except for the runs performed in the presence of water, showing that this simple scheme is inadequate.

The effect of water on the reaction kinetics has likewise not been explained. Water is likely to preferentially solvate the $VCl_2(py)_4$, but this may have little effect on the electron transfer step since the oxidation of $VCl_2(py)_4$ by aralkyl halides is unaffected by water.[1] No reaction scheme has been found which will reconcile the rate and product yield data and explain the effect of water and the differences between the oxidations of $VCl_2(py)_4$ by 2,2,2-trichloroacetanilides and aralkyl halides.

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