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SHORT COMMUNICATIONS

FREE RADICAL CHAIN REACTIONS OF ATE COMPLEXES. ELECTRON TRANSFER PROCESSES 42

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ABSTRACT

Iodide ion promotes the free radical reaction of isopropylmercury iodide with bromotrichloromethane to yield isopropyl bromide with rate enhancement in the order of 10^4. The reaction involves electron transfer from $i\text{-PrHgI}_2^-$ to the trichloromethyl radical in a long kinetic chain process. Iodide ion also promotes the free radical chain conjugate addition of *tert*-butylmercury chloride to α,β-unsaturated ketones, esters, phosphonate esters and sulfones. Competitive reactivity studies indicate that lithium di-*tert*-butylcuprates or tri-*tert*-butylzincates react with 2-cycloalkenones by a mechanism involving attack by *tert*-butyl radicals. No evidence for radical attack is observed for the corresponding *n*-butyl ate complexes of copper or zinc.

Photostimulated chain processes have been described for the reactions of alkylmercury chlorides with substituted alkenes or alkynes containing electron-withdrawing or accepting groups, Processes (1) (EWG = $(\text{EtO})_2\text{PO}$, PhSO_2, $p\text{-C}_6\text{H}_4\text{NO}_2$)[1] and (2) (EWG = PhSO_2, PhSO, PhS, halogen).[2] These processes involve

$$\text{CH}_2{=}\text{CH(EWG)} + t\text{-BuHgCl} \xrightarrow{h\nu} t\text{-BuCH}_2\text{CH(HgCl)(EWG)} \xrightarrow[\text{NaBH}_4]{\text{H}^+\text{ or}} t\text{-BuCH}_2\text{CH}_2\text{(EWG)} \quad (1)$$

$$\text{PhCH}{=}\text{CH(EWG)} + t\text{-BuHgCl} \xrightarrow{h\nu} t\text{-BuCH}{=}\text{CHPh} + \text{(EWG)HgCl} \quad (2)$$

the attack of an electron-accepting radical (either the adduct radical $t\text{-BuCH}_2\text{CH(EWG)}\cdot$ in Process (1) or the eliminated EWG radical in Process (2) upon t-BuHgCl to generate $t\text{-Bu}\cdot$ in a step which often determines the efficiency of the overall process. As shown in Table 1, iodide ion in Me_2SO increases the yields and rates of these processes. Telomerization, which is a serious problem with $\text{CH}_2{=}\text{CHCO}_2\text{Et}$ or $\text{CH}{=}\text{CHP(O)(OEt)}_2$ in Process (1), is not observed in the presence of 2 equiv. of NaI if a slight excess of the mercurial is employed, particularly when a proton donor such as NH_4^+ or MeOH is present. This suggests that the effect of iodide ion may involve electron transfer from I^- or $t\text{-BuHgI}_2^-$ to the electron-accepting adduct or eliminated radicals as shown in Reactions (3) and (4) ($\text{A}\cdot$ = electron accepting radical). Formation of

$$\text{A}\cdot + \text{I}^- \longrightarrow \text{A}^- + \text{I}\cdot \xrightarrow{t\text{-BuHgI}} \text{HgI}_2 + t\text{-Bu}\cdot \quad (3)$$

$$\text{A}\cdot + t\text{-BuHgI}_2^- \longrightarrow \text{A}^- + \text{HgI}_2 + t\text{-Bu}\cdot \quad (4)$$

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Table 1. Photostimulated reactions of *tert*-butylmercury chloride

		% yield (equiv. *t*-BuHgCl; hv; time)[a]	
substrate	product	*t*-BuHgCl[b]	*t*-BuHgCl + 2NaI[c]
$CH_2{=}CHSO_2Ph$	*t*-$BuCH_2CH_2SO_2Ph$	39(1;R;4h)	85(1;R;4h)[d]
$CH_2{=}CHP(O)(OEt)_2$	*t*-$BuCH_2CH_2P(O)(OEt)_2$	30(1;S;2h)	86(1;S;2h)[d]
$CH_2{=}CHCO_2Et$	*t*-$BuCH_2CH_2CO_2R$	5(2;R;10h)[e]	80(1;R;6h)[d,f]
$CH_2{=}CHCOMe$	*t*-$BuCH_2CH_2COMe$	7(2;R;10h)	85(2;R;6h)[d]
2-cyclohexenone	3-*t*-Bu-cyclohexanone	35(2;R;10h)	85(2;R;2h)[d]
2,3-dichloro-MA[g]	2,3-di-*t*-Bu-MA	27(5;S;8h)	98(4;S;5h)
(*E*)-$PhCH{=}CHSO_2Ph$	(*E*)-*t*-$BuCH{=}CHPh$	45(5;S;24h)	73(5;S;24h)
	$PhCH(Bu$-*t*$)CH_2SO_2Ph$	16(5;S;24h)	27(5;S;24h)
$PhC{\equiv}CSO_2Ph$	*t*-$BuC{\equiv}CPh$	49(5;S;17h)[h]	85(5;S;2h)[h]
(*E*)-$PhCOCH{=}CHCl$	(*E*)-*t*-$BuCH{=}CHCOPh$		100(5;S;1h)
(*E*)-$PhCOCH{=}CHCl$	i-$PrCH{=}CHCOPh$	<10(5;S;12h)	62(5;S;2h)[i]
$CH_2{=}CHCH_2Cl$	*t*-$BuCH_2CH{=}CH_2$	95(5;S;4h)	100(5;S;3h)
$HC{\equiv}CCH_2Cl$	*t*-$BuCH{=}C{=}CH_2$	20(5;S;7h)	71(5;S;5h)

[a] Reaction mixtures containing the substrate (0·2–0·4 mmol) in 10 ml of deoxygenated solvent were irradiated at 35–40 °C; S, 275 W sunlamp ca. 20 cm from reacton vessel; R, Rayonet 350 nm photoreactor.
[b] Workup by $NaBH_4$ or H_3O^+.
[c] Workup with 1% hydrochloric acid or $Na_2S_2O_3$.
[d] Me_2SO (60%)-MeOH (40%).
[e] Major product was *t*-$BuCH_2CH(CO_2Et)CH_2CH_2CO_2Et$.
[f] *t*-$BuCH_2CH_2CO_2Me$, no telomer observed.
[g] MA = maleic anhydride.
[h] *t*-$BuCH{=}CPh_2$ is also formed by an unknown mechanism.
[i] With i-PrHgCl, $E/Z = 97/3$.

t-$BuHgI_2^-$ in d_6-Me_2SO can be measured from the increase in the value of the ^{199}Hg–^{13}C NMR coupling constant upon addition of I^- to *t*-BuHgI, but the value of the complexation constant is only ~1 M^{-1} at 25 °C.

The reactions of Table 1 will occur slowly in the dark in the presence of iodide salts by processes which are completely inhibited by $(t\text{-}Bu)_2NO\bullet$. With $CH_2{=}CHP(O)(OEt)_2$, the initial kinetic chain length measured in the dark by the inhibition method was >500. The thermal production of *t*-Bu• from *t*-BuHgX at 60 °C in Me_2SO as measured by ESR spin trapping with *tert*-butylphenylnitrone is a first order process with k increasing from $3{\cdot}5 \times 10^{-9}$ for X = Cl to $1{\cdot}4 \times 10^{-7}$ with X = I and $2{\cdot}0 \times 10^{-5}\ s^{-1}$ with X = *t*-Bu. In the presence of 2 equiv. of I^-, the thermolysis of 0·1 M *t*-BuHgX at 60 °C is accelerated by 200-fold for X = Cl and 10-fold for X = I with the formation of *t*-Bu• occurring primarily by a process first order in both *t*-BuHgI and I^-. The photochemical decomposition of *t*-BuHgI is typically 5 to 10-times greater than *t*-BuHgCl (measured by the consumption of $(t\text{-}Bu)_2NO\bullet$ in an ESR experiment) with no significant effect of excess I^- on the rate of radical formation from *t*-BuHgI. With the irradiation utilized in Table 1, the photochemical decomposition of *t*-BuHgCl was typically 3–5%/h (as measured by $(t\text{-}Bu)_2NO\bullet$ product inhibition).

Although in Processes (1) and (2) it has not been possible to distinguish between Reactions (3) and (4) as the dominant step in the iodide promoted reactions, a decision in favor of Reaction (4) can be made in the free radical reaction between i-PrHgI and $BrCCl_3$, a process which also displays dramatic acceleration by iodide ion. Photolysis of $BrCCl_3$ and i-PrHgI in Me_2SO forms i-PrBr and only traces of $HCCl_3$,[3] but with a rate only ~0·5 the rate of formation of radicals as measured by $(t\text{-Bu})_2NO\bullet$ product inhibition. In the presence of 1–2 equiv. of NaI a much faster reaction yielding i-PrBr occurs by a process completely inhibited by $(t\text{-Bu})_2NO\bullet$ for a discrete period of time. The reaction is conveniently followed by 300 MHz ^{1}H-NMR in d_6-Me_2SO. There is a significant upfield shift of the ^{1}H-NMR isopropyl heptet of i-PrHgI upon complexation with I^- from which the complexation constant of $9 \pm 1\ \text{M}^{-1}$ in d_6-Me_2SO at 25 °C can be obtained (the alkyl groups are rapidly time-averaged between RHgI and $RHgI_2^-$). Addition of 2 equiv. of $BrCCl_3$ to an equilibrated solution containing i-$PrHgI_2^-$ in the dark and in the absence of $(t\text{-Bu})_2NO\bullet$ results in a rapid initial reaction for which an initial chain length $>2 \times 10^4$ is calculated (10 mol% of $(t\text{-Bu})_2NO\bullet$ inhibits the reaction for 7 days). The yield of i-PrBr in the initial rapid reaction is approximately equal to the starting concentration of i-$PrHgI_2^-$. Moreover, the initial rapid reaction is accompanied by a shift of the isopropyl ^{1}H-NMR heptet to a value near uncomplexed i-PrHgI, i.e. i-$PrHgI_2^-$ is preferentially consumed at a rate faster than it is regenerated. After the initial fast consumption of i-$PrHgI_2^-$, the reaction proceeds to completion but at a slower rate. In the presence of NH_4I the reaction yields $CHCl_3$ and i-PrBr in a 1:1 ratio consistent with Reactions (5) and (6).

$$CCl_3\bullet + \text{i-}PrHgI_2^- \longrightarrow CCl_3^- + HgI_2 + \text{i-}Pr\bullet \qquad (5)$$

$$\text{i-}Pr\bullet + BrCCl_3 \longrightarrow \text{i-}PrBr + CCl_3\bullet \qquad (6)$$

We have examined competitive conjugate addition reactions to determine if other ate complexes, such as '$(t\text{-Bu})_2CuLi$' or '$(t\text{-Bu})_3ZnLi$', can also react by a mechanism involving *tert*-butyl radicals. Stereochemical evidence demonstrates that 2°-alkyl or 1-alkenyl cuprates do not generate the alkyl or alkenyl radicals in conjugate addition or substitution reactions[4,5] even though electron transfer between the cuprate and α-β-unsaturated ketones or alkyl iodides seems to be involved.[6,7] However, formation of alkyl radicals from ate complexes may be a more favorable process when the radicals are tertiary.

Competition of 2-cyclopentenone (C_5) and 2-cyclohexenone (C_6) for alkyl radicals in the $RHgCl/NaI/Me_2SO/h\nu$ system at 40 °C (reactions leading to the 3-alkylcycloalkanones, see Table 1) yields a C_5/C_6 reactivity ratio of 3·8 for t-Bu• and 2·4 for n-Bu•. With $(n\text{-Bu})_2CuLi$ or $(n\text{-Bu})_3ZnLi$/TMEDA[8] in Et_2O at 0°, 2-cyclohexenone is more reactive than 2-cyclopentenone, $C_5/C_6 = 1/5$ and 1/2·5, respectively. However, with $(t\text{-Bu})_2CuLi$, LiI (−78 or −30 °C), or $(t\text{-Bu})_3ZnLi$/TMEDA (0 °C), C_5 is more reactive than C_6 by factors of 5·0, 4·2, and 3·9, respectively. We interpret the selectivity in these reactions of *tert*-butyl ate complexes in terms of predominant radical attack upon the α,β-unsaturated ketones to yield an enolyl radical which regnerates t-Bu• by Reaction (7).

$$\text{enolyl}\bullet + \text{ate complex} \longrightarrow t\text{-Bu}\bullet + \text{enolate ate complex} \qquad (7)$$

Further evidence favoring radical attack with $(t\text{-Bu})_2CuLi$ is furnished by the use of $Ph_2C{=}CH_2$ is a radical trap. With $(n\text{-Bu})_2CuLi$, 10 equiv. of $Ph_2C{=}CH_2$ had no effect on the nearly quantitative yield of alkylation product from 2-cyclohexenone at −78 °C. However with $(t\text{-Bu})_2CuLi$ (1 equiv.) at −78 °C, the presence of 5 equiv. of $Ph_2C{=}CH_2$ decreased the yield of 3-t-butylcyclohexanone from 0·90 to 0·42 equiv. with the formation of 0·32 equiv. of $t\text{-}BuCH_2CPh_2\bullet$ disproportionation products ($t\text{-}BuCH_2CHPh_2$ and $t\text{-}BuCH{=}CPh_2$). Essentially the same result was observed in Me_2SO at 40 °C for the photostimulated t-BuHgCl/NaI system.

Stability of cuprates in homolysis may be important in determining whether a radical chain process is initiated or if electron transfer cage processes[6] dominate. Thus, it is recognized that $(t\text{-Bu})_2Cu(CN)Li_2$[9] and $(t\text{-Bu})_2Cu(PBu_3)Li$[10] are thermally more stable than $(t\text{-Bu})_2CuLi$. These reagents yield a C_5:C_6 ratio of 1:4 at −78 °C in a reaction unaffected by the presence of

$Ph_2C{=}CH_2$ and which we interpret as 'ionic' addition. Attempts to stimulate a radical alkylation by photolysis of these reagents has been unsuccessful.

Competitive substitution reactions of allyl (A) and propargyl (P) chlorides with $(t\text{-}Bu)_2CuLi$ also gave evidence for *t*-Bu• attack. With *t*-BuHgCl/hν (Table 1), k_A/k_P was 12 ± 1 in Me_2SO (with NaI) or Et_2O. With $(t\text{-}Bu)_2CuLi$ in Et_2O at −78 or 0 °C, k_A/k_P had a similar value (10–13), but with $(t\text{-}Bu)_2Cu(CN)Li_2$ the propargyl chloride reacted preferentially, $k_A/k_P = 0{\cdot}7 \pm 0{\cdot}1$. Again, a change in mechanism between $(t\text{-}Bu)_2CuLi$ and $(t\text{-}Bu)_2Cu(CN)Li_2$ is indicated.

In another test for *t*-Bu• attack, the regio and chemoselectivity for the reactions of $PhCH{=}CHSO_2Ph$ and $PhC{\equiv}CSO_2Ph$ were examined. For $PhCH{=}CHSO_2Ph$ attack of *t*-Bu• occurs 2·7 times as readily at the β-position as at the position α to the benzene ring at 40 °C (Me_2SO, Table 1). The observed regiochemistry with *t*-BuLi in THF was 2·8:1 at 0 °C. With $PhC{\equiv}CSO_2Ph$ or $PhC{\equiv}CSPh$, only β-substitution was observed with either *t*-BuLi or *t*-BuHgCl/hν. The relative reactivities in β-substitution for the series $PhC{\equiv}CSPh$, $PhC{\equiv}CSO_2Ph$ and $PhCH{=}CHSO_2Ph$ at 40 °C were 0·3:1·6:1·0 and 0·3:1·8:1·0 for *t*-BuHgCl/Me_2SO/hν and *t*-BuLi/THF, respectively. Reactions of *t*-BuLi with these substrates may involve a radical process in which the eliminated radical (PhS•, $PhSO_2$•) or the adduct radical ($PhCH(t\text{-}Bu)CHSO_2Ph$) attacks *t*-BuLi to generate *t*-Bu•. At −78 °C, *t*-BuLi and $(t\text{-}Bu)_2CuLi$ gave similar relative reactivities for β-substitutions in $PhC{\equiv}CSO_2Ph$ and $PhCH{=}CHSO_2Ph$ (k_{rel} = 1·7–2·0:1). Interestingly, $(t\text{-}Bu)_2Cu(CN)Li_2$ at −78 °C failed to react with $PhCH{=}CHSO_2Ph$ but yielded the α-addition product in 98% yield with $PhC{\equiv}CSO_2Ph$.

Nucleophilic substitutions or conjugate additions proceed by a variety of mechanisms. Radical chain mechanisms can become dominant in both processes as has been observed to be the case with alkylmercury halides where the polarity of the carbon—mercury bond is not conducive to either nucleophilic attack at carbon,[11] or to the transfer of a carbon nucleophile from mercury to an α-β-unsaturated system. Radical chain processes become particularly attractive when facile electron transfer can occur between an organometallic reagent and a radical or radical ion derived from the substrate, e.g. the formation of R• from RHgCl upon reduction by $RNu^{\bullet -}$ or other donor species[11,12] and from $RHgI_2^-$ upon oxidation by acceptor species such as CCl_3• or $RCH_2CH{=}C(O\bullet)R'$.

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