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NUCLEOPHILIC CHARACTER OF ALKYL RADICALS—XIII

ABSOLUTE RATE CONSTANTS FOR THE ADDITION OF ALKYL RADICALS TO ACRYLONITRILE AND METHYL ACRYLATE

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Abstract—The absolute rate constants for the addition of alkyl radicals to acrylonitrile and methyl acrylate are determined by evaluating the ratio of ligand-transfer oxidation and addition to the double bond. Secondary alkyl radicals appear to be more reactive than primary alkyl radicals, despite the less favourable energetics. The classical selectivity:reactivity relationship is reversed owing to the nucleophilic character of the alkyl radicals.

Knowledge of the addition rates of the main types of carbon-centred free-radicals to vinyl monomers involves several mechanistic and synthetic aspects: polymerization, copolymerization and telomerization of the vinyl monomers; structure:reactivity relationships of the carbon-centred free-radicals in the reactions with olefins; and development of new syntheses from cheap materials, such as vinyl monomers.

In previous studies[2] concerning the relative rates of the addition of alkyl radicals to conjugated olefins it was observed that alkyl radicals are more reactive with electron-deficient olefins (i.e. acrylic monomers) than with electron-rich olefins (butadiene, styrene), despite the higher resonance stabilization of allyl and benzyl radicals compared with α-cyano- and α-carboxyalkyl radicals. This behaviour was ascribed to the nucleophilic character of the alkyl radicals; the selectivity increases from methyl to primary and secondary alkyl radicals according to the increasing nucleophilic character.

In order to understand better the structural causes of this selectivity, which could allow further synthetic developments, we undertook the determination of the absolute rate constants of the reactions between the main carbon-centred free-radicals and vinyl monomers. In this paper we report the results obtained with primary and secondary alkyl radicals and acrylonitrile and methyl acrylate.

RESULTS AND DISCUSSION

Some years ago[3] we showed that most of the aspects of the Sandmeyer reaction of diazonium salts in aliphatic series conformed to the generall free-radical redox chain reaction in eqns (1) and (2)

$$(RCOO)_2 + MX \longrightarrow R^{\cdot} + MX^{\cdot} + CO_2 + RCOO^{-} \quad (1)$$

$$R^{\cdot} + MX^{\cdot} \xrightarrow{k_{ox}} R\text{-}X + M^{+} \quad (2)$$

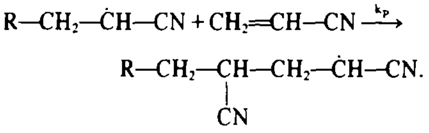
$$M^{+} + X^{-} \longrightarrow MX$$

$M^{+} = Cu^{\cdot}$ or Fe^{2+}; $R^{\cdot}$ = alkyl radical; X = Cl, Br, I, CN, SCN, N_3, $S_2O_3^{-}$, SC(S)OR.

Later on[4] we showed that this reaction, carried out in the presence of acrylonitrile and acrylic esters, leads to the haloalkylation of the double bond according to the free-radical redox chain of eqns (3) and (4), which suggests the Meerwein reaction of diazonium salts:

$$R^{\cdot} + CH_2{=}CH{-}CN \xrightarrow{k_a} R{-}CH_2{-}CH{-}CN \quad (3)$$

$$R{-}CH_2{-}\dot{C}H{-}CN + CuCl^{+} \xrightarrow{k_{tr}} R{-}CH_2{-}CHCl{-}CN + Cu^{+} \quad (4)$$



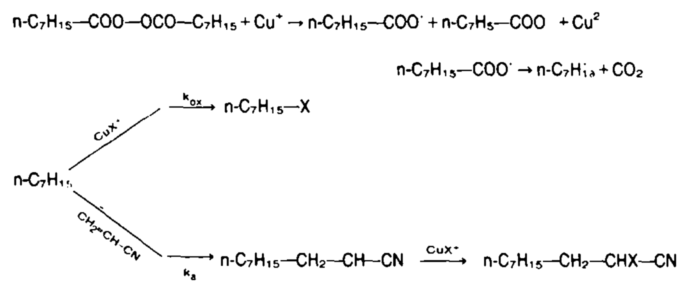
$$R{-}CH_2{-}\dot{C}H{-}CN + CH_2{=}CH{-}CN \xrightarrow{k_p} R{-}CH_2{-}\underset{\underset{CN}{|}}{CH}{-}CH_2{-}\dot{C}H{-}CN. \quad (5)$$

Since the rate of propagation (k_P), eqn (5), for the polymerization of acrylonitrile[5] is about $10^3\, M^{-1}\, sec^{-1}$ at 60°C, the absence of polymer formation and the presence of only traces of telomers indicated that k_{tr} is considerably higher than k_p. Moreover the significant amount of haloalkylation products obtained clearly indicated that the alkyl radical $R^{\cdot}$ is much more reactive than α-cyanoalkyl radical $R{\cdot}CH_2{\cdot}\dot{C}H{\cdot}CN$ towards acrylonitrile because it could be reasonably excluded for polar and resonance reasons that the α-cyanoalkyl radical is more reactive than $R^{\cdot}$ towards cupric chloride.

Recently the absolute rate constants (k_{ox}) of the reactions of primary alkyl radicals and cupric salts according to eqn (2) were determined[6] for X = Cl and SCN. The very high values of the second-order rate constants, close to the diffusion-controlled limit, well explain the absence of polymerization and telomerization of acrylonitrile in the haloalkylation reactions. The knowledge of the rate constants of eqn (2) has now allowed us to determine the absolute rate constants (k_a) for the addition of alkyl radicals to very reactive monomers, such as acrylonitrile and acrylic esters. The kinetic treatment was based on the reaction mechanism shown in the Scheme 1.

The reaction of the Scheme 1 is very clean, only octanoic acid and $n\text{-}C_7H_{15}X$ and $n\text{-}C_7H_{15}{\cdot}CH_2{\cdot}CHX{\cdot}CN$ are formed; the amount of telomers is negligible (< 1%).

Since the reaction of n-heptyl radical with cupric salt competes with the addition of acrylonitrile, the final yields should be related to acrylonitrile and cupric salts



Scheme 1.

concentrations according to the expression (6)

$$\frac{k_a}{k_{ox}}\frac{[\text{acrylonitrile}]}{[\text{CuX}^+]} = \frac{[\text{n-C}_7\text{H}_{15}\cdot\text{CH}_2\cdot\text{CHX}\cdot\text{CN}]}{[\text{n-C}_7\text{H}_{15}\text{X}]} \qquad (6)$$

As cupric halides are generally a composite of individual species (i.e. $CuCl^+$, $CuCl_2$, $CuCl_3^-$, $CuCl_4^{2-}$), which can all transfer a chlorine atom according to eqn (2), it was important to use for the addition to acrylonitrile the same experimental conditions[7] used for the determination of k_{ox}. The results are given in Table 1. A plot of eqn (6) affords a straight line passing through the origin, which enables k_a/k_{ox} to be evaluated. The value of k_{ox}[7] for $CuCl_2$ was estimated to be 1.1×10^9 M^{-1} sec^{-1} for a primary alkyl radical; it follows a value for $k_a = 5.9 \times 10^5$ M^{-1} sec^{-1}. The same kinetic treatment was carried out by using $Cu(SCN)_2$ instead of $CuCl_2$. Also in this case the reaction is very clean; the only reaction products are octanoic acid and the thiocyanoderivatives C_7H_{15}–SCN and C_7H_{15}–$CH_2CH(SCN)$–CN. The results are given in Table 2; also in this case a linear graph is obtained, which enables k_a/k_{ox} to be evaluated. A value of $k_a = 5.2 \times 10^5$ M^{-1} sec^{-1} has been therefore obtained by assuming $k_{ox} = 3.6 \times 10^8$ M^{-1} sec^{-1} for $Cu(SCN)_2$.[7] The agreement between the two values of k_a obtained by the different reactions is very good. The value of k_a for n-heptyl radical is about 1000 times higher than k_p. We think that this large difference of reactivity is mainly due to the nucleophilic character of the alkyl radicals, involving a considerable contribution of polar forms to the transition state, eqn (7), which decreases the activation energy of the reaction

$$\text{R}^{\cdot}\,\text{CH}_2{=}\text{CH—CN} \leftrightarrow \text{R}^+[\text{CH}_2\text{—CH—CN}]^{\cdot -}. \qquad (7)$$

The same kinetic treatment was carried out with methyl acrylate; the reaction is once more very clean; the thiocyano-derivatives and C_7H_{15}–CH_2–$CH(SCN)$–$COOCH_3$ were obtained. The results are given in Table 3. From the plot of these results a value of $k_a = 4.6 \times 10^5$ M^{-1} sec^{-1} has been evaluated for the addition of the heptyl radical to methyl acrylate. This last is slightly less reactive than acrylonitrile towards n-heptyl radical in agreement with the higher electronwithdrawing effect of the

Table 1. Kinetics of addition of the n-heptyl radical to acrylonitrile in the presence of copper chloride[a]

Run	$[CuCl_2]$(M)	[LiCl](M)	$[CH_2CHCN]$	$R = \frac{[CH_2CHCN]}{[CuCl_2]}$	Products (% mole) $n\text{-}C_7H_{15}\cdot CH_2\cdot CHX\cdot CN$	Products (% mole) $n\text{-}C_7H_{15}X$	Product ratio R'	$\frac{R'}{R}\cdot 10^3$
1	0.021	0.015	6.38	305	15	79	0.18	5.90
2	0.015	0.015	6.38	425	17	76	0.22	5.18
3	0.010	0.015	6.38	638	22	61	0.36	5.64
4	0.008	0.015	6.38	725	24	58	0.41	5.58
5	0.006	0.015	6.38	1063	31	55	0.57	5.36
6	0.004	0.015	6.38	1593	38	46	0.83	5.21
7[b]	0.002	0.035	6.38	3186	—[c]	—	1.51	4.75

[a] All reactions were run in CH_3CN at 0°C with di-n-octanoyl-peroxide 0.01 M and CuCl 0.002 M.
[b] Reaction with di-n-octanoyl-peroxide 0.03 M.
[c] Not determined.

Table 2. Kinetics of addition of the n-heptyl radical to acrylonitrile in the presence of copper thiocyanide[a]

Run	$[Cu(SCN)_2]$(M)	[KSCN](M)	$[CH_2CHCN]$(M)	$R = \frac{[CH_2CHCN]}{[Cu(SCN)_2]}$	Products (% mole) $C_7H_{15}\cdot CH_2\cdot CH(CN)SCN$	Products (% mole) $C_7H_{15}SCN$	Product ratio R'	$\frac{R'}{R}\cdot 10^3$
8	0.010	0.03	0.51	51	6	84	0.07	1.37
9	0.008	0.05	0.60	75	9	82	0.11	1.47
10	0.010	0.03	1.02	102	13	79	0.16	1.57
11	0.010	0.03	1.50	150	15	73	0.21	1.40
12	0.008	0.03	1.50	187.5	19	70	0.27	1.44
13[b]	0.028	0.06	12.0	430	—[c]	—	0.57	1.33

[a] All reactions were run in CH_3CN at 0°C, with di-n-octanoyl-peroxide 0.01 M.
[b] Reaction with di-n-octanoyl-peroxide 0.03 M.
[c] Not determined.

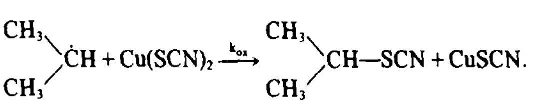
Table 3. Kinetics of addition of the n-heptyl radical to methyl acrylate in the presence of copper(II) thiocyanide[a]

					Products (% mole)			
Run	$[Cu(SCN)_2]$(M)	[KSCN](M)	$[CH_2CHCOOMe]$	$R = \frac{[CH_2CHCOOMe]}{[Cu(SCN)_2]}$	$C_7H_{15}{\cdot}CH_2{\cdot}CH(SCN){\cdot}Co_2CH_3$	$C_7H_{15}SCN$	Product ratio	$\frac{R'}{R}\cdot 10^3$
14	0.01	0.03	1.5	150	14	79	0.18	1.20
15	0.01	0.03	2.0	200	18	72	0.25	1.25
16	0.01	0.03	2.5	250	21	67	0.31	1.24

[a]All reactions were.run in CH_3CN at 0°C with di-n-octanoyl peroxide (0.01 M).

cyanogroup. The rate of propagation (k_p) is slightly higher with methyl acrylate than with acrylonitrile.

The reaction was further investigated with isopropyl radicals. By using $Cu(SCN)_2$ in the redox system a clean reaction was again obtained with acrylonitrile; the thiocyano-derivatives $(CH_3)_2CH{-}SCN$ and $(CH_3)_2CH{-}CH_2{-}CH(SCN){-}CN$ were the sole products of the reaction. The results are reported in Table 4. A plot of their ratio against [acrylonitrile]/$Cu(SCN)_2$ affords a straight line. However in this case we do not know exactly the rate constant of the ligand-transfer oxidation of the isopropyl radical by cupric thiocyanate, eqn (8),



$$(CH_3)_2\dot{C}H + Cu(SCN)_2 \xrightarrow{k_{ox}} (CH_3)_2CH{-}SCN + CuSCN.$$

If we assume that k_{ox} is substantially the same for primary and secondary alkyl radicals, we obtain a value of $k_a = 4.3\times10^6\ M^{-1}\ sec^{-1}$ for the isopropyl radical, higher than the addition rate of n-heptyl radical. An analogous result of a single experiment with isopropyl radical and methyl acrylate was obtained. This assumption is, in our opinion, reasonable for two reasons: (i) the ligand-transfer oxidation is scarcely affected by the nature of the carbon-centered radical;[8] (ii) the oxidation rate by cupric acetate of the isopropyl radical is not substantially different from that of n-propyl radical[9] (the respective values reported for log k are 7.70 and 7.64); in any case the secondary alkyl radical is slightly more reactive than the primary alkyl radical towards the cupric salt. These considerations suggest that, even if k_a for the addition of isopropyl radical to acrylonitrile is not strictly exact, it is almost certainly higher than the corresponding value for the addition of n-heptyl radical.

Secondary alkyl radicals are generally considered less reactive than primary alkyl radicals because the energetics is less favourable. In the addition of the alkyl radicals to electron-deficient olefins the sequence of reactivity, expected from the energetics, appears to be reversed, due to important contributions of polar effects. The classical relationship high reactivity: low selectivity is also reversed; secondary alkyl radicals are more selective than primary alkyl radicals, but they appear to be also more reactive towards electron-deficient olefins owing to their higher nucleophilic character. Of course we expect that with electron-rich olefins (ethylene, butadiene, styrene) the usual sequence of reactivity will be observed for both polar factors and energetics.

We have recently reported[10] that, when polar effects mainly determine the reaction rates, a high selectivity can be associated with a high reactivity. Thus the homolytic acylation of protonated heteroaromatic bases is a very selective process, whereas the homolytic arylation is an extremely unselective process. The acyl radicals are however considerably more reactive than the aryl radicals towards protonated heteroaromatic bases.[10] The same behaviour we have observed in the homolytic alkylation of protonated heteroaromatic bases; alkyl radicals are more reactive and much more selective than aryl radicals.[11] The results reported in this paper are a further example of this behaviour.

Another interesting aspect of the reactions investigated is offered by the synthetic developments; it is possible to prepare a large variety of α-substituted esters or nitriles starting from acrylic monomers.

The knowledge of the rate constants k_{ox}, k_a and k_p allows the best experimental conditions for these syntheses to be deduced.

EXPERIMENTAL

IR spectra were recorded on a Perkin Elmer 177 spectrometer. NMR spectra were recorded on a Varian A60 spectrometer operating at 60 MHz with TMS as internal standard. For analytical GLC a Hewlett-Packard 5750 G instrument was used equipped with a flame ionization detector, carrier gas: N_2 (20 ml/min), using a 6 ft 1/8 in. steel column packed with silanized Gas-Chrom-p and 1% SE-30, 80–100 mesh, programmed temperature 100–240°C (5–15°/mm increase).

Materials. Acrylonitrile and methyl acrylate were distilled before use. Acetonitrile was refluxed on P_2O_5 and distilled. Copper(II) thiocyanate and solution of copper(I) chloride in acetonitrile were prepared according to Kochi.[7] Di n-octanoyl peroxide was commercial product crystallized several times (its

Table 4. Reactions of the isopropyl radical with acrylonitrile and methyl acrylate in presence of copper(II) thiocyanate[a]

					Products (% mole)			
Run	$[Cu(SCN)_2]$(M)	[KSCN](M)	$[CH_2CH{-}X]$	$R = \frac{[CHCH{-}X]}{[Cu(SCN)_2]}$	$Me_2CHCl_2{\cdot}CH(SCN)CN$	$Me_2CH{\cdot}SCN$	$R' = IX:VIII$	$\frac{R'}{R}\cdot 10^2$
17	0.01	0.03	0.5^b	50	32	57	0.56	1.12
18	0.01	0.03	1.0^b	100	48	41	1.17	1.17
19	0.01	0.03	1.3^b	130	52	36	1.45	1.11
20	0.01	0.03	1.3^c	130	48^d	39	1.20	0.92

[a]All reactions were run in CH_3CN at 0°C with diisobutanoyl-peroxide 0.01 M. [b]X = CN. [c]X = COOMe. [d]$(CH_3)_2CH{-}CH_2{-}CH(SCN)COOMe$.

purity was proved by iodometric analysis to be >98%). Diisobut-anoyl-peroxide was prepared from isobutanoyl chloride and H_2O_2 according to Kochi[12] (purity: 98%).

n-Heptyl chloride was obtained from Merck-Schuchard and distilled (b.p. 159°C). Its purity by GLC was 98%.

n-Heptyl thiocyanate. A mixture of potassium thiocyanate (18 g, 0.2 mol) and benzyltriethylammonium chloride in 80 ml of water and heptyl chloride (16 g, 0.1 mol) in 100 ml of $CHCl_3$ was refluxed for 5 h under vigorous stirring. The $CHCl_3$ layer was separated, washed with water (2 × 100 ml), dried over Na_2SO_4, filtered, concentrated and distilled to yield 5 g of n-heptyl thiocyanate (b.p. 135–136°, 28 mmHg). Its purity by GLC was >95%. IR and NMR spectra were consistent with the structure of n-heptyl thiocyanate.

Isopropyl thiocyanate. 11 ml of isopropyl iodide (0.1 mole) was added to 9 g of potassium thiocyanate (0.1 mole) in 100 ml of ethanol and the solution was refluxed for 6 h. The reaction mixture was concentrated to 20 ml, mixed with water and extracted with ether. The ethereal extract was dried and concentrated. The residue was distilled to yield 2.8 g of isopropyl thiocyanate (b.p. 151–152°, 760 mmHg). The product was purified by column chromatography (SiO_2, eluent: hexane). Its purity (GLC) was 99%. IR, NMR and MS were consistent with the structure of isopropyl thiocyanate.

2-*Thiocyanononyl cyanide* was isolated (240 mg, 21%) in a control experiment (run 13) starting from 1 g of dioctanoyl peroxide. The reaction mixture was concentrated at 0°C to 10 ml, water added (200 ml) and extracted with ether (3 × 50 ml). The ethereal extract was washed with water and 10% aq$NaHCO_3$, dried and concentrated. The crude product (0.92 g) was chromatographed on Silica-gel (Merck) eluting with hexane. IR: 5.55 (C≡N), 5.38 (SCN). NMR (CCl_4) δ: 3.95 (1H, t, CH_2–C$\underline{H}$(CN)–SCN), 1–2.1 (14H, m, aliphatics), 0.91 (3H, t, CH_3). Its purity by GLC was 95% (5% heptyl thiocyanate was present).

2-*Thiocyano-4-methylbutyl cyanide* was isolated by column chromatography (350 mg, 47%) starting from 1 g of isobutanoyl peroxide (run 19) as described above. Its purity (GLC) was 98%. IR: 5.5 (CN), 5.38 (SCN), NMR (CCl_4) δ: 4.12 (1H, t, CH_2–C$\underline{H}$(CN)–SCN), 1.8–2.1 (3H, m, –C$\underline{H}_2$–C$\underline{H}$(CH_3)$_2$), 1.05 (6H, d, CH_3). MS: *m/e* 154 ($M^{\cdot+}$), 139', 124, 98 (M–C_4H_8), 69, 55, 43.

2-*Chloro-n-nonyl cyanide* was isolated by column chromatography (hexane–SiO_2) in run 7. IR, NMR and retention time were identical to those of an authentic sample prepared by chlorination with $SOCl_2$ of n-nonyl-cyanohydrin (b.p. 124°C).

Methyl ester of 2-*thiocyanoundecanoic acid* was isolated by column chromatography (hexane–SiO_2) in run 16 (0.21 g) starting from 1 g of dioctanoyl-peroxide. IR: 5.3 (SCN), 6.2 (COOMe), NMR (CCl_4) δ: 3.6 (1H, t, CH_2–C$\underline{H}$(SCN)COOMe), 3.8 (3H, s, O–CH_3), 1–2.3 (14H, m, aliphatics), 0.9 (3H, t, CH_3).

Methyl ester of 2-*thiocyano-4-methylpentanoic acid* was isolated by preparative GLC in run 20. IR: 5.3 (SCN), 6.2 (COOMe), NMR (CCl_4) δ: 3.7 (1H, t, CH_2–C$\underline{H}$(SCN)COOMe), 3.9 (3H, s, OCH_3), 1.7–2.1 (3H, m), 1.05 (6H, d, CH_3). MS: *m/e* 187 ($M^{\cdot+}$), 131 (M–C_3H_6), 129, 95, 73, 59, 43.

Kinetics. General procedure with copper(II) thiocyanate

The copper(II) and alkali thiocyanate and the acrylonitrile (or methyl acrylate) were dissolved in acetonitrile at 0°C. The solution was flushed with a stream of N_2 for 15 min. The degassed solution of diacyl peroxide in acetonitrile was added and the solution (50 ml) was stirred for 2 hr at 0°C.

General procedure with copper(II) chloride

The copper(II) chloride dihydrate was dissolved in acetonitrile and standard solutions of acrylonitrile and diacyl-peroxide were added. The solution was flushed with N_2 for 15 min. A copper(I) chloride solution in acetonitrile was added to initiate the decomposition. The reaction was magnetically stirred for 2 h at 0°C.

Analysis. All products were analyzed by standard GLC procedure with calibration of products, using the internal standard procedure for determination of the yield. The analysis were performed by removing an aliquot of reaction mixture and an aliquot of internal standard solution, mixing and eluting with ethyl ether through neutralized Al_2O_3. The resulting solution was analyzed directly or after concentration to reduced volume at 0°C. This method of analysis gave results in good agreement with those obtained by washing an aliquot of reaction mixture and standard solution with excess of water, extraction with pentane, washing the extract with water and 10% $NaHCO_3$ and concentrating at 0°C.

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