26. Compounds **12c** and **13c** were then transformed into the corresponding hydrazinothioazetidinones **17** and **18**. Cyclization of **17** under the conditions described before, afforded **22**[16] (Δ^2 and Δ^3 mixture) in 20% yield and **23**[17] (Δ^3 isomer) in a very small amount. Instead, ring closure of **18** gave only the expected **24** (10% yield) with the corresponding Δ^2 isomer (20% yield). Synthesis of 3-thiomethyl-3-cephem derivatives from the bromides **5c** and **6c** is currently being investigated in our laboratories.

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(4) Proofs of the assigned structures were obtained by mass spectral fragmentation and IR and NMR spectroscopy.
(5) The corresponding 3-methylcepham, apparently arising from a not oxidative side reaction involving an addition of the thiol intermediate to the isopropenyl double bond, was also isolated, 5% yield: mp 120–121 °C.
(6) Compound **1** (R = Ph, X = H) appeared not to undergo the ring opening reaction.
(7) Compounds **2** can be deacylated to the corresponding aminohydrazinothioazetidinones and reacylated to the desired acylamino analogues of **2**, thus extending the synthetic usefulness of these intermediates. M. Foglio, G. Franceschi, P. Masi, and A. Suarato, German Offenlegungsschrift 2 525 510.
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G. Franceschi,* M. Foglio, P. Masi, A. Suarato
G. Palamidessi, L. Bernardi, F. Arcamone
Farmitalia, Ricerca Chimica
Milano, Italy

G. Cainelli
Istituto di Chimica "G. Ciamician"
Università di Bologna
Bologna, Italy

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Free Radical Participation in the Reaction of Metalate Anions with Alkyl Halides[1]

Sir:

The displacement of halides and other groups from alkyl substrates by metalate anions represents one of the most important routes for the formation of metal–carbon σ bonds. The generally high stereoselectivity of these reactions has been widely interpreted as evidence against the intermediacy of free alkyl radicals and in favor of an S_N2 pathway.[2] Other studies, particularly those of Traylor[3] and Kuivila,[4] have suggested the possibility that certain carbon–metal bond-forming reactions, considered to take place by nucleophilic substitution, may proceed by other pathways. Here we wish to describe spectroscopic and chemical evidence establishing that the reaction of certain metalate anions with the more reactive alkyl halides proceeds in substantial part through the intermediacy of free alkyl radicals produced by electron transfer.[5,6]

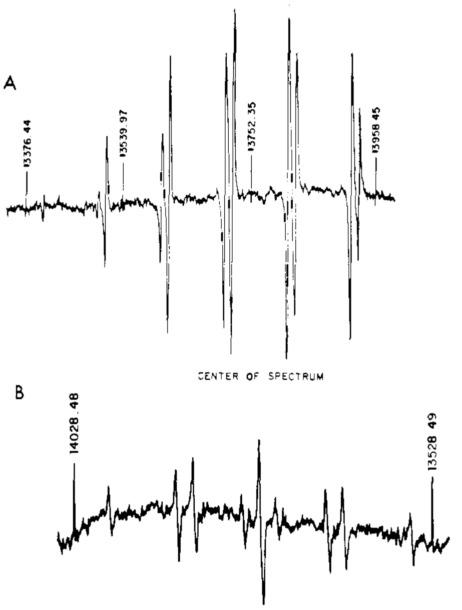
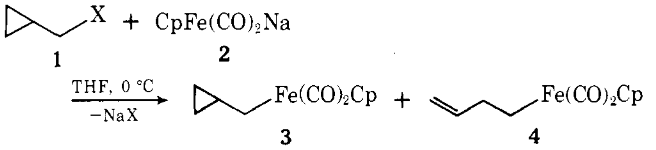


Figure 1. (A) ESR spectrum of the $(CH_3)_2CH$ radical (septet of doublets) obtained by reacting $CpFe(CO)_2Na$ with isopropyl iodide in THF. (B) ESR spectrum of the $CH_2{=}CHCH_2\dot{C}H_2$ radical (triplet of triplets) obtained by reacting $CpFe(CO)_2Na$ with cyclopropylcarbinyl iodide in THF. The proton NMR field markers are in kilohertz.

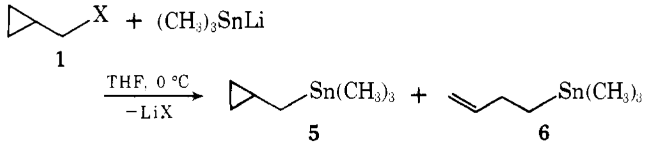
An intense ESR spectrum of isopropyl radicals (Figure 1a) can be detected by mixing at room temperature 0.1 M THF solutions of sodium cyclopentadienyl(dicarbonyl)iron, **2,** and isopropyl iodide in a flat mixing cell of simple design inserted into the ESR cavity so as to minimize the time between mixing and observation. The solutions were contained in 50–100-ml syringes and were driven by a dual syringe pump at a flow rate of about 9 ml/min. Radical concentration increased with increasing flow rates and concentrations of the starting solutions. Similar quality ESR spectra of ethyl, *n*-butyl, *sec*-butyl, and *tert*-butyl radicals were detected in reactions of **2** with the corresponding iodides under similar conditions. While the corresponding bromides and chlorides did not yield detectable concentrations of alkyl radicals, the more stable allyl and benzyl radicals were observed in the reactions of **2** with allyl and benzyl bromides, respectively.[7] Significantly, reaction of **2** with tropylium tetrafluoroborate in THF/acetonitrile gave rise to an intense spectrum of the tropyl radical. No ESR signals attributable to organometallic radical species were observed in the above reactions, presumably because of the combined effects of short lifetimes, low steady-state concentrations, and the broad line widths expected for such species.

The foregoing results are insufficient to establish the extent to which alkyl radicals participate in the principal product-forming reaction, although the high rates of generation required to produce detectable concentrations of such short-lived radicals argue against an insignificant role. Consequently, we have sought chemical evidence which would more quantitatively define the role of radical intermediates in these processes. Thus, the reaction of cyclopropylcarbinyl iodide, **1** (X = I), with sodium cyclopentadienyl(dicarbonyl)iron in THF at 0 °C, followed by an unexceptional workup, produces a 70:30 mixture of cyclopropyl- and allylcarbinyl(cyclopentadienyl)(dicarbonyl)iron, **3** and **4,** respectively, as ascertained by their characteristic H^1 NMR spectra.[8] If this reaction is carried out in the ESR cavity, the spectrum of the allylcarbinyl radical is observed (Figure 1b).[9] By contrast, the reaction of cyclopropylcarbinyl bromide with **2** yields, within the limits of detection (>3%), only **3.**[12]



X = I 70:30
X = Br >97:<3

In a related context we have also examined the reactions of lithium trimethyltin with cyclopropylcarbinyl halides. Again we observe the formation of rearranged product, trimethyl(allylcarbinyl)tin, the extent of formation of which depends, inter alia, on concentration, solvent, temperature, and the nature of the halide group. In all instances, control experiments established that neither **1** nor **3–6** are isomerized under the respective reaction conditions.[13]



X = I $54^a(42)^b:46^a(33)^b$
X = Br 83 (64) :17 (13)
X = Cl 99 (85) :<1(<1)

^{a}relative yield, ^{b}absolute yield

Taken together, these results demonstrate that a substantial fraction of the reactions of $CpFe(CO)_2Na$ and $(CH_3)_3SnLi$ with certain alkyl halides occurs by a pathway involving free alkyl radicals. A reasonable mechanistic interpretation of these data is that *at least one* competing reaction is operating in addition to any direct S_N2 displacement that may be occurring. Specifically, the spectroscopic and chemical results discussed above are consistent with either a reaction path involving an initial one-electron transfer, followed by nongeminate (and presumably also geminate) radical combination processes (Scheme I),[14,15] or a radical chain process[15] (eq 3–4). It follows that a minimum of 30 and 46%, respectively, of the substitution products produced by the reaction of $CpFe(CO)_2Na$ and $(CH_3)_3SnLi$ with **1** (X = I) results from nongeminate radical combinations.[9,16]

Scheme I

$$\begin{tikzcd}
RX + CpFe(CO)_2^- \arrow[r] \arrow[d, "S_N2"] & \overline{R\cdot + X^- + [CpFe(CO)_2]^\cdot} \arrow[d, "k_D"] \arrow[dl, "k_c'"'] \\
RFe(CO)_2Cp + X^- & R\cdot + X^- + [CpFe(CO)_2]^\cdot \arrow[l, "k_c"']
\end{tikzcd}$$

Finally, in the attempt to determine the role of electron transfer in the reactions of the other metalate anions with alkyl halides, we treated several simple alkyl iodides with solutions of $Mn(CO)_5Na$, $CpMo(CO)_3Na$, and $Co(CO)_4Na$ in THF under flow conditions. The fact that no alkyl radicals were detected by ESR is presumably attributable to the slower substitution rates and/or the less negative oxidation potentials observed for these anions,[18] since their treatment under similar conditions with tropylium (0.01 M) and trityl (0.001 M) tetrafluoroborates provides intense spectra of the tropyl and triphenylmethyl radicals, respectively. These results further establish the importance of metal radicals such as $[Mn(CO)_5]^\cdot$, $[CpMo(CO)_3]^\cdot$, $[Co(CO)_4]^\cdot$ and $[CpFe(CO)_2]^\cdot$ as viable reaction intermediates in organometallic reactions.[19] Additional discussion of these and related studies will be presented in future papers.

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(8) (a) Compound **3:** δ (CCl_4) 0.12 (2 H, complex multiplet, cyclopropyl), 0.55 (3 H, complex multiplet, cyclopropyl), 1.43 (2 H, d, $-CH_2Fe$), 4.58 (5 H, s, cyclopentadienyl). Compound **4:** δ (CCl_4) 1.47 (2 H, t, CH_2Fe), 2.23 (2 H, q, allylic CH_2), 4.52 (5 H, s, cyclopentadienyl), 5.02 (2 H, complex multiplet, $C{=}CH_2$), 5.93 (1 H, complex multiplet, $C{=}CH$). (b) A report describing the preparation of compound **3** has appeared without experimental or spectroscopic details: W. P. Giering and M. Rosenblum, *J. Am. Chem. Soc.*, **93,** 5299 (1971).

(9) The rearrangement of the cyclopropylcarbinyl radical to the allylcarbinyl radical has been examined in detail.[10,11] This process is rapid ($k = 1.3 \times 10^8\ s^{-1}$ at 25 °C),[11] but *not* rapid enough to compete with geminate coupling processes.

(10) J. K. Kochi, P. J. Krusic, and D. R. Eaton, *J. Am. Chem. Soc.*, **91,** 1877 (1969).

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(12) This conclusion is consistent with the observation of Whitesides and coworkers (ref 2a) that the reaction of 3,3-dimethyl-*1,2-d₂*-butyl bromide takes place with essentially complete (>95%) inversion of configuration.

(13) Control experiments establish that cyclopropylcarbinyl iodide and bromide are not significantly isomerized during the course of these reactions. Specifically, GLPC analysis of these halides reclaimed from the reaction of $CpFe(CO)_2Na$ and $(CH_3)_3SnLi$ with excess **1** (X = I, Br) indicate $\lesssim$4% isomerization to the corresponding allylcarbinyl halide. The extent of rearrangement of **1** under these conditions is influenced by a number of factors (e.g., concentration and efficiency of mixing) which suggest local concentration effects must be minimized to prevent significant rearrangement of these starting halides. The stability of **3** and **4** and of **5** and **6** under reaction conditions is suggested by the fact that they can be recovered unchanged after treatment with, respectively, $CpFe(CO)_2Na$ and $(CH_3)_3SnLi$.

(14) A similar pathway was suggested by Traylor and co-workers[3] in their study of the reaction of Me_3SnLi with various alkyl halides, but subsequently dismissed in favor of an exchange mechanism involving S_N2 displacement on halogen.[15]

(15) Additional elementary steps as outlined in eq 1–4 cannot be completely dismissed. The exchange reaction (eq 1), originally proposed by Traylor[3] and Kuivila,[4] remains to be established. Under some circumstances eq 2 may be a viable reaction as suggested by the detection of an intense spectrum of the *tert*-butyl radical in the ESR-monitored reaction of *tert*-butyllithium with $CpFe(CO)_2I$.

$$RX + CpFe(CO)_2^- \rightarrow R^- + CpFe(CO)_2X \rightarrow \text{product} \qquad (1)$$

$$R^- + CpFe(CO)_2X \xrightarrow[-X^-]{} R\cdot + [CpFe(CO)_2]^\cdot \rightarrow \text{product} \qquad (2)$$

$$R\cdot + CpFe(CO)_2^- \rightarrow R^- + [CpFe(CO)_2]^\cdot \qquad (3)$$

$$R\cdot + CpFe(CO)_2^- \rightarrow [RFe(CO)_2Cp]^{\cdot -} \xrightarrow[-X^-]{RX} \text{product} + R\cdot \qquad (4)$$

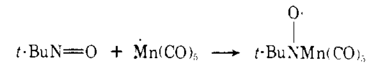
(16) The rearrangement of cyclopropylcarbinyl anion to allylcarbinyl anion has been studied extensively by Roberts and co-workers.[17] These authors report that the rearrangement of cyclopropylcarbinylmagnesium bromide to allylcarbinylmagnesium bromide is a first-order reaction with a half-life in dimethyl ether of 121 min at −24 °C. It follows that the value of the rate constant for this process is $k = 9.5 \times 10^{-5}\ s^{-1}$. In the absence of rate data specific to the rearrangement of the cyclopropylcarbinyl anion under the conditions employed in our study, it is not possible to rigorously exclude the possibility that the rearrangement leading to the allylcarbinyl products

observed in the present investigations do not occur by way of intermediate carbanions such as might be generated by reactions similar to eq 1 and 3. It is important to note, however, that for such a process to be competitive with the rearrangement of the cyclopropylcarbinyl radical would require a minimum increase of $>10^{10}$ in the rate of rearrangement of the cyclopropylcarbinyl anion over that observed for cyclopropylcarbinylmagnesium bromide. While perhaps *not* impossible, an increase of such magnitude seems physically unreasonable under the present circumstances. We, therefore, feel justified in concluding that the rearrangement leading to **4** and **6** occurs essentially exclusively by a free radical pathway.

(17) D. J. Patel, C. L. Hamilton, and J. D. Roberts, *J. Am. Chem. Soc.*, **87,** 5144 (1965), and references therein.

(18) R. E. Dessy, R. L. Pohl, and R. B. King, *J. Am. Chem. Soc.*, **88,** 5121 (1966).

(19) (a) Indirect ESR evidence for the involvement of the manganese pentacarbonyl radical in the above reaction with tropylium cations was obtained by reacting the manganate anion with a mixture of *tert*-nitrosobutane and the tropylium salt in the ESR cavity. An intense spectrum of 18 lines of equal intensity was obtained under flow conditions which is appropriate for the nitroxide adduct 7 ($a^N = 17.39$ G, $a^{Mn} = 12.56$ G, $g = 2.0056$). Control



$$t\text{-BuN}{=}\text{O} + \dot{\text{M}}\text{n(CO)}_5 \longrightarrow t\text{-Bu}\overset{\overset{\text{O}\cdot}{|}}{\text{N}}\text{Mn(CO)}_5$$

7

experiments with each reagent and *tert*-nitrosobutane did not yield nitroxide radicals under the same conditions.

(b) Cf. also A. Hudson, M. F. Lappert, P. W. Lednor, and B. K. Nicholson, *J. Chem. Soc., Chem. Commun.*, 966 (1974).

Paul J. Krusic*
Contribution No. 2439
Central Research and Development Department
E. I. du Pont de Nemours and Company
Wilmington, Delaware 19898

Paul J. Fagan, Joseph San Filippo, Jr.*
Wright and Rieman Chemistry Laboratories
Rutgers, The State University of New Jersey
New Brunswick, New Jersey 08903

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Homogeneous Catalysis by Ruthenium Carbonyl in Alkaline Solution: the Water Gas Shift Reaction

Sir:

Methods of activating the reactions of carbon monoxide have long been a major area of catalysis research.[1] Of particular interest, both from the standpoint of its fundamental chemistry and for its obvious commercial value, is the water gas shift reaction (eq 1).

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad (1)$$

By this process, the reducing equivalents of CO can be converted to the more useable form of molecular hydrogen with relatively little loss in thermochemical potential.[2] Current methods for effecting this conversion involve heterogeneous catalysis at high temperature,[3] and to our knowledge there are no published examples of systems which catalyze this reaction cleanly in homogeneous solution.[4] In considering possible homogeneous catalysts, metal carbonyl complexes are logical candidates given the recent reports that certain coordinated carbonyls are activated toward nucleophilic attack of water.[5] In addition, various metal carbonyl clusters have been shown as homogeneous catalysts in the oxidation and/or reduction of carbon monoxide.[6] In these contexts we are exploring the possible catalysis of the water gas shift reaction by metal carbonyl complexes, and here we describe conditions where a homogeneous solution prepared from triruthenium dodecacarbonyl [$Ru_3(CO)_{12}$] is an active catalyst under relatively mild conditions. It is additionally noteworthy that the catalyst is very active toward decomposition of formate to H_2 and CO_2 under conditions active for the water gas shift reaction.

For a run under typical conditions, the catalysis solution contained the following components in 15 ml of purified ethoxyethanol solvent: $Ru_3(CO)_{12}$ (0.126 g, 2×10^{-4} mol), KOH (~0.5 g, ~0.01 mol), and H_2O (1.0 g, 0.06 mol). When this solution was heated at 100 °C with stirring under 1 atm of carbon monoxide, the initially yellow color of the solution (attributed to the dissolved $Ru_3(CO)_{12}$) changed to a deep red-brown. Periodic sampling of the gaseous phase over the solution (total volume ~320 ml at 25 °C) and analysis by high resolution VPC (Hewlett Packard 5830A programmable GC) demonstrated conversion of the initially pure CO phase to one containing substantial amounts of H_2 and CO_2. Analysis of the gas phase after 73 h gave a composition of 5.6% H_2, 6.5% CO_2, plus 88% CO, while analysis after 144 h gave 10.4% H_2, 8.5% CO_2, plus 77% CO. The latter figures indicate production of ~1.4×10^{-3} mol of H_2 representing 7 mol of H_2 per mole of $Ru_3(CO)_{12}$ initially added. The catalyst maintains an approximately constant activity over this sampling period with no observable changes in appearance. Also, the catalyst activity remains approximately constant or is perhaps slightly enhanced after flushing the system with fresh CO and restarting. (In contrast, carrying out the reaction under a N_2 rather than a CO atmosphere leads to an apparently stoichiometric reaction giving some H_2 and CO_2 but also simultaneous catalyst decomposition to metallic ruthenium.) When the temperature of reaction solutions is raised to 110 °C the rate of H_2 formation is approximately quadrupled over that at 100 °C and a similar increase is noted again for the 10° raise to 120 °C. When the temperature was lowered back to 100 °C the catalyst activity returned approximately to that noted above. Over a period of 30 days the total hydrogen produced by this system equaled ~3×10^{-2} mol, which represents a ratio of 150 mol of H_2 per mole of $Ru_3(CO)_{12}$ initially added or 3 mol of H_2 per mole of KOH added.[7] Notably, the gas phase analyses also indicated trace quantities of a peak with the same retention time as methanol; however, GC analysis of the solvent at reaction conclusion showed no methanol as a solution phase product. Methane, another possible CO reduction product, was not found in either analysis.

The following observations support our conclusion that the described system is a *homogeneous catalyst,* for the water gas shift reaction. (1) The identity of the H_2 product was confirmed by mass spectrometry. (2) When the reaction was carried out with a solution prepared from deuterium exchanged solvent (CH_3OD or $C_2H_5OCH_2CH_2OD$) and D_2O,[8] D_2 (>90%), HD (4–8%), and H_2 (<2%) were the hydrogen products as analyzed by mass spectrometry. This confirms that water or water exchangeable hydrogen is the source of the molecular hydrogen produced and that this hydrogen is not the product of solvent decomposition.[9] (3) Formation of H_2 clearly exceeds the molar quantities of KOH and $Ru_3(CO)_{12}$ added and thus cannot represent the stoichiometric reaction of base with coordinated carbon monoxide. That this system can be catalytic in base undoubtedly results from the fact that under the reaction conditions potassium bicarbonate in ethoxyethanol is unstable and decomposes to CO_2 plus KOH.[10] (4) Lastly, the homogeneity of the reaction solution is indicated by its clarity (no turbidity) when examined visually with a strong light and by the fact that an active catalyst solution displayed the same rate of H_2 production at 110 °C before and after filtration of the catalyst solution through a Fluoropore filter (FHLP, 0.5 μ pore size) under a purified nitrogen atmosphere.

Formate ion or formic acid are potential products or intermediates in a reaction system involving the oxidation of carbon monoxide by water.[4,11] Thus it is of interest to note that the present catalyst solution is very active toward the decomposition of formate to H_2 plus CO_2 (eq 2).

$$HCO_2H \rightarrow H_2 + CO_2 \qquad (2)$$