Homolytic and Ionic Mechanisms in the Ligand-Transfer Oxidation of Alkyl Radicals by Copper(II) Halides and Pseudohalides

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Abstract: The facile oxidation of alkyl radicals by various copper(II) halides and pseudohalides involves the transfer of the ligand from the copper(II) oxidant to the alkyl radicals. Two simultaneous processes are described in which atom transfer occurs primarily *via* a homolytic transition state involving minimal polar character. The competing oxidative substitution proceeds *via* cationic intermediates, and an alkylcopper species similar to those described in oxidative solvolysis during electron-transfer oxidation is proposed. Atom transfer usually prevails during ligand-transfer oxidation with most alkyl radicals, but the cationic route becomes important when alkyl radicals such as cyclobutyl and β-anisylethyl, which afford stabilized carbonium ions, undergo ligand-transfer oxidation. The cationic route can also be promoted by use of dioxane as solvent. The scrambling of carbon atoms in cyclobutyl radicals and isotopic labeling in β-anisylethyl radicals are used as probes for cationic intermediates. In a more general sense, ligand-transfer and electron-transfer categories are superseded by a unified mechanism for the oxidation and reduction of free radicals by metal complexes based on the hard and soft acid–base classification.

A variety of alkyl radicals R· are readily oxidized by copper(II) halides (Cl, Br, I) and pseudohalides (SCN, N_3, CN) by a process which has been described as *ligand transfer.*[1] The relevant reaction involves the transfer of the ligand associated with the metal [copper(II)] to the free radical and concomitant reduction of the metal as given in eq 1. These reactions proceed at

$$R\cdot + Cu^{II}X_2 \longrightarrow R\text{–}X + Cu^{I}X \qquad (1)$$

$$X = Cl, Br, I, SCN, N_3, CN$$

rates which approach the diffusion-controlled limit, having second-order rate constants of 3.6×10^8, 1.1×10^9, and 4.3×10^9 M^{-1} sec^{-1} at 25° for the transfer of thiocyanate, chloride, and bromide, respectively. Iodide, azide, and cyanide can also be efficiently transferred from copper(II) complexes to alkyl radicals. Thus, they can and do form the vital link in a number of catalytic reactions involving copper.[2]

In this report we wish to examine the mechanism of the *ligand-transfer* oxidation of alkyl radicals by copper(II) halides and pseudohalides in the light of our knowledge of the electron-transfer process described in the foregoing paper.[3] The role of carbonium ions as intermediates and the effect of the solvent in ligand-transfer oxidation of alkyl radicals are of particular importance in probing for the mechanism of this interesting process. The oxidations of homoallylic (cyclobutyl, cyclopropylmethyl, and allylcarbinyl) radicals are examined in detail, and factors leading to cationic rearrangement delineated. Finally, deuterium labeling in β-phenethyl and β-anisylethyl radicals establishes a duality of mechanisms, one path homolytic and the other heterolytic in which carbonium ions participate.

The catalytic decomposition of diacyl peroxides by copper complexes represents a method generally adaptable for the production of a variety of alkyl radicals for ligand-transfer studies.[1] For example, the catalytic reaction of propionyl peroxide and copper(II) chloride has been shown to proceed *via* a chain reaction involving the copper(I)–copper(II) redox cycle (X = Cl). The kinetic chain length in these catalytic re-

$$(CH_3CH_2CO_2)_2 + Cu^{I}X \longrightarrow CH_3CH_2\cdot + CO_2 + CH_3CH_2CO_2Cu^{II}X \qquad (2)$$

$$CH_3CH_2CO_2Cu^{II}X + X^- \rightleftharpoons CH_3CH_2CO_2^- + Cu^{II}X_2 \qquad (3)$$

$$CH_3CH_2\cdot + Cu^{II}X_2 \longrightarrow CH_3CH_2X + Cu^{I}X\text{, etc.} \qquad (4)$$

actions is in excess of 20. Other alkyl radicals used in this study were produced by the catalytic decomposition of the appropriate diacyl peroxide.

Results

Oxidation of Neopentyl Radicals by Copper(II) Chloride. Neopentyl radicals were derived in the catalytic decomposition of *tert*-butylacetyl peroxide. The oxidation of neopentyl radicals by copper(II) chloride afforded neopentyl chloride exclusively as shown in Table I. Control experiments showed that *tert*-amyl chloride which was deliberately added prior to the initiation of the reaction could be recovered quantitatively.

Oxidation of Homoallylic Radicals by Copper(II) Halides and Pseudohalides. The allylcarbinyl, cyclobutyl, and cyclopropylmethyl species are designated here as homoallylic radicals. Each of these radicals was derived separately in acetonitrile from the corresponding diacyl peroxide by the catalytic method described above. Independent studies have shown that cyclobutyl and allylcarbinyl radicals did not undergo rearrangement under these conditions.[4] The isomerization of cyclopropylmethyl radical to allylcarbinyl radical, on the other hand, proceeds with a first-order rate constant[5] of at least 1×10^8 sec^{-1}.

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[1] (a) J. K. Kochi and R. V. Subramanian, *J. Amer. Chem. Soc.*, 87, 1508 (1965); (b) C. L. Jenkins and J. K. Kochi, *J. Org. Chem.*, 36, 3095, 3103 (1971.

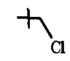
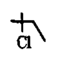
[2] J. K. Kochi, *Rec. Chem. Progr.*, 27, 207 (1966).

[3] C. L. Jenkins and J. K. Kochi, *J. Amer. Chem. Soc.*, **94**, 843 (1972).

[4] J. K. Kochi and A. Bemis, *ibid.*, **90**, 4038 (1968).

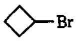
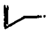
[5] Estimated from the rate of isocholesteryl to cholesteryl rearrangement [D. J. Carlsson and K. U. Ingold, *ibid.*, **90**, 7047 (1968)].

Table I. Reaction of Neopentyl Radicals with Copper(II) Chloride in Acetonitrile at 25°

Reagents, *M*				Products, mol %		
$CuCl_2$	LiCl	CuCl	*tert*-Butyl acetyl peroxide	CO_2		
0.040	0.080	0.010	0.040	97	96	0
0.040	0.080	0.020	0.040	99	85	24[a]

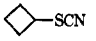
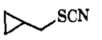
[a] Control experiment, 0.24 mmol (24 mol % based on peroxide) was added prior to reaction.

Table II. Oxidation of Homoallylic Radicals by Copper(II) Bromide[a]

$(RCO_2)_2$, *M*	$CuBr_2$, *M*	Products, mol %			
		CO_2			
	0.100	98	0	97	0
	0.100	95	90	0	0
	0.050	99	30	2.8	65
	0.150	100	0.8	4.6	85

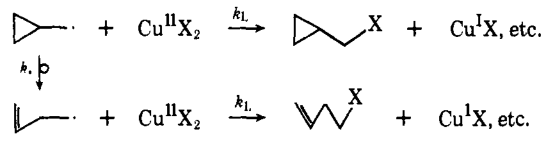
[a] Reactions carried out with 0.06 *M* peroxide contained in 20 ml of propionitrile at 0°.

Table III. Oxidation of Homoallylic Radicals by Copper(II) Thiocyanate[a]

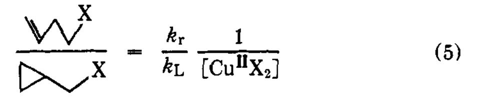
$(RCO_2)_2$	*M*	$Cu^{II}(SCN)_2$, *M*	KSCN, *M*	Products, mol %			
				CO_2			
	(0.040)	0.040	0.200	100	1.0	99	3.8
		0.020	0.080	100	1.7	95	5.1
	(0.040)	0.080	0.200	100	99	0	0
		0.120	0.280	101	99	0	0
	(0.040)	0.040	0.120	98	79	1.2	12
		0.120	0.280	96	64	2.5	25

[a] Reaction carried out with 0.040 *M* peroxide contained in 25 ml of acetonitrile at 0°.

The oxidation of cyclobutyl and allylcarbinyl radicals with copper(II) *bromide* occurred with no rearrangement. Some representative results are given in Table II. The oxidation of cyclopropylmethyl radical by copper(II) afforded predominately cyclopropylmethyl bromide. The smaller amounts of allylcarbinyl bromide were attributable to the isomerization of the radical, the competition from which could be largely overwhelmed by increasing the concentration of copper(II) bromide. A kinetic scheme presented below was based



on a knowledge of this competing first-order rate constant for isomerization. If we assume that k_L for allylcarbinyl and cyclopropylmethyl radicals are approximately the same and the isomerization is irreversible, the relative yields of products may be expressed as



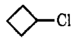
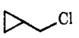
$$= \frac{k_r}{k_L}\frac{1}{[Cu^{II}X_2]} \quad (5)$$

A value of $k_L(Br) = 4.3 \times 10^9 M^{-1} sec^{-1}$ at 25° was obtained.[1] No isomerization of any of the homoallylic bromides occurred under these reaction conditions.

The oxidation of allylcarbinyl radicals by copper(II) thiocyanate proceeded without rearrangement. A similar treatment of cyclobutyl radicals also produced mainly cyclobutyl thiocyanate, but small amounts of the isomeric allylcarbinyl and cyclopropylmethyl thiocyanates were also produced as shown in Table III. The oxidation of cyclopropylmethyl radicals by copper(II) thiocyanate afforded a mixture consisting largely of cyclopropylmethyl and allylcarbinyl thiocyanate, the relative amounts of which were directly determined by the concentration of copper(II) thiocyanate. A quantitative determination of the latter by use of eq 5 led to a value of the second-order rate constant k_L for thiocyanate transfer of $3.6 \times 10^8 M^{-1} sec^{-1}$. Small but discrete amounts of cyclobutyl thiocyanate were also formed. Scrutiny of the reaction showed, however, that no homoallylic isothiocyanates were formed or isomerized under the conditions of the reaction.

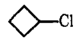
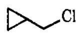
The oxidation of cyclobutyl and allylcarbinyl radicals by copper(II) *chloride*, in contrast to copper(II) bromide or copper(II) thiocyanate, afforded a mixture of homoallylic chlorides representing extensive rearrangement of the structure of the parent radical. *The composition of each mixture was independent of the concentration of the copper(II) chloride.* Some typical results are summarized in Table IV. The composition of the products resulting from the oxidation of cyclopropylmethyl radical was highly dependent on the concentration of copper(II) chloride, and at very low concentrations of copper(II) the isomeric mixture was the same as that obtained from the oxidation of allylcarbinyl radical. It could be shown from studies[1b] carried out at higher concentrations of copper(II) chloride that the oxidation of cyclopropylmethyl radicals also produced the unique mixture of homoallylic chlorides given in eq 8, the composition of which was also independent of the concentration of copper(II) chloride. Kinetic analysis of the type described for bromide and thiocyanate led to a second-order rate constant for chlorine transfer of $k_L(Cl) = 1.1 \times 10^9 M^{-1} sec^{-1}$.

Table IV. Oxidation of Homoallylic Radicals by Copper(II) Chloride[a]

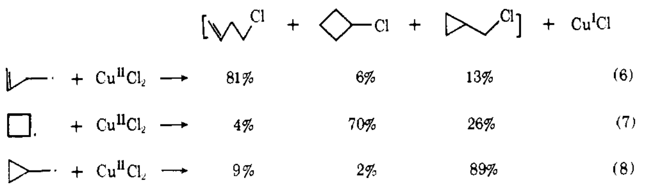
			Products, mol %		Distribution, %		
$(RCO_2)_2$	$Cu^{II}Cl_2$	$Cu^{I}Cl$[b]	CO_2	C_4H_7Cl			
	0.020	0.013	95	91	4	71	25
	0.230	0.057	100	93	5	70	25
	0.040	0.013	89	89	81	6	13
	0.120	0.013	95	92	82	5	13
	0	0.020	95	65	80	6	14
	0.240	0.010	97	88	29	9	62

[a] Reaction carried out with 0.040 M peroxide in acetonitrile at 0°. [b] Initiation by $Cu^{I}Cl$ with an equimolar amount of lithium chloride added.

Table V. Oxidation of Cyclobutyl Radicals by Copper(II) Chloride in Nonaqueous Solutions[a]

	Reactants		Products		Distribution, %		
Solvent	$CuCl_2$, M	LiCl, M	CO_2, %	C_4H_7Cl, %			
Pyridine[b]	0.043	0	96	58	0	100	0
HMPA[c]	0.052	0	99	100	1	86	13
DMSO[d]	0.040	0	103	57	3	83	14
	0.040	0.106	102	56	1	95	4
	0.080	0	98	63	2	84	14
	0.080	0.213	99	87	2	92	6
	0.120	0.320	98	79	0.5	96	3.5
DMF[e]	0.050	0	95	58	2	68	20
HOAc[f]	0.044	0.480	100	71	1	72	24
CH_3CN	0.060	0	99	90	3	70	27

[a] In solutions containing 0.04 M cyclobutanecarbonyl peroxide at 0°. Reactions initiated by 0.01 M copper(I) chloride. [b] With 2.5 vol % acetonitrile. [c] Hexamethylphosphoric triamide with 4% acetonitrile. [d] Dimethyl sulfoxide with 4 vol % acetonitrile. [e] Dimethylformamide with 4% acetonitrile. [f] With 4% acetonitrile.



The oxidation of each homoallylic radical by copper(II) chloride in acetonitrile thus produced a *unique* mixture of homoallylic chlorides characteristic of that radical, and the composition of this mixture was independent of the concentration of copper(II) chloride. Moreover, the predominant isomer in each mixture was that resulting from the intact structure of the precursor radical. Careful study proved that no rearrangement of the products occurred subsequent to their formation. The observed distribution of isomeric homoallylic chlorides shown in eq 6–8 thus resulted from a kinetically controlled oxidation process.

Effect of Solvent on the Oxidation of Cyclobutyl Chloride by Copper(II) Chloride. Since the foregoing studies showed that oxidation of cyclobutyl radicals in acetonitrile produced a mixture of homoallylic chlorides, the medium was varied in order to determine the effect of solvent on the distribution of homoallylic chlorides and its relationship to the mechanism. In fact, cyclobutyl chloride was the only product of oxidation of cyclobutyl radicals by copper(II) chloride when the reaction was carried out in pyridine (Table V). The reaction was slightly less selective in dimethyl sulfoxide (DMSO) and hexamethylphosphoric triamide (HMPA). Acetic acid, acetonitrile, and *N*,*N*-dimethylformamide, despite their different chemical and physical properties, induced approximately the same amount of rearrangement. The stability of cyclobutyl chloride to isomerization was established in each solvent under these conditions.

The specificity of the oxidation of cyclobutyl radicals by copper(II) chloride was enhanced by the addition of lithium chloride. Thus, the selectivity in the formation of cyclobutyl chloride was raised from 83% in the presence of 0.040 M copper(II) chloride to 95% on the addition of 0.106 M lithium chloride in DMSO solutions.

The specificity could also be deliberately *lowered* by the use of 1,4-dioxane or 1,2-dimethoxyethane as the solvent. Copper(II) chloride by itself was insoluble in dioxane and small amounts of water (>2 wt %) were required for dissolution. However, the presence of water in varying amounts caused very little change in the distribution of homoallylic chlorides produced in aqueous dioxane solutions as shown in Table VI. Water alone could not have been responsible for these changes since it had little effect in acetonitrile solutions in amounts up to 16 wt %. At the upper limit of water studied, a mixture of both homoallylic chlorides as well as alcohols was produced. Significantly, the distribution of isomeric homoallylic *alcohols* obtained under these conditions was essentially the same as the composition of the homoallylic *chlorides* produced in dioxane. Furthermore, the mixture of homoallylic chlorides obtained in these aqueous solutions had a slightly higher component of rearranged chlorides than that obtained in pure acetonitrile (Table VI).

Copper(II) Chloride Species in Solution. The absorption spectrum of copper(II) chloride dissolved in various media was examined. The principal absorption bands in the visible region are listed in Table VII. Howald, *et al.*,[6] examined the spectra of mixtures of

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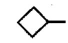
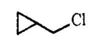
(6) R. P. Eswein, E. S. Howald, R. A. Howald, and D. P. Keeton,

Table VI. Oxidation of Cyclobutyl Radicals by Copper(II) Chloride in Ethereal or Partially Aqueous Solutions[a]

Reactants				Products, %		Distribution		
Solvent	H_2O, wt %	$CuCl_2$, *M*	LiCl, *M*	CO_2	C_4H_7Cl			
Dioxane	2[b]	0.041	0	91		6	55	39
	4[b]	0.045	0	93	74	6	51	43
	4[b]	0.042	0.144	93	82	6	59	35
	4[c]	0.045	0	90		6	52	42
	8[c]	0.044	0	88		6	58	41
	12[c]	0.044	0	87		6	54	40
	16[c]	0.055	0	85		6	54	40
CH_2OCH_3	2[b]	0.049	0	98	84	3	59	38
CH_2OCH_3	2[b]	0.052	0	83	62	3	57	40
CH_3CN	0	0.060	0	99	90	3	70	27
	2	0.040	0	99	84	3	70	27
	4	0.045	0	99	79	3	68	29
	16	0.049	0	101	64	3	63	34
					18[d]	3[d]	52[d]	45[d]

[a] In solutions containing 0.04 *M* cyclobutanecarbonyl peroxide at 0°. Reactions initiated with 0.01 *M* copper(I) chloride. [b] in addition to 2 vol % acetonitrile. [c] In addition to 4 vol % acetonitrile. [d] Alcohols.

Table VII. Visible Spectra of Copper(II) Chloride in Various Solvents

Solvent	Added ligand	λ_{max}, nm	ϵ,[a] M^{-1} cm^{-1}	Principal species
CH_3CN		750	55	$\left\{\begin{matrix} CuCl_2 \\ CuCl_3^- \end{matrix}\right\}$
		462	508	
		312	3620	
CH_3CN	LiCl[b]	465	1580	$\left\{\begin{matrix} CuCl_3^- \\ CuCl_4^{2-} \end{matrix}\right\}$
		315	3750	
HMPA		750	19	
		465 (s)	51	$\left\{\begin{matrix} CuCl_2 \\ CuCl_3^- \end{matrix}\right\}$
		360 (s)	600	
		340	1920	
DMSO		300	3820	$CuCl_2$
DMSO	LiCl[c]	405	1330	$CuCl_{4,3,2}{}^{2-,-,0}$
		300	3170	
Dioxane[d]		750	38.4	$CuL_6{}^{2+}2Cl^-$[e]

[a] Apparent extinction coefficient (*i.e.* absorbance divided by the molar concentration of copper). [b] 2 equiv of LiCl/$CuCl_2$. [c] Excess. [d] Containing 4 wt % water. [e] L = dioxane, water.

copper(II) chloride and lithium chloride in acetonitrile and acetic acid solutions and concluded that the appearance of bands at 375 and 450 nm was due to the tetrachlorocuprate ion. The absorption bands of various analogous chlorocopper(II) complexes have also been described in other solvents. It is apparent from data presented in Table VII that solutions of copper(II) chloride in hexamethylphosphoric triamide, dimethylformamide, pyridine, and dimethyl sulfoxide also consisted predominantly of chlorocopper(II) species.[7] Furthermore, the addition of lithium chloride to a solution of copper(II) chloride promoted the formation of the more highly chlorinated copper(II) species, in accord with expectations based on the mass-action principle.

On the other hand, it was immediately apparent from visual observations that a solution of copper(II) chloride in dioxane consisted of species which were significantly different from the chlorocopper(II) complexes present in those media described above. For example, the latter consisted of dark yellow to green solutions, whereas solutions of copper(II) chloride in either dioxane or dimethoxyethane were almost *colorless*. The difference was further apparent in the visible absorption spectra shown in Figure 1. The similarity of the absorption spectrum of copper(II) chloride in dioxane to that of copper(II) perchlorate in water,[8] as well as the absence of charge-transfer bands[7] (associated with electronic transitions from the chloride ligands to copper), indicates that these are outer sphere complexes of copper(II) chloride.[9] Solvolysis shown in eq 9 was only

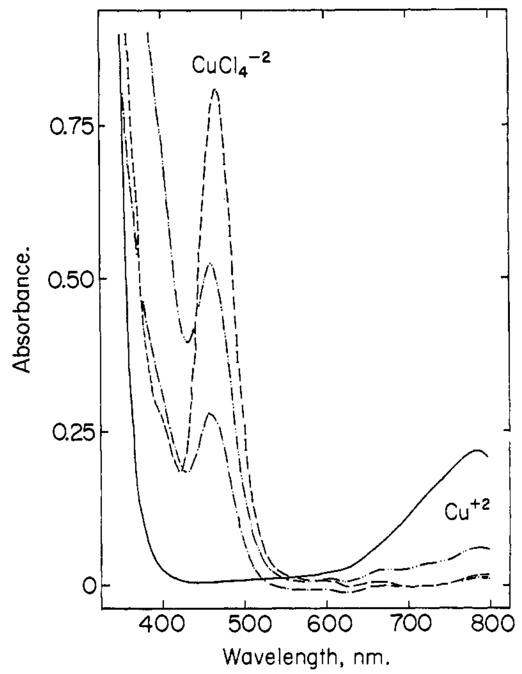


Figure 1. Absorption spectra of 3.95×10^{-3} *M* copper(II) chloride in 96 vol % dioxane–water (——). Comparison with 4.70×10^{-4} *M* copper(II) chloride (—·—) and 9.4×10^{-4} *M* copper(II) chloride (·—··) in acetonitrile. Solution of 4.75×10^{-4} *M* copper(II) chloride and 1.00×10^{-3} *M* lithium chloride (- - -).

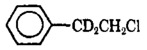
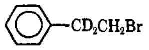
J. Inorg. Nucl. Chem., **29**, 437 (1967); see also R. D. Willet, *et al.*, *Inorg. Chem.*, 6, 1666, 1885 (1967); C. Furlani and G. Morpurgo, *Theor. Chim. Acta*, **1**, 102 (1963).

(7) W. E. Hatfield and R. Whyman, *Transition Metal Chem.*, **5**, 47 (1969); F. Gutmann, *Coord. Chem. Rev.*, **2**, 239 (1967); D. W. Meek, W. E. Hatfield, R. S. Drago, and T. S. Piper, *Inorg. Chem.*, **3**, 841, 1637 (1964); D. Culpin, P. Day, R. Edwards, and R. J. P. Williams, *Chem. Commun.*, 450 (1965)

(8) F. A. Cotton and G. Wilkinson, "Advanced Inorganic Chemistry," second ed, Interscience, New York, N. Y., 1966, p 906.

(9) V. E. Mironow, Yu. A. Makashev, and I. Ya. Mavrina, *Russ. J. Inorg. Chem.*, **14**(5), 746 (1969); M. W. Andreeva and V. G. Khaldin, *ibid.*, **14**(5), 626 (1969).

Table VIII. Oxidation of β-Phenethyl and β-Anisylethyl Radicals by Copper(II) Chloride and Bromide. Effect of Solvents[a]

Radical	CuX_2	Solvent	Product[b,f]		Rearrangement, %
$C_6H_5CD_2CH_2\cdot$	$CuCl_2$	CH_3CN	 100%		0
	$CuCl_2$	Dioxane[c]	100%		0
	$CuBr_2$	CH_3CN	 100%		0
			$C(-Ar)D_2CH_2Cl$	$C(-Ar)H_2CD_2Cl$	
$CH_3OC_6H_4CH_2CD_2\cdot$	$CuCl_2$	CH_3CN	28 (25)	72 (75)	54
	$CuCl_2$	Dioxane[d]	47 (46)	53 (54)	94
			$C(-Ar)D_2CH_2Br$	$C(-Ar)H_2CD_2Br$	
	$CuBr_2$	CH_3CN	6	94	12
	$CuBr_2$	Dioxane[e]	9	91	18

[a] Radicals obtained from copper-catalyzed decomposition of the corresponding hydrocinnamoyl peroxide (0.04 *M*) with 0.045 *M* copper(II) halide and 0.01 *M* copper(I) halide at 0°. [b] Absolute yields of aralkyl halides high but not determined. Values given are relative purity after separation by preparative gas chromatography and analysis by pmr. Values in parentheses determined by d(deuterium)mr. [c] Containing 3 wt % water and 3 wt % acetonitrile. [d] Containing 3 wt % water and 7 wt % acetonitrile. [e] Containing 4 wt % water and 1 wt % acetonitrile. [f] Ar = p-$CH_3OC_6H_4$–.

$$\mathrm{Cu^{II}Cl_2 + 6L \rightleftharpoons Cu^{II}L_6{}^{2+}2Cl^-} \qquad (9)$$

L = dioxane, water

slightly reversed by anation in the presence of excess chloride. Furthermore, hydrolysis was much less important in aqueous acetonitrile solutions than in aqueous dioxane solutions.

Oxidation of Arylethyl Radicals by Copper(II) Chloride and Bromide. Phenonium Ions as Intermediates. Phenethyl and anisylethyl radicals do not isomerize under these conditions.[4,10] The corresponding cations, on the other hand, are known to undergo extensive rearrangement to equilibrate the α- and β-carbon atoms.[11] These aralkyl radicals have been successfully employed to probe for carbonium ion intermediates in the previous study of electron-transfer oxidation by copper(II) actate.[12]

The oxidation of phenethyl and anisylethyl radicals was examined in this study with copper(II) chloride and bromide as oxidants in acetonitrile and in dioxane. The oxidation of β,β-dideuterio-β-phenethyl radical by either copper(II) chloride or bromide afforded no evidence of rearranged products being formed in acetonitrile or in dioxane. Excellent yields of only β,β-dideuterio-β-phenethyl chloride and bromide were obtained in the presence of copper(II) chloride and bromide, respectively, as shown in Table VIII.

On the other hand, the oxidation of α,α-dideuterio-β-anisylethyl radicals under the same conditions gave significant amounts of products of rearrangement. Thus, the oxidation of α,α-dideuterio-β-anisylethyl radical by copper(II) chloride in acetonitrile afforded a mixture of dideuterio-β-anisylethyl chlorides containing 26% deuterium label in the β position. The same oxidation in dioxane produced 94% rearrangement. Analysis of the isomeric mixture by proton magnetic resonance spectroscopy gave the same results as those obtained from the examination of the deuterium magnetic resonance spectra. Oxidation of α,α-dideuterio-β-anisylethyl radicals by copper(II) bromide produced only 12% rearrangement in acetonitrile. Slightly more rearrangement (18%) was observed when the oxidation with copper(II) bromide was carried out in dioxane solutions.

Rearrangement of the β-arylethyl moiety during oxidation thus depended on both the copper(II) halide as well as the solvent, since β-phenethyl radical afforded no products of rearrangement. The oxidation of β-anisylethyl radical, however, led to a 12% scrambling of the α and β carbon atoms during oxidation by copper bromide in acetonitrile and 18% scrambling when the same oxidation was carried out in dioxane. Similarly, the equilibration of the side chain was extensive (52%) when the oxidation of β-anisylethyl radical was carried out by copper(II) chloride in acetonitrile and almost complete (94%) when carried out in dioxane.

Discussion

The ligand-transfer oxidation of alkyl radicals by metal complexes presents several interesting mechanistic questions. Thus, the reactivity of alkyl radicals in atom-transfer processes, particularly those involving hydrogen and halogen, are well-known phenomena in the area of free-radical chemistry.[13] The importance of polar effects in the transition states of some atom-transfer processes has been described, but carbonium ions are not intermediates in these processes.[14] On the other hand, the role of copper(II) in wholly inorganic redox processes[15] can be described both in terms of inner sphere and outer sphere mechanisms.[16] The first ques-

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(12) J. K. Kochi, A. Bemis, and C. L. Jenkins, *J. Amer. Chem. Soc.*, 90, 4616 (1968).

(13) W. A. Pryor, "Free Radicals," McGraw-Hill, New York, N. Y., 1966, p 149ff; C. Walling, "Free Radicals in Solution," Wiley, New York, N. Y., 1957.

(14) E. S. Huyser, "Free Radical Chain Reactions," Wiley-Interscience, New York, N. Y., 1970, p 77ff.

(15) F. Basolo and R. G. Pearson, "Mechanisms of Inorganic Reactions," Wiley, New York, N. Y., 1967, p 543ff.; O. J. Parker and J. H. Espenson, *J. Amer. Chem. Soc.*, **91**, 1313, 1968 (1969); **89**, 5730 (1968); *Inorg. Chem.*, 7, 1619 (1968).

(16) H. Taube, *Chem. Rev.*, **50**, 69 (1950); *Advan. Inorg. Radiochem.*, **1**, 1 (1959); A. G. Sykes, *ibid.*, **10**, 394 (1967).

tion we pose, therefore, is whether carbonium ions are intermediates in the ligand-transfer oxidation of alkyl radicals by copper(II) chloride.

Carbonium Ions as Intermediates in Ligand Transfer. The facile oxidation of alkyl radicals by various copper(II) halides and pseudohalides involves the transfer of a ligand from the copper(II) oxidant to the alkyl radical. *Free* carbonium ions as such are not intermediates since the transfer of chloride, bromide, iodide, thiocyanate, azide, and cyanide can be effected in protic media such as acetic acid without direct intervention of the external nucleophile.[1] However, cationoid intermediates are not necessarily precluded, since the subtleties of reactions occurring from ion pairs can exclude direct participation of solvent, as studies of the solvolysis of alkyl derivatives have shown.[17]

A much more sensitive probe for the participation of carbonium ions along the reaction coordinate is provided by the study of alkyl moieties prone to cationic rearrangement. Three such systems have been employed in this study: neopentyl, homoallylic, and β-arylethyl radicals. A comparison of these alkyl radicals shows that the contribution from a cationic pathway varies with both the alkyl moiety as well as the copper(II) oxidant. Thus, ligand-transfer oxidation of neopentyl radical occurs with *no evidence of rearrangement*, since *tert*-amyl derivatives are absent.[4] On the other hand, homoallylic systems represented by cyclobutyl, allylcarbinyl, and cyclopropylmethyl are more susceptible to cationic rearrangement.[18] The predominant product obtained from the oxidation of each homoallylic radical by copper(II) chloride in acetonitrile was that isomeric chloride resulting from the radical with the structure intact. That is, cyclobutyl radical afforded principally cyclobutyl chloride, allylcarbinyl radical gave largely allylcarbinyl chloride. Even cyclopropylmethyl radical produced mainly cyclopropylmethyl chloride, provided the copper(II) chloride concentration was sufficiently high. In every case, the by-product from the oxidation of each isomeric radical was a mixture of the other two homoallylic chlorides.

Oxidation of each homoallylic radical by copper(II) bromide and by copper(II) thiocyanate gave similar results, although the amount of rearrangement varied appreciably with the copper(II) oxidant. The approximate extent of rearrangement accompanying ligand-transfer oxidation of each homoallylic radical by various copper(II) complexes in acetonitrile is summarized in Table IX.

Homoallylic cations are implicated as the precursors for the rearranged products, since the distributions of the isomeric by-products from the ligand-transfer oxidations of all of the homoallylic radicals shown in Tables II–IV are characteristic of the results obtained in solvolytic studies of these systems.[18,19] Furthermore, any isomerization of the alkyl radical precursors has been taken into account in these results.

Table IX. Rearrangement Resulting from Ligand-Transfer Oxidation of Homoallylic and Neopentyl Radicals by Copper(II) Complexes[a]

$Cu^{II}X_2$	Relative rate[b]	Homoallylic radical, %			Neopentyl radical, %
					
$Cu^{II}Br_2$	12	0	0	<1	
$Cu^{II}Cl_2$	3	20	50	15	0
$Cu^{II}(NCS)_2$	1	0	5	3	

[a] The extent of arrangement extrapolated from Tables II–VI. [b] $[Cu(NCS)_2]$ = 1.0.

The contribution of a polar substituent effect in promoting the cationic pathway is obtained by comparing the ligand-transfer oxidation of β-phenethyl and β-anisylethyl radicals. Isotopic labeling allows the examination of carbonium ion intermediates in this system, since complete equilibration of the α and β carbons invariably results from a phenonium ion intermediate.[12] Solvolysis studies show that an even greater driving force for cation formation in the form of the bridged anisonium ion is provided by the presence of a *p*-methoxy group.[20] Rearrangement accompanying ligand transfer is summarized in Table X, which shows that a significantly greater driving force for the cationic path is, indeed, derived from the oxidation of β-anisylethyl radical compared to β-phenethyl radical.

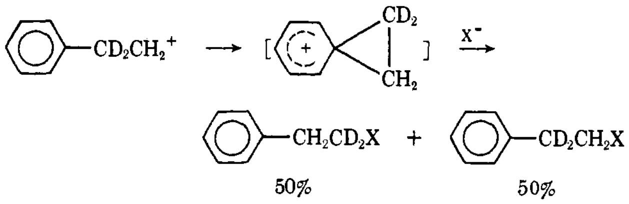

Table X. Contribution from the Cationic Path in the Ligand-Transfer Oxidation of β-Arylethyl Radicals in Acetonitrile

$Cu^{II}X_2$	Rearrangement, %	
	$C_6H_5CD_2CH_2\cdot$	$CH_3OC_6H_4CH_2CD_2\cdot$
$Cu^{II}Cl_2$	0	54
$Cu^{II}Br_2$	0	12

Dual Mechanisms in Ligand-Transfer Oxidation. These studies show that two modes of oxidation occur during ligand-transfer oxidation of alkyl radicals by copper(II) halides and pseudohalides. One pathway involves *direct conversion* of the alkyl radical (R·) to the substitution product (RX). The other more *indirect route* generates a carbonium ion of sufficient integrity somewhere along the reaction coordinate to undergo complete equilibration of the α- and β-carbon

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(17) (a) S. Winstein, B. Appel, R. Baker, and A. Diaz, *Chem. Soc., Spec. Publ.*, No. **19**, 109 (1965); (b) S. G. Smith and J. P. Petrovich, *J. Org. Chem.*, **30**, 2882 (1965); H. L. Goering, *et al.*, *J. Amer. Chem. Soc.*, **92**, 7401 (1970); **93**, 1224 (1971); A. Ceccon, A. Fava, and I. Papa, *ibid.*, **91**, 5547 (1969); L. A. Spurlock and W. G. Cox, *ibid.*, **93**, 146 (1971).

(18) R. Breslow, "Molecular Rearrangements," Part I, P. de Mayo, Ed., Interscience, New York, N. Y., 1963, p 254ff; G. A. Olah and P. v. R. Schleyer, "Carbonium Ions," Wiley, New York, N. Y., 1969.

(19) *Cf.* M. Hanack and A. J. Schneider, *Angew. Chem., Int. Ed. Engl.*, **6**, 666 (1967); R. Moss and F. Shulman, *Tetrahedron*, **24**, 2881 (1968); *J. Amer. Chem. Soc.*, **90**, 2731 (1968); Z. Majerski, S. Borcic, and D. E. Sunko, *Tetrahedron*, **25**, 301 (1969); K. L. Servis and J. D. Roberts, *J. Amer. Chem. Soc.*, **87**, 1331 (1965); P. v. R. Schleyer and G. W. Van Dine, *ibid.*, **88**, 2321 (1966); K. L. Servis and J. D. Roberts, *Tetrahedron Lett.*, 1369 (1967); H. G. Richey and J. M. Richey, *J. Amer. Chem. Soc.*, **88**, 4971 (1966). A common intermediate is not necessarily implied. See I. Lillien and L. Handloser, *ibid.*, **93**, 1682 (1971); *J. Org. Chem.*, **33**, 3841 (1968); **34**, 3658 (1969); P. v. R. Schleyer and Z. Majerski, *J. Amer. Chem. Soc.*, **93**, 665 (1971); D. D. Roberts, *J. Org. Chem.*, **36**, 1913 (1971).

(20) W. H. Saunders, S. Asperger, and D. Edison, *J. Amer. Chem. Soc.*, **80**, 2423 (1958); G. A. Olah, M. Comisarow, E. Namenworth, and B. Ramsey, *ibid.*, **89**, 711 (1967).

atoms of the β-anisylethyl moiety and extensive scrambling of the carbon atoms in the homoallylic precursors. Stabilization of the alkyl cation in these systems plays an important role in the indirect route, since the neopentyl and β-phenethyl analogs show no tendency to afford carbonium ion intermediates under the same conditions.

The results of ligand-transfer oxidation of the series of neopentyl, homoallylic, and β-arylethyl radicals given here are in sharp contrast to the electron-transfer oxidation of the same radicals previously examined under comparable conditions. In every example pertaining to the electron-transfer oxidation of these alkyl radicals, *oxidative solvolysis invariably led to complete cationic rearrangement of the alkyl moiety.* Thus, electron-transfer oxidation of neopentyl radicals afforded only products derived from the *tert*-amyl cation.[4] Similarly, oxidative substitution of the β-phenethyl radical by copper(II) acetate led to complete equilibration of the α- and β-carbon atoms.[12] Finally, the oxidation of cyclobutyl radicals under the same conditions produced the same mixture of extensively rearranged homoallylic acetates derived by other cationic processes.[4]

The partial cationic rearrangement observed during the ligand-transfer oxidation of certain alkyl radicals and the absence of rearrangement in others indicate that at least two processes are operative (*cf.* Tables IX and X). The extent of rearrangement, furthermore, is invariant with the concentration of the copper(II) halide or pseudohalide, but highly dependent on the structure of, and the ligand associated with, the copper(II) nucleus. These results are inconsistent with competition from a kinetically first-order process. We propose that the *direct* and *indirect* pathways in ligand-transfer oxidation are represented by independent simultaneous second-order processes. The direct process is described as *atom transfer* and the indirect route is represented as *oxidative substitution*. These mechanisms will be elaborated further.

The Role of Oxidative Substitution in Ligand-Transfer Processes. Ligand-transfer oxidation proceeding *via* a pathway represented as *oxidative substitution* is given by eq 10 and 11, in which copper(II) chloride is used

$$\mathrm{R}\cdot + \mathrm{CuCl_2} \rightleftharpoons \underset{\mathrm{I}}{\mathrm{RCuCl_2}}$$ (10)[21]

$$\mathrm{I} \rightleftharpoons \mathrm{RCuCl^+Cl^-} \longrightarrow \mathrm{R{-}Cl} + \mathrm{Cu^ICl}$$ (11)

for illustrative purposes. The formation of a carbonium ion intermediate by this route is accommodated by a metastable alkylcopper species I akin to that presented earlier in connection with electron-transfer processes (see the preceding paper).[3]

According to this formulation, the formation of carbonium ion intermediates leading to ligand transfer is promoted by ionization of the alkylcopper intermediate I. Evidence for ionization of copper(II) complexes is obtained from an examination of the absorption spectra. Thus, the visible absorption spectrum of copper(II) chloride shows that it exists in dioxane as an outer sphere complex (see Figure 1). In strong contrast, inner sphere chlorocopper(II) species are prevalent in acetonitrile.[22]

$$\mathrm{CuCl_2} \underset{}{\overset{\text{dioxane}}{\rightleftharpoons}} \mathrm{Cu^{2+}\ 2Cl^-} \tag{12}$$

$$\mathrm{CuCl_2} \overset{\mathrm{CH_3CN}}{\rightleftharpoons} \mathrm{Cu^{2+}\ 2Cl^-} \tag{13}$$

The formation constants of chlorocopper(II) have not as yet been measured in dioxane. However, aqueous solutions form a reasonable approximation since the visible absorption spectrum of copper(II) chloride is virtually the same in dioxane as in water. The formation constants of inner sphere chlorocopper(II) species also differ markedly in acetonitrile and in water as shown in Table XI.

Table XI. Formation Constants of Inner Sphere Chlorocopper(II) Species in Acetonitrile, Water, and Methanol

Equilibrium	K_1 formation constant[a] CH$_3$CN	CH$_3$OH	H$_2$O
$\mathrm{Cu^{II} + Cl^- \rightleftharpoons Cu^{II}Cl^+}$	$K_1 = 10^{9.7}$	$10^{4.2}$	1.0
$\mathrm{Cu^{II}Cl^+ + Cl^- \rightleftharpoons Cu^{II}Cl_2}$	$K_2 = 10^{7.9}$	$10^{6.6}$	0.2
$\mathrm{Cu^{II}Cl_2 + Cl^- \rightleftharpoons Cu^{II}Cl_3^-}$	$K_3 = 10^{7.1}$		0.04
$\mathrm{Cu^{II}Cl_3^- + Cl^- \rightleftharpoons Cu^{II}Cl_4^{2-}}$	$K_4 = 10^{3.7}$		0.01

[a] From ref 22a, d, and e.

The ionization of the metastable chloroalkylcopper intermediate I should be promoted by dioxane much like the chlorocopper(II) species themselves. Copper(II) complexes are, in general, highly substitution labile

$$\mathrm{RCuCl_2} \overset{\text{dioxane}}{\rightleftharpoons} \mathrm{RCuCl^+Cl^-} \tag{14}$$

and anation should not place kinetic restraints on the reactivity of the alkylcopper species. The coordinatively unsaturated cationic alkylcopper species are subject to heterolysis of the alkylcopper bond in a manner reminiscent of the previously described oxidative substitution in electron-transfer oxidation[3] and demercuration of alkylmercurinium cations.[23]

$$\mathrm{RCuCl^+} \longrightarrow \mathrm{R^+Cu^ICl,\ etc.} \tag{15}$$

Extensive cationic rearrangement of the cyclobutyl moiety during ligand-transfer oxidation of cyclobutyl radicals by copper(II) chloride in dioxane is consistent with this formulation. A qualitative comparison of the importance of the cationic (oxidative substitution) route in acetonitrile and dioxane is presented in Table XII. The same phenomenon can be evaluated quan-

Table XII. Promotion of Oxidative Substitution by Solvent in Ligand-Transfer Oxidations

Radical	Cu^{II}X$_2$	Solvent	Cationic rearrangement, %
	$\mathrm{Cu^{II}Cl_2}$	CH$_3$CN	~50
	$\mathrm{Cu^{II}Br_2}$	CH$_3$CN	0
	$\mathrm{Cu^{II}Cl_2}$	Dioxane	~100
$\mathrm{CH_3OC_6H_4CH_2CD_2\cdot}$	$\mathrm{Cu^{II}Cl_2}$	CH$_3$CN	54
	$\mathrm{Cu^{II}Cl_2}$	Dioxane	94
	$\mathrm{Cu^{II}Br_2}$	CH$_3$CN	12
	$\mathrm{Cu^{II}Br_2}$	Dioxane	18

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(21) All of the coordination around the copper nucleus is not included explicitly, unless required for the discussion.

(22) (a) S. E. Manahan and R. T. Iwamoto, *Inorg. Chem.*, 4, 1409 (1965); (b) see also C. C. Hinckley, *ibid.*, 7, 396 (1968); (c) R. Meyers and R. D. Willet, *J. Inorg. Nucl. Chem.*, 29, 1546 (1967); (d) J. Bjerrum, *Kem. Maanedsbl. Nord. Handelsblad Kem. Ind.*, 26, 24 (1945); (e) S. E. Manahan and R. T. Iwamoto, *J. Electroanal. Chem.*, 13, 411 (1967).

(23) F. R. Jensen, R. Ouellette, G. K. Knutson, D. Babbe, and R. Hartgerink, *Trans. N. Y. Acad. Sci.*, 30 (2), 751 (1968).

Table XIII. Rates of Ligand-Transfer Oxidation by Copper(II) Halides and Pseudohalides

Radical	Copper(II)	k_r/k_L	k_L[a]	k_L (relative)[b]
5-Hexenyl	$Cu^{II}(NCS)_2$	3.9×10^{-4}	2.6×10^8	1
Cyclopropylmethyl	$Cu^{II}(NCS)_2$	2.7×10^{-1}	3.6×10^8	
5-Hexenyl	$Cu^{II}Cl_2$	$<4 \times 10^{-4}$	$>2 \times 10^8$	3
Cyclopropylmethyl	$Cu^{II}Cl_2$	9.2×10^{-2}	1.1×10^9	
5-Hexenyl	$Cu^{II}Br_2$	$<4 \times 10^{-4}$	$>2 \times 10^8$	12
Cyclopropylmethyl	$Cu^{II}Br_2$	2.3×10^{-2}	4.3×10^9	

[a] At 25° assuming $k_r = 1 \times 10^5$ sec^{-1} for 5-hexenyl radical and 1×10^8 sec^{-1} for cyclopropylmethyl radical in units of M^{-1} sec^{-1}. [b] $k[Cu(NCS)_2] = 1.0$.

titatively by examining the ligand-transfer oxidation of isotopically labeled β-anisylethyl radical. The magnitude (both absolute and relative) of the solvent effect shown in Table XII is also more marked with copper(II) chloride than bromide.

The similarity between the pathways involving oxidative substitution in ligand transfer and oxidative solvolysis in electron transfer is shown by the oxidation of cyclobutyl radicals with copper(II) chloride in aqueous acetonitrile (Table VI). The homoallylic alcohols formed under these conditions represent oxidative solvolysis. The composition of this mixture of isomeric alcohols is strikingly similar to the mixture of homoallylic chlorides obtained from the ligand-transfer oxidation of cyclobutyl radicals by copper(II) chloride in dioxane. The transition states for the reaction of the cyclobutyl moiety with water or chloride during these oxidative processes are, no doubt, related to similar alkylcopper species.

The Role of Atom Transfer in Ligand-Transfer Processes. The alternate route available in ligand-transfer oxidation is represented as *atom transfer* in eq 16. The transition state for atom transfer is free

$$R\cdot + Cu^{II}Cl_2 \longrightarrow [R\cdots Cl\cdots CuCl]^{\ddagger} \longrightarrow R\text{-}Cl + Cu^{I}Cl \quad (16)$$

radical in nature, and polar effects are small. Thus, even alkyl radicals with electron-withdrawing α substituents such as cyano, carbonyl, and halogen are readily oxidized by copper(II) chloride.[24a] The same radicals are, by and large, inert to electron-transfer oxidants.[24b] Furthermore, the microscopic reverse process is represented by the direct transfer of a halogen atom from an alkyl halide to chromium(II),[25] and

$$R\text{-}X + Cr^{II} \longrightarrow R\cdot + Cr^{III}X \quad (17)$$

a kinetic study of the reduction of substituted benzyl halides shows no polar effect.[26] The atom-transfer mechanism is, thus, an example of a more general inner sphere process involving a bridge-activated complex. A classic example of the latter is represented in eq 18.[16,27]

$$(NH_3)_5Co^{III}Cl + Cr^{II} \longrightarrow [(NH_3)_5Co\cdots Cl\cdots Cr]^{\ddagger} \longrightarrow (NH_3)_5Co^{II} + Cr^{III}Cl, \text{ etc.} \quad (18)$$

An atom-transfer mechanism, of course, also bears a direct relationship to chain-transfer reactions of alkyl radicals with a variety of halogen compounds.[13,14,28]

Rates of Ligand-Transfer Oxidation of Alkyl Radicals. The ligand-transfer oxidations of alkyl radicals by copper(II) halides and pseudohalides are characterized by their extremely high rates. Competitive kinetic studies based on the isomerization of 5-hexenyl and cyclopropylmethyl radicals provide results which are in remarkable agreement with one another,[1] considering a variation in rates of a factor of 10^3. The second-order rate constants, k_L, for the ligand-transfer oxidation of copper(II) radicals by copper(II) thiocyanate, chloride, and bromide are summarized in Table XIII.

The values of k_L, however, represent a composite of a number of individual rate constants k_i for various copper(II) species: $k_L[CuCl_2] = k_1[CuCl^+] + k_2[CuCl_2] + k_3[CuCl_3^-] + k_4[CuCl_4^{2-}]$. For example, the various chlorocopper(II) species represented in Table XI are present in appreciable amounts in acetonitrile solutions. At this juncture it is impossible to separate the specific rate constant k_i by which each of these chlorocopper(II) species oxidizes an alkyl radical. If the composite value of k_L listed in Table XIII includes all of these species, it is reasonable to expect that some values of k_i (particularly for $CuCl_4^{2-}$) may actually be at the diffusion-controlled limit since even the value of k_e for oxidative elimination by copper(II) acetate is in the range of 10^6–10^7 M^{-1} sec^{-1}.[12,29]

Summary

Atom Transfer *vs.* Oxidative Substitution in Ligand-Transfer Processes. In ligand-transfer oxidations, the atom-transfer mechanism (eq 16) is generally the energetically more favorable process and usually represents the major course of reaction. The alternative pathway involving oxidative substitution (eq 10 and 11) by virtue of the formation of carbonium ion intermediates is more applicable to alkyl radicals capable of forming stabilized carbonium ions. Although solvents such as dioxane promote oxidative substitution, the effect is apparent in the ligand-transfer oxidation of only radicals such as cyclobutyl and β-anisylethyl, in which the competition between atom transfer and oxidative substitution is already delicately balanced. Thus, oxidative substitution cannot be promoted in neopentyl and phenethyl radicals by solvent changes, and only atom transfer prevails.

For a given alkyl radical, the relative importance of atom transfer and oxidative substitution pathways also depends on the ligand involved. For example, the ligand-transfer oxidation of cyclobutyl radicals by copper(II) bromide occurs only by atom transfer (Table IX). On the other hand, as much as 50% of the oxidation of cyclobutyl radicals by copper(II) chloride takes place by oxidative substitution. Copper(II) thiocya-

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(24) (a) J. K. Kochi and F. F. Rust, *J. Amer. Chem. Soc.*, **84**, 3946 (1962); J. Kumamoto, H. E. DelaMare, and F. F. Rust, *ibid.*, **82**, 1935 (1960); C. H. Bamford, A. Jenkins, and R. Johnston, *Proc. Roy. Soc., Ser. A*, **239**, 214 (1957); (b) J. K. Kochi and D. M. Mog, *J. Amer. Chem. Soc.*, **87**, 522 (1965).

(25) J. K. Kochi and J. W. Powers, *ibid.*, **92**, 137 (1970).

(26) J. K. Kochi and D. D. Davis, *ibid.*, **86**, 5264 (1964).

(27) H. Taube and H. Meyers, *ibid.*, **76**, 2103 (1954); H. Taube, H. Meyers, and R. C. Rich, *ibid.*, **75**, 4118 (1953).

(28) D. F. DeTar and D. V. Wells, *ibid.*, **82**, 5839 (1960); L. O. Moore, *J. Phys. Chem.*, **75**, 2075 (1971).

(29) J. K. Kochi and R. V. Subramanian, *J. Amer. Chem. Soc.*, **87**, 4855 (1965).

nate occupies an intermediate position. The same general trend of $Cu^{II}Br > Cu^{II}NCS > Cu^{II}Cl$ in atom-transfer processes is also established with cyclopropylmethyl and allylcarbinyl radicals.

The competition between atom transfer and oxidative substitution is summarized in Scheme I.

Scheme I. Mechanisms of the Ligand-Transfer Oxidation

Atom transfer (direct)

$$R\cdot + Cu^{II}X_2 \longrightarrow [R\text{---}X\text{---}CuX]^{\ddagger} \longrightarrow R\text{-}X + Cu^{I}X$$

Oxidative substitution (alkylcopper intermediate)

$$R\cdot + Cu^{II}X_2 \rightleftharpoons RCuX_2$$

$$RCuX_2 \rightleftharpoons RCuX^{+}X^{-} \rightleftharpoons R^{+}\,Cu^{I}X_2^{-}$$

$$R^{+}Cu^{I}X_2^{-} \longrightarrow R\text{-}X + Cu^{I}X$$

A Unified View of Ligand-Transfer and Electron-Transfer Oxidations of Alkyl Radicals. In a more general sense, the oxidation of alkyl radicals by copper(II) oxidants transcends the relatively arbitrary classification into electron-transfer and ligand-transfer categories, which are based largely on stoichiometry. For example, a distinction between the analogous metastable alkylcopper intermediates leading to (1) oxidative solvolysis in electron transfer and (2) oxidative substitution during ligand transfer cannot be clearly made. In each, the ionization of the ligand plays an important role in the formation of carbonium ion intermediates.

A more unified and general classification of the mechanisms of oxidation of free radicals by metal complexes may be made by considering the position at which the metal complex is attacked by the free radical. Within the present context, for example, the reaction of alkyl radicals with copper(II) complexes by attack on the ligand leads to atom transfer, a process which is largely free radical or homolytic in nature. On the other hand, attachment of the alkyl radical to the copper(II) nucleus results in an alkylcopper intermediate which can be subsequently partitioned in a variety of ways including (1) oxidative elimination to afford alkenes, (2) oxidative substitution to form an alkyl derivative from the ligand,[30] and (3) oxidative solvolysis by participation of the solvent.

Central to this mechanistic classification is the ability of the free radical to discriminate among several sites on the metal complex. We propose as a working hypothesis for further study that such a distinction be based on the hard and soft acid-base classification proposed by Pearson and others.[31]

Ligands and alkyl radicals are listed in Table XIV qualitatively in *order of descending hardness*. The horizontal dashed line represents the border region above which alkyl radicals react with copper(II) complexes by attachment to the copper nucleus. Below the dashed line, reaction occurs primarily on the ligand and an-atom transfer (inner sphere) mechanism prevails. Attack on ligand and attachment to copper are competitive with the chloro ligand which lies in the borderline region.

Table XIV. Hard and Soft Acid-Base Classification of the Oxidation of Alkyl Radicals by Cupric Complexes

	$Cu^{II}(X_2)(L)_4$		Alkyl radical
	X^-(anion)	L(neutral)	
Perchlorato	ClO_4^-	Water	Methyl
Triflato	$CF_3SO_3^-$	Acetonitrile	Ethyl
Fluoroborato	BF_4^-	1,4-Dioxane	*n*-Butyl
Trifluoroacetato	$CF_3CO_2^-$	Pyridine	Isopropyl
Acetato	$CH_3CO_2^-$	2,2′-Bipyridine	*sec*-Butyl
Chloro	Cl^-	Phenanthroline	*tert*-Butyl
Thiocyanato	SCN^-	Acetic acid	Benzyl
Bromo	Br^-	Dimethyl sulfoxide	Allyl
Iodo	I^-	Dimethylformamide	

Alkyl radicals can be similarly placed on a hardness scale, which increases from benzyl and allyl radicals to tertiary, secondary, and primary alkyl radicals and finally to methyl radical itself. The mode of reaction between a given alkyl radical and a copper(II) complex would then be determined by their relative positions on these scales. The extension of these concepts to the oxidation and reduction of other free radicals and metal systems would be desirable.

Experimental Section

Materials. Reagents and chemicals used in the previous study have been described[1] and others are given below.

Copper(II) Thiocyanate. Cupric sulfate pentahydrate (0.5 mol) was dissolved in 750 ml of water and potassium thiocyanate (1.0 mol) was added slowly with rapid stirring under an argon blanket. The black precipitate was filtered and washed twice with ethanol and three times with ethyl ether. The material was then dried overnight in a vacuum oven at 50° (20 mm) giving a 63% yield of $Cu(NCS)_2$. The copper content was determined by electrodeposition. *Anal.* Calcd for $Cu(NCS)_2$: Cu, 35.4. Found: Cu, 37.4.

Solutions of copper(I) chloride, bromide, and acetate in acetonitrile were prepared by simply allowing the copper(II) salt and copper metal to react in a closed vessel fitted with a rubber septum. The resulting copper(I) solution was standardized by reaction with an excess of acidic ferric chloride solution and then titrating the ferrous produced with cerium(IV) to a ferrous phenanthroline end point.

Homoallylic Halides. Samples of allylcarbinyl, cyclobutyl, and cyclopropylcarbinyl chlorides and bromides were generously donated by Dr. H. Lin.[32]

Allylcarbinyl Thiocyanate. To 15.6 g of toluenesulfonyl chloride (0.083 mol) in 30 ml of pyridine was added 4 g of allylcarbinyl alcohol at 0°. The reaction was stirred for 3 hr and then poured into an ice-water mixture and extracted with methylene chloride. After, the extract was washed successively with dilute sulfuric acid, sodium bicarbonate, and water. After drying, the solvent was removed at room temperature by rotary evaporation to yield 10.2 g of yellow oil (allylcarbinyl tosylate). This yellow oil (10.1 g) was added to 15 g of potassium thiocyanate in 200 ml of reagent grade acetone and refluxed for 2 hr. After the work-up described for 5-hexenyl thiocyanate,[1b] distillation yielded 1.5 g of allylcarbinyl thiocyanate; bp 82–83° (25 mm). The product was confirmed by its infrared and pmr spectra.

Cyclopropylcarbinyl Thiocyanate.[33] By the procedure described for allylcarbinyl thiocyanate, 10 g of cyclopropylcarbinyl alcohol reacted with 40 g of toluenesulfonyl chloride to yield 27 g of cyclopropylcarbinyl tosylate. Reaction of 20 g of cyclopropylcarbinyl tosylate with 43 g of potassium thiocyanate was carried out at room temperature. After the work-up (see 5-hexenyl thiocyanate), distillation resulted in a mixture boiling over a wide range (45–90°

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(30) Oxidative substitution in the ligand-transfer oxidation of alkyl radicals by copper(II) halides and pseudohalides is akin to a similar process for the formation of methyl acetate from the electron-transfer oxidation of methyl radicals by copper(II) acetate (see preceding paper). The relationships among oxidative solvolysis and oxidative displacement in electron transfer and oxidative substitution in ligand transfer are intertwined, but not yet completely clear.

(31) R. G. Pearson, *Science*, **151**, 172 (1966); *J. Amer. Chem. Soc.*, 85, 3533 (1963); S. Arhland, J. Chatt, and N. R. Davies, *Quart. Rev., Chem. Soc.*, **12**, 265 (1958); M. M. Jones and H. R. Clark, *J. Inorg. Nucl. Chem.*, 33, 413 (1971).

(32) *Cf.* G. A. Olah and C. H. Lin, *J. Amer. Chem. Soc.*, **90**, 6468 (1968).

(33) L. A. Spurlock and P. E. Newallis, *Tetrahedron Lett.*, 303 (1966).

(22 mm)). Approximately 1 g of material boiling at 89–90° (22 mm) was collected, and the pmr spectrum indicated that it was predominately of cyclopropylcarbinyl structure. By means of preparative gc on a 9-ft 20% FFAP column at 100°, 53 mg of material was obtained which was confirmed by pmr and infrared spectroscopy to be cyclopropylcarbinyl thiocyanate.

Cyclobutyl Thiocyanate. Cyclobutanol (10.5 g) was prepared from cyclopropylcarbinol and allowed to react with 40 g of toluenesulfonyl chloride in 80 ml of pyridine at 0° by the procedure described for allylcarbinyl thiocyanate to afford 31 g of cyclobutyl tosylate. To 26 g of potassium thiocyanate in 150 ml of reagent grade acetone 26 g of cyclobutyl tosylate was added and refluxed for 12 hr. After the work-up (see 5-hexenyl thiocyanate), 5 g of crude material was obtained. Analysis by gas chromatography (11-ft XF1150 at 150°) gave the following composition of products: allylcarbinyl isothiocyanate, 1.4%, cyclobutyl isothiocyanate, 7.5%, cyclopropylmethyl isothiocyanate, 8.3%, allylcarbinyl thiocyanate, 14.5%, cyclobutyl thiocyanate, 23.5%, cyclopropylmethyl thiocyanate, 44.5%. A pure sample of cyclobutyl thiocyanate was obtained by preparative gas chromatography on a 9-ft XF1150 column at 130°. The structure was confirmed by infrared and pmr analysis.

Homoallylic Isothiocyanates. Each of the homoallylic isothiocyanates was prepared by reaction of the corresponding amine with carbon disulfide by the method of Hodgkins and Ettlinger.[34] Cyclobutylamine was generously donated by Dr. L. Friedman. Each of the amines gave isomerically pure material by gas chromatography, pmr, and infrared analysis.

Hydrocinnamic-β,β-d_2 Acid. Ethyl benzoate (0.225 mol) was reduced with 0.119 mol of lithium aluminum deuteride (E. Merck AG, 99% min D) in ethyl ether to yield 0.14 mol (62% yield) of benzyl-α,α-d_2 tosylate *via* the sodium salt.[35] Pmr spectrum of the tosylate showed no resonances at τ 5 characteristic of the benzyl protons. Sodium diethylmalonate (0.15 mol) was benzylated in 70 vol % dimethyl sulfoxide–ethanol by addition of benzyl tosylate (0.13 mol) to a solution containing a 200% excess of diethyl malonate. After work-up, distillation yielded 26 g of diethyl benzylmalonate-d_2 boiling at 108–113° (1 mm). It was then saponified by treating diethyl benzylmalonate with 2.2 equiv of aqueous potassium hydroxide at 100° for 3 hr, acidified with dilute sulfuric acid, and decarboxylated by heating at 100° for 2 hr. The acid was then extracted with pentane and on crystallization afforded 8 g of hydrocinnamic-β,β acid, mp 47.8–48.2° [lit.[37] mp 48.6°]. The pmr spectrum in carbon tetrachloride showed aromatic resonance (τ 2.9) and the broadened α-methylene protons (τ 7.4). The integrated intensities of aromatic to methylene were 5:2 and no resonances for the benzyl protons. The acid was also analyzed for deuterium by combustion followed by the falling drop method.[37] *Anal.* Calcd for $C_9H_8D_2O$: C, 71.0; H, 5.3; D, 2.7. Found: C, 71.5; H, 5.5; D, 2.6; 1.96, 1.99 atoms of D/molecule. *p*-Methoxyhydrocinnamic-α,α-d_2 acid was described previously.[4]

Preparation of Diacyl Peroxides. A solution of 1.1 equiv of pyridine and 50 ml of diethyl ether was cooled to −10°, and 0.55 equiv of 30% hydrogen peroxide was added portionwise so that the temperature did not exceed 0°. The solution was stirred rapidly and the acid chloride (1.0 equiv) added dropwise, maintaining the temperature between −5° and −10°. The reaction was stirred an additional 2 hr at 0°, after which it was neutralized with a small amount of chilled 10% sulfuric acid (throughout the work-up the solution is *not allowed to warm above 10°*). The reaction was diluted with ether and the peroxide extracted after flooding with excess ice–water. The solution was diluted further with pentane, and washed with chilled 10% sulfuric acid, 10% sodium bicarbonate, and distilled water. The pentane–ether extract was dried and concentrated on a rotary evaporator with the aid of a water aspirator. Final traces of solvent were removed by use of a vacuum pump. (The flask was always maintained in an ice bath throughout the evaporation.) The diacyl peroxide was also made directly from the carboxylic acid and anhydrous hydrogen peroxide in the presence of dicyclohexylcarbodiimide by the method of Greene and Kazan.[38] Diacyl peroxides were analyzed by infrared spectroscopy and showed characteristic doublets at 1780 and 1800 cm^{-1}. The purity was further determined by iodometric titration using ferric chloride (0.02% solution) as a catalyst. Peroxides were not used unless their purity exceeded 98%.

The General Procedure for Reaction. The copper(II) complex and any other additives were dissolved in the appropriate solvent contained in a 125-ml Erlenmeyer flask. The diacyl peroxide was then added from a standard solution by means of a glass pipet. The flask was capped with a rubber septum and flushed with a stream of helium for approximately 15 min to remove any oxygen from the system. The appropriate copper(I) species in solution was then added by means of a hypodermic syringe through the rubber septum to initiate the decomposition. The reactions were then run until carbon dioxide was liberated completely.

General Reaction Procedure for Copper(II) Bromide and Thiocyanate. The copper(II) complex and additives, if any, were dissolved in the appropriate solvent. The 125-ml Erlenmeyer flask was then capped with a rubber septum and the solution flushed with helium for approximately 15 min to remove oxygen. A solution of the diacyl peroxide was added by means of a hypodermic syringe. The reaction was then run until carbon dioxide was no longer evolved.

Analysis. All gaseous and liquid products were analyzed by standard gas chromatographic procedures using the internal standard method. In all cases standard solutions or standard gas samples were prepared, and calibrations of products against the internal standard were determined under reaction conditions. Carbon dioxide, methane, ethane, and ethylene were determined on a 2-ft Porapax Q (150–200 mesh) column at room temperature by gas chromatography using thermal conductivity detectors. Gaseous hydrocarbons were determined on a 15-ft column of 15% Dowtherm A on firebrick or a 20-ft column of 20% silver nitrate and 25% benzonitrile on Chromosorb W. The analyses for liquid products were performed by removing an aliquot of the reaction mixture and an aliquot of the internal standard solution to a separatory funnel. Excess water was added and the organic products were extracted with an appropriate solvent, usually ethyl ether or pentane. The extract was then washed several times with water and 10% sodium bicarbonate to remove the solvents (usually acetonitrile). In those cases where the products were soluble in water the reaction mixture was analyzed directly by adding an aliquot of the internal standard to an aliquot of the reaction mixture. Possible interference in the analysis from the presence of copper salts was carefully checked.

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