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Activation and Oxidative Functionalization of Alkanes by Metal Complexes in Protic Media[1]

E. G. Chepaikin

Institute of Structural Macrokinetics and Material Sciences, Russian Academy of Sciences,
Chernogolovka, Moscow oblast, 142432 Russia

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Abstract—Examples and mechanisms of activation and oxidative functionalization of alkanes in the presence of metal-complex catalysts in protic media are considered. Special attention is given to methane as the main component of natural gas.

INTRODUCTION

The interest of researchers in the activation and conversions of alkanes, especially methane, in the presence of metal-complex catalysts was aroused in the mid-1960s. At that time Halpern pointed to the fact that the most challenging task of homogeneous catalysis is C–H bond activation in alkanes [1]. Halpern's claim followed a report by Chatt on the possibility of intramolecular activation of C–H in the CH_3 group of a phosphine ligand in a ruthenium complex with tetramethyldiphosphinoethane and the oxidative addition of naphthalene to this complex [2].

Currently the activation and functionalization of methane is the most topical. Methane is the main component of natural gas, which is the least reactive of all alkanes. The cost of transporting methane to consumers is another concern because of its very unfavorable critical conditions ($t_{cr} = -82.5°C$, $P_{cr} = 45.8$ atm). Moreover, methane has a rather low energy density (1344 kJ/l at 5 MPa and 25°C) compared to methanol (15834 kJ/l under standard conditions). Therefore, methane conversion into liquid oxygenates near methane fields and their transport would create considerable benefits.

Alkane activation and functionalization by metal complexes were considered in monographs [3–6] and review papers, including some recent ones [7–17].

An analysis of the literature data makes it possible to formulate possible mechanisms of C–H bond activation in saturated hydrocarbons:

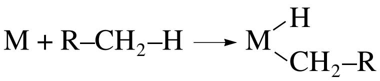
(1) Electrophilic substitution:

$$M{-}X + R{-}CH_2{-}H \longrightarrow M{-}CH_2{-}R + HX.$$

Because alkanes do not possess nucleophilic properties, A.E. Shilov proposed calling this mechanism dissociative [3].

In this case, the remaining group should be as electrophilic as possible because the oxidation state of a metal is high, whereas the leaving group should possess the least possible complex-formation properties.

(2) Oxidative addition:



$$M + R{-}CH_2{-}H \longrightarrow M\begin{cases}H\\ CH_2{-}R\end{cases}$$

This reaction is thermodynamically unfavorable and several factors have positive effects: a metal should be in a low oxidation state and coordinatively unsaturated. It is better when the C–H bond belongs to a ligand. In this case, the stimulating factor is the formation of a metallacycle. Thermal or photochemical generation of coordinatively unsaturated species is also possible.

(3) Homolytic cleavage of the metal–metal bond in the corresponding binuclear complexes, which is a specific case of oxidative addition:

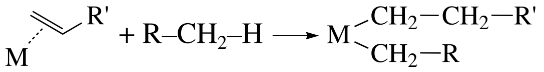
$$M{-}M \longrightarrow 2M^{\bullet} \xrightarrow{R-CH_2-H} M{-}CH_2{-}R + M{-}H.$$

(4) Metathesis:

$$M{-}R' + R{-}CH_2{-}H \longrightarrow M{-}CH_2{-}R + R'{-}H.$$

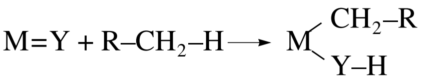
This is a thermally neutral reaction.

(5) Elimination of the thermodynamic constraint by hydrogen transfer onto the coordinated olefin:



$$M\cdots(CH_2{=}CH{-}R') + R{-}CH_2{-}H \longrightarrow M\begin{cases}CH_2{-}CH_2{-}R'\\ CH_2{-}R\end{cases}$$

(6) 1,2–Addition of alkanes to a multiple M=Y bond.



$$M{=}Y + R{-}CH_2{-}H \longrightarrow M\begin{cases}CH_2{-}R\\ Y{-}H\end{cases}$$

The =Y group may be $=CR'_2$, =O, =N–R', or some other.

(7) Oxene mechanism, which is typical of biocatalysts and several model systems:

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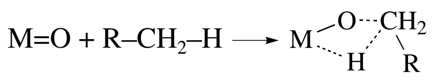
[1] Dedicated to the memory of E.A. Grigoryan.



(8) One-electron mechanisms, which consist in the abstraction of a hydrogen atom by a metal in a high oxidation state:

$$M^{n+} + R\text{–}CH_2\text{–}H \longrightarrow M^{(n-1)+} + H^+ + RC\dot{H}_2$$

The reactive alkyl reacts with the medium and gives some products. These processes are usually unselective.

1. TWO-ELECTRON PROCESSES WITHOUT THE PARTICIPATION OF MOLECULAR OXYGEN

1.1. Stoichiometric Reactions

Let us consider several examples of stoichiometric two-electron oxidation of alkanes by transition metal compounds in protic media. Thus, Sen *et al.* reported that $Pd(OAc)_2$ oxidizes methane to methyltrifluoroacetate (MTFA) in the medium of trifluoroacetic acid (TFAA) at 80°C and 5.6 MPa with 60% yield based on Pd [18]. Unfortunately, other authors (Moiseev and coworkers [19, 20] and Gol'dsheger and co-workers [21]) failed to reproduce these data. It was assumed that this is due to the presence of unknown admixtures [20]. It was considered in [21] that the yield of MTFA in [18] might be due to the oxidation of acetic acid formed in the reaction of $Pd(OAc)_2$ with the medium. Also, it was shown that methane can be oxidized by cobalt(III) trifluoroacetate with a yield of 90 ± 10% based on the oxidant at $T = 150\text{–}190°C$ and $P_{CH_4} = 3.0\text{–}3.5$ MPa in the mixture of TFAA. Under these conditions iron(III) and copper(II) trifluoroacetates were inefficient, whereas manganese(III) and lead(IV) trifluoroacetates produced MTFA with yields of 30 ± 5 and 10 ± 3%, respectively, based on the metal oxidation equivalent [19, 20]. It is important that, in the case of cobalt trifluoroacetate, methyltrifluoroacetate is completely stable, and CO_2 is probably formed by TFAA decarboxylation. At the time these data were published no other selective partial oxidation of methane was known [20].

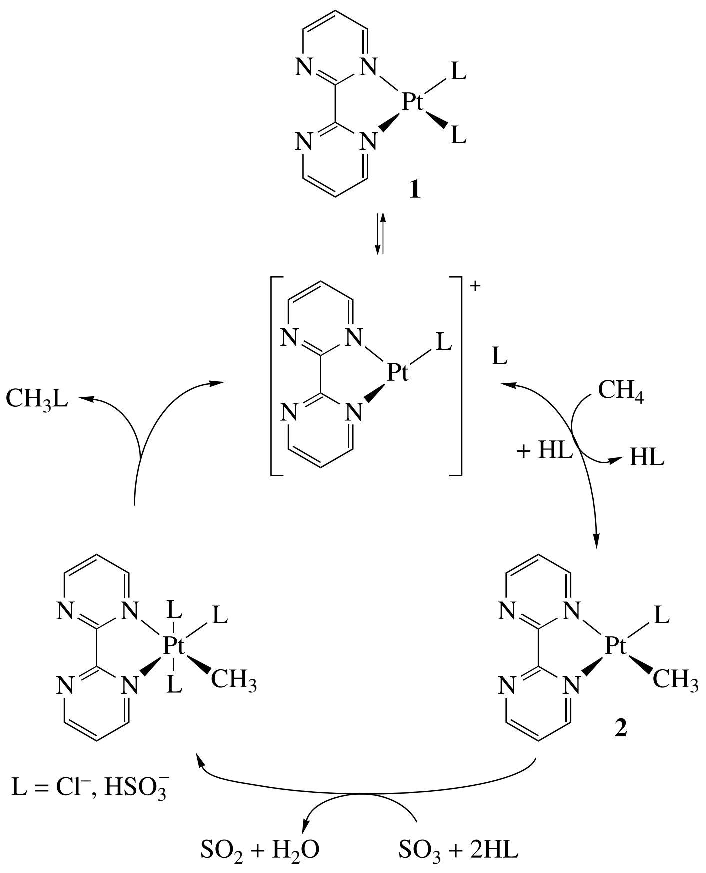
It was reported in [21] that $Pt_2(O_2CCF_3)_6$, $Pt(O_2CCF_3)_4$, $Pt(O_2CCF_3)_2$, and $Rh(O_2CCF_3)_3$ oxidize methane in the medium of TFAA with an MTFA yield of 0.5–5.0% at 70–150°C and 5–10 MPa for several hours. Other products were metal blacks, CO_2, and CH_3F. It was assumed that TFAA enhances the electrophilic properties of oxidants by favoring the primary interaction with the C–H bond in methane.

1.2. Catalytic Reactions

In 1967, Garnet and Hodges found that platinum(II) salts catalyze deuterium exchange with the medium in aromatic compounds in $CH_3COOD\text{–}D_2O$ [22]. Somewhat more recently A.E. Shilov and co-workers showed for the first time that methane activation and catalytic deuterium exchange are possible in this system [23]. They further established that methane catalytically converts into methyl chloride and methanol in the system Pt(II)–Pt(IV)–H_2O–CH_3COOH [24]. Under conditions of deuterium exchange, the addition of Pt(IV) leads to the oxidation of acetic acid into chloroacetic acid [23, 24].

After the first studies by A.E. Shilov and co-workers, the platinum system was studied by several research groups. The results of these efforts were published in a number of monographs and review papers cited above. Some of them consider possible mechanisms of platinum system action in detail, which are now called "Shilov chemistry." In the Pt(II)–Pt(IV) system, the catalyst for methane activation and functionalization is Pt(II), while Pt(IV) plays the role of an oxidant. It has been proven that a methyl complex of Pt(II), which is initially formed, is then oxidized to Pt(IV) due to electron transfer possibly through chloride bridges. The Pt(IV) methyl complex gives CH_3Cl by reductive elimination and methanol under the action of water. The $CH_3Pt(IV)$ fragment was found by ^{1}NMR (δ = 3.04 ppm) upon methane interaction with the $PtCl_6^{2-}$–$PtCl_4^{2-}$ system at $P \approx 10$ MPa for 30 min and a further drastic decrease in the temperature [26]. However, the *in situ* study of this system in a sapphire ampule under methane pressure did not show the presence of the $CH_3Pt(IV)$ complex [27]. There is no common opinion on the step of C–H bond activation. It is reasonable to assume that the alkane associates with the coordinatively unsaturated Pt(II) complex. In this associate, a carbon atom is closer to Pt(II) than hydrogen atoms. The associated methane is deprotonated by water with the formation of $CH_3Pt(II)$ [28]. According to the discoverers of this system, the process of methane activation may begin as the oxidative addition of CH_4 to Pt(II) and end with the synchronous formation of CH_3–Pt(II) and the formation of a proton and chloride ion [4]. The simple oxidative addition of methane is thermodynamically very unfavorable, and the mechanism of electrophilic substitution contradicts the process kinetics [25].

1.2.1. Sulfuric acid oxidation. A great contribution to the kinetic and mechanistic studies of alkane activation was made by Rudakov and co-workers [6, 28]. Specifically, they showed that alkane oxidation in sulfuric acid is catalyzed by mercury(II) salts with the intermediate formation of alkylmercury bisulfate $RHgOSO_3H$. More recently [29] it was reported that methane is also oxidized in this system at 180–210°C and 3.4 MPa. It was assumed that at the first step methane forms a complex with the coordinatively unsaturated cation $[Hg(OSO_3H)]^+$. Then this intermediate transforms into methylmercury bisulphate by electrophilic substitution. The latter is formed at room temperature, but at 180°C it transforms into methyl bisulfate. Thus, the overall process can be described by the equation



Scheme 1.

$$CH_4 + 2H_2SO_4 \xrightarrow{Hg(II)} CH_3OSO_3H + 2H_2O + SO_2. \quad (I)$$

A Pt(II) complex with 2,2'-dipyrimidine (bpym) appeared to be more efficient [30]. It is interesting that this complex (**1**, Scheme 1) is very stable in sulfuric acid. At a methane conversion of 90%, the yield of methyl bisulfate is 73% for 2.5 h under the following conditions: P_{CH_4} = 3.4 MPa, 220°C, $[Pt(bpym)Cl_2] \approx$ 0.6 M in 102% H_2SO_4. The main by-product is CO_2. The specific activity of the catalyst is not high and is ~3.6–8.4 mol (mol Pt)$^{-1}$ h^{-1}. The authors assumed that the reaction mechanism corresponds to Scheme 1.

The key intermediate is the Pt(II) methyl complex (**2**). By contrast to the methylmercury derivative, which is relatively stable in H_2SO_4 (several days at room temperature), complex **2** steadily evolves methane under these conditions. However, it was possible to detect complex **2** by ^{1}NMR spectroscopy. Under the conditions of the catalytic reaction (T = 180–220°C), methane is evolved instantaneously.

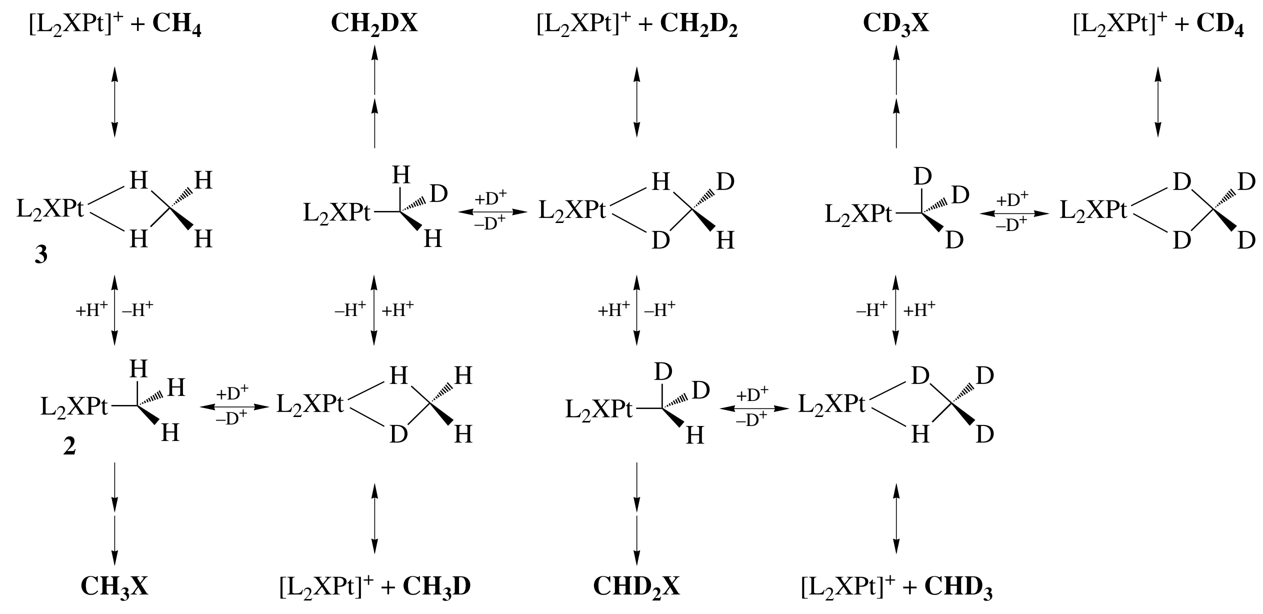
In a medium of D_2SO_4 in the presence of complex **2** at room temperature, multiple deuterium exchange of methane was observed and occurred according to Scheme 2.

Note that the high stability of the catalyst is due to the high affinity of bpym to platinum. In the presence of bpym under catalytic conditions, even metallic platinum is dissolved via the reaction

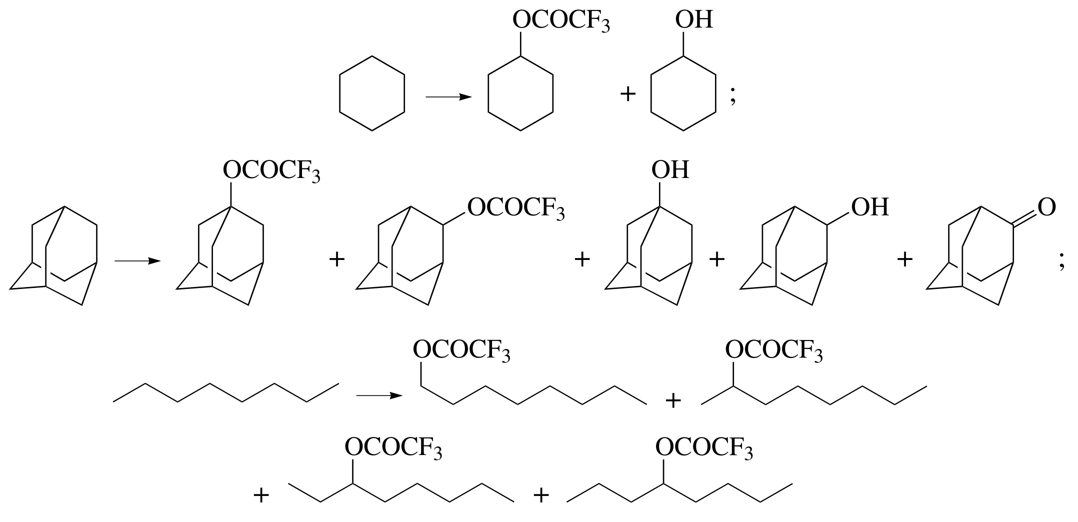
$$\begin{aligned} &Pt(0) + bpym + 3H_2SO_4 \\ &\longrightarrow (bpym)Pt(HSO_4)_2 + SO_2 + 2H_2O. \end{aligned} \quad (II)$$

Concerning the step of methane activation, the authors cannot distinguish oxidative addition with further fast deprotonation and electrophilic substitution. However, one should bear in mind that a radical mechanism is possible in sulfuric acid and oleum in the presence of the one-electron oxidants to which Hg(II) belongs [9, 31].

1.2.2. Oxidation of hydrogen peroxide and its equivalents. In 1991 Sen *et al.* Reported that $Pd(OAc)_2$ in a solution of TFAA with the additives of its anhydride catalyzes methane oxidation by hydrogen peroxide at 90°C and 61 MPa [32]. Reaction products are methanol and MTFA with an overall yield of 4 mol/mol Pd for 25 h. Isotopic labels were used to show that a small amount of MTFA is formed from the acetate ligand according to the reaction



Scheme 2.

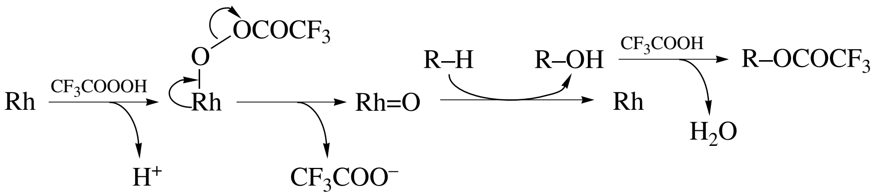


Scheme 3.

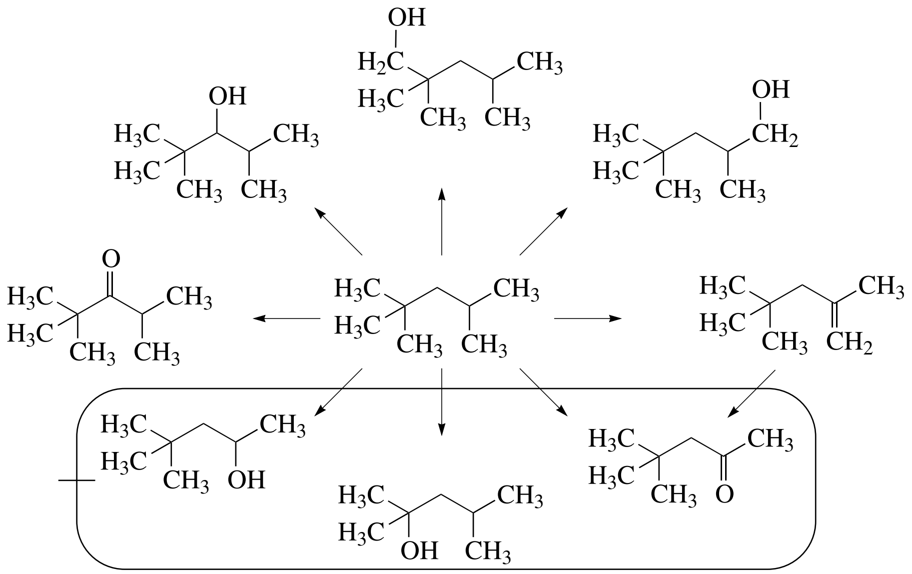
$$\mathrm{Pd(O_2CCD_3)_2} \xrightarrow{\mathrm{H_2O_2,\,(CF_3CO)_2O}} \mathrm{CD_3C(O)OOC(O)CF_3} \xrightarrow{-\mathrm{CO_2}} \mathrm{CD_3OC(O)CF_3}. \qquad \text{(III)}$$

According to the authors, the oxidant is pertrifluoroacetic acid formed from H_2O_2 and TFAA in the presence of trifluoroacetic anhydride. The reaction mechanism includes the electrophilic substitution of hydrogen in a methane molecule. This is confirmed by the results of *p*-xylene oxidation, in which an attack on the aromatic ring is 100 times more efficient than an attack on the benzyl group. Moreover, the oxidation of *cis*- and *trans*-1,2-dimethylcyclohexane occurs with complete retention of configuration. Cyclohexane, *n*-octane, and adamantane are oxidized in an analogous manner in the presence of the H_2O_2–TFAA system [33]. Various compounds of Rh, Pd, Ru, Pt, and Fe were studied as catalysts. The highest activity was seen in the case of μ-oxotrirhodium acetate $[Rh_3O(OAc)_6(H_2O)_3]OAc$. For two days at 25°C, cyclohexane formed cyclohexanol and cyclohexyl trifluoroacetate in a ratio of ~1 : 40 with an overall turnover number of ~1900. Octane mostly forms all the three isomeric secondary trifluoroacetates

$$H_2O_2 + CF_3COOH \longrightarrow CF_3COOOH + H_2O,$$



Scheme 4.



Scheme 5.

in approximately equal amounts. Adamantane reacts so that ketone is formed together with alcohols and ethers (Scheme 3).

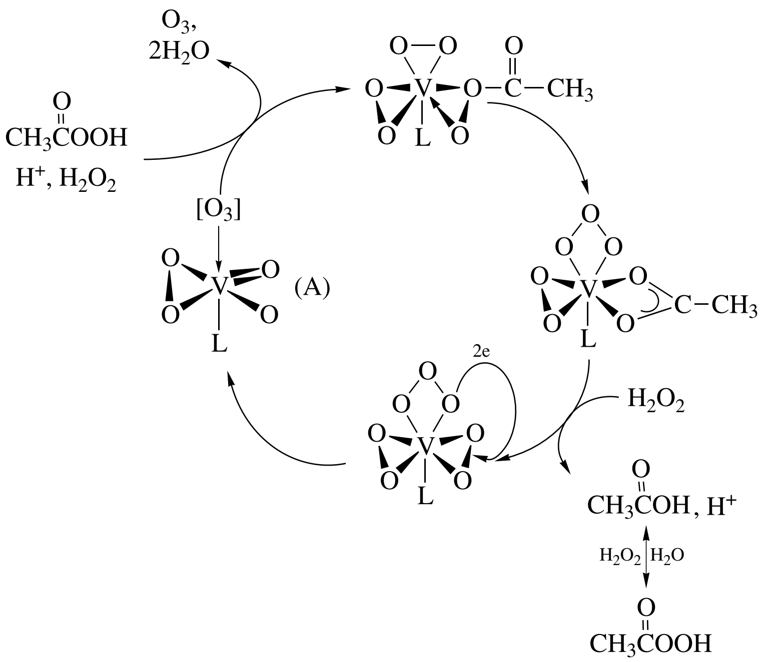
It is assumed that the process mechanism (Scheme 4) includes the activation of alkanes on the rhodium oxo complex.

In the catalytic systems that model enzymatic oxidation, various equivalents of hydrogen peroxide were used: iodobenzene, hypochlorites, *N*-oxides of alkylamines, organic hydroperoxides [4, 7, 8, 14]. The dissociation energy of these reactants with the elimination of an oxygen atom is in the interval of 30–60 kcal/mol, which is much lower than the corresponding value for molecular oxygen (104 kcal/mol).

Alkane oxidation by hydrogen peroxide in the presence of transition metals usually occurs via a one-electron mechanism. However, according to I.I. Moiseev and co-authors, the use of metals with a d^0-nonbonding configuration switches such oxidation to the routes of two- and four-electron oxidation of alkanes with the formation of alcohols and ketones. Thus, it was shown that, in the absence of ligands that stabilize V(IV), one-electron reduction of V(V) by hydrogen peroxide is not the main reaction pathway even in a solution of acetic acid [34]. Cyclohexane, *n*-alkanes C_5–C_{20}, branched alkanes C_6–C_8, and methyl esters of fatty acids C_8–C_9 and cyclohexanecarboxylic acid were chosen for the study. It was found that the conversion and the yield of oxidation products increase with an increase in $[H_2O_2]$. Only nonterminal C–H bonds in normal alkanes are oxidized to form alcohols and ketones, and alcohols are not the intermediates in ketone formation. Note that in this case, as well as in the cases considered below, ionol and *p*-benzoquione do not affect the process regularities. This fact points to the molecular pathway of the reactions studied. It is interesting that it has been well established that isoalkanes are oxidized with C–C bond breaking. Thus, isoocatane oxidation occurs via Scheme 5.

Thus, methyl groups at tertiary and quarternary carbon atoms are oxidatively abstracted from the initial molecules, but it remains unclear which of the products are formed from the mentioned methyl groups.

The oxidation of methyl esters of *n*- and *iso*-carboxylic acids of an acyclic series and cyclohexanecarboxylic acid usually occur with the partial cleavage of C–C

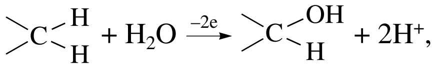


Scheme 6.

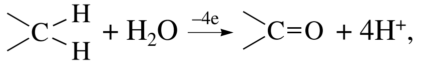
bonds and the products of these reactions are the corresponding oxycarboxylic acids.

It was found that the reactivity of *n*-alkanes in the series C_5–C_{20} decreases with an increase in the number of carbon atoms.

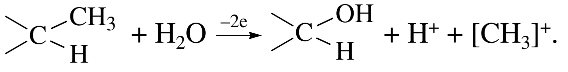
The authors assume that the data that they obtained can be described by the reactions



$$>C\begin{smallmatrix}H\\H\end{smallmatrix} + H_2O \xrightarrow{-2e} >C\begin{smallmatrix}OH\\H\end{smallmatrix} + 2H^+, \qquad (IV)$$



$$>C\begin{smallmatrix}H\\H\end{smallmatrix} + H_2O \xrightarrow{-4e} >C{=}O + 4H^+, \qquad (V)$$



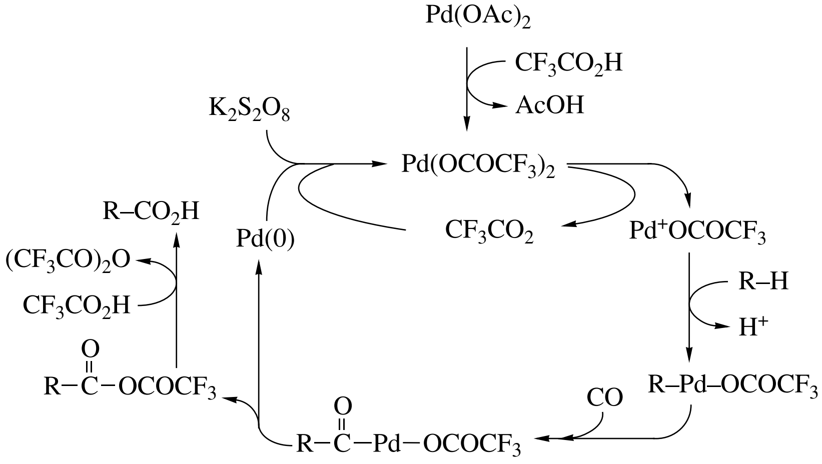
$$>C\begin{smallmatrix}CH_3\\H\end{smallmatrix} + H_2O \xrightarrow{-2e} >C\begin{smallmatrix}OH\\H\end{smallmatrix} + H^+ + [CH_3]^+. \qquad (VI)$$

The involvement of C–C bonds (isooctane) in the oxidation reaction is an unusual phenomenon as the authors assumed

Scheme 6 shows how vanadium derivatives interact with hydrogen peroxide. One may assume that the catalytically active intermediate is the oxo complex like complex A.

1.2.3. Carbonylation of alkanes with persulfate as an oxidant. A series of papers on the carbonylation of alkanes in the presence of palladium and/or copper complexes (cocatalyst) and potassium persulfate as an oxidant in TFAA solutions was published by Fujiwara and co-workers [16, 35–40]. It was found that cyclohexane undergoes carbonylation in the $Pd(OAc)_2$–$Cu(OAc)_2$ system at 80°C and 2.0 MPa CO with a yield of 4.3% based on cyclohexane and with a turnover number of ~20 for 20 h. Other cocatalysts (metallic Fe, $FeCl_2$, $FeCl_3$, $Co(OAc)_2$, $Ni(OAc)_2$, and $Zn(OAc)_2$) were inefficient. The activity of $Pd(OAc)_2$ was ~2.6 turnovers, and the activity of $Cu(OAc)_2$ was 1.5 turnovers (for 20 h). Ethane and propane formed propionic acid (76 turnovers) and butyric acids (71 turnovers, *iso*/*n* ≅ 3.4) under the same conditions [36, 37]. It was shown that in propane carbonylation on Pd black or in the presence of $Pd(OAc)_2$ (with $Cu(OAc)_2$, CuCl, $CuCl_2$, or Cu powder as cocatalysts), the efficiency of the systems formed changes insignificantly (from 42 to 61 turnovers for 20 h) [38]. Note that methane carbonylation to acetic acid in the $Cu(OAc)_2$–$K_2S_2O_8$ system is ~3 times more efficient than in the presence of $Pd(OAc)_2$–$Cu(OAc)_2$–$K_2S_2O_8$ [37]. In the former case, the turnover number is ~40 for 25 h. According to the authors, this is explained by different mechanisms in the $Pd(OAc)_2$–$Cu(OAc)_2$ system and in the presence of the $Cu(OAc)_2$ complex. The $Cu(OAc)_2$ complex acts via the one-electron mechanism (see below in Section 3). However, it remained unclear why there is a substantial difference between the activities of Cu(OAc) (13), $Cu(OAc)_2$ (30), Cu_2O (19), CuO (10), $Cu(OH)_2$ (23), $Cu(O_2CCF_3)$ (17), and $Cu(OOCCF_3)_2$ (12). It is expectable that all these compounds should transform into $K_2S_2O_8$ in the presence of $Cu(O_2CCF_3)_2$ in TFAA and have approximately the same activity.

To elucidate the role of copper in the system $Pd(OAc)_2$–$Cu(OAc)_2$, spectral studies have been carried out [39]. A study of the electron spectra at different component ratios showed that, at Cu(II) : Pd(II) = 1 : 1 a band at 369 nm was observed, which remained unchanged with a further increase in this ratio. The absorption bands of $Cu(OAc)_2$ and $Pd(OAc)_2$ in



Scheme 7.

CF_3COOH are observed at 727 and 406 nm, respectively. At Cu(II) : Pd(II) ratios ≤1, there is correlation between the yield of butyric acids and the position of λ_{max}. Thus, $Pd(OAc)_2$ and $Cu(OAc)_2$ form the catalytically active complex with a 1 : 1 composition. According to the XPS and ^{19}F NMR data, the electron density partially transfers from Pd to Cu in this complex to enhance the electrophilic character of Pd. According to the XRD data, the sample $Pd(OAc)_2$–$Cu(OAc)_2$ does not show the signals from the initial compounds, but new signals are detectable.

It was assumed that, in the cited Pd and Pd–Cu systems, the mechanism of electrophilic substitution of alkanes is effective (Scheme 7) [40].

The kinetic isotope effect value (k_H/k_D) in the carbonylation of C_6H_{12} and C_6D_{12} is 3, pointing to the fact that the slow step is the attack of a strongly electrophilic species $Pd(CF_3COO)^+$ on the C–H bond in the alkane with the formation of an alkyl-$Pd(CF_3COO)$ bond. CO is then coordinated to the complex and inserted into the Pd–alkyl bond. The reductive elimination produces a mixed anhydride which transforms into a carboxylic acid (the product) in excess CF_3COOH.

1.2.4. Carbonylation of alkanes in the presence of alcohols and olefins. In connection with methane oxidation in sulfuric acid (see section 1.2.1), it is interesting to mention a series of papers by Souma *et al.* [41–44]. These papers are devoted to alkane carbonylation in the presence of copper and silver carbonyls and cationic carbonyl complexes of Pd, Pt, Os, and Hg in sulfuric acid, superacids, and BF_3–H_2O. These reactions occur at room or somewhat higher temperatures and atmospheric pressure but require the presence of alcohols and olefins. According to the authors, the reaction medium generates a carbocation from the alcohol and olefin. The carbocation formed accepts a hydride ion from an alkane, and the new carbocation is carbonylated. Further interaction with water leads to the formation of a carboxylic acid (Scheme 8).

The yield of products is 40–95% based on the initial alkane.

An interesting development has been reported by researchers from Japan [45]. They found that, in the presence of $Rh_2Cl_2(CO)_4$ in an isopropanol solution, 1-(2-pirydyl)–2-pyrrolidone and ethylene are carbonylated to 1-[1-(2-pirydyl)–2-pyrrolidinyl]–1-propanone according to Scheme 9.

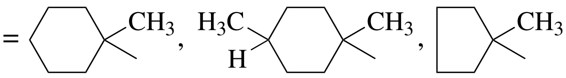
The yield of products depends on a substituent in the pyridine fragment. The introduction of the methyl group into position 3 and 4 practically does not affect the yield, whereas its introduction into position 5 increases the yield to 84%. At the same time, due to steric hindrances, the presence of a methyl group in position 6 leads to a decrease in the yield to 12%. The

$$(R^1)^+ + R^2H \longrightarrow R^1H + (R^2)^+,$$

$$(R^2)^+ + CO \xrightarrow{CuCO_3^+} R_2CO^+ \xrightarrow{H_2O} R_2COOH,$$

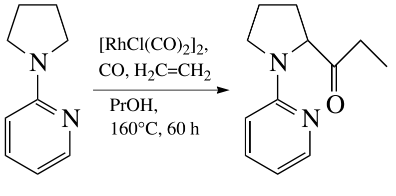
R^1 = alkyl (primary, secondary, tertiary),

R^2 =

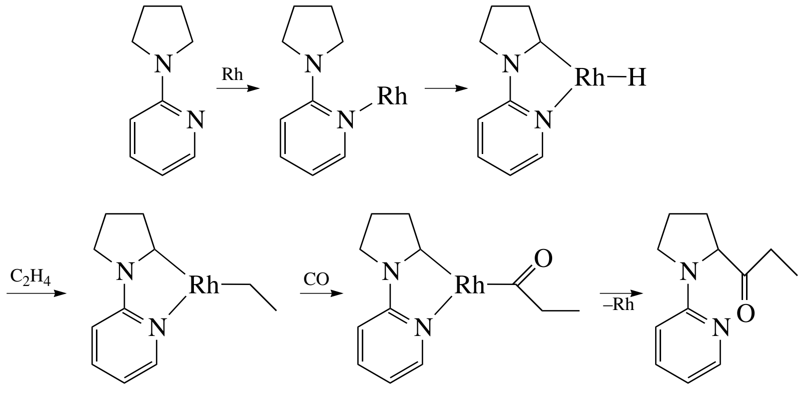


$CH_3(CH_2)_2C(CH_3)_2$–, $CH_3CH_2C(CH_3)_2$–

Scheme 8.



Scheme 9.



Scheme 10.

introduction of an electron-acceptor group CF_3 into position 5 also leads to a decrease in the yield (to 15%). The proposed mechanism is shown in Scheme 10.

A rhodium hydride complex is initially formed, which is stabilized by a chelate effect. Then ethylene activation and insertion takes place. Carbon monoxide is inserted into an Rh–ethyl bond, and the last step is reductive elimination.

2. TWO-ELECTRON PROCESSES WITH THE PARTICIPATION OF MOLECULAR OXYGEN

Molecular oxygen is a relatively inert molecule, because the O=O bond energy is 105 kcal/mol.

One of the important principles of biocatalyst action is the transformation of molecular oxygen under the action of reducing agents into species allowable for alkane oxidation according to the reactions

$$\text{Fe–O=O} + e + H^+ \longrightarrow \text{Fe–O–O–H}, \qquad \text{(VII)}$$

$$\text{Fe–O–O–H} + H^+ \longrightarrow Fe^+\text{=O} + H_2O. \qquad \text{(VIII)}$$

Reducing agents in model systems are hydrogen, sodium borane, zinc, ascorbic acid, carbon monoxide, and others. In my opinion, one of the most convenient reducing agents is CO, because its oxidation leads to the formation of only carbon dioxide, which is easy to remove from the reaction zone.

2.1. Reactions of Alkane Oxidation in the Absence of a Reducing Agent

There are at least three examples for which oxygen activation does not require a reducing agent. Mosieev and co-workers [19, 20] have found that cobalt(III) trifluoroacetate stoichiometrically oxidizes methane in a TFAA solution to methyl trifluoroacetate at 30 atm and 180°C according to the following equation:

$$CH_4 + 2Co(CF_3COO)_3 \longrightarrow CF_3COOCH_3 + 2Co(CF_3COO)_2 + CF_3COOH. \qquad \text{(IX)}$$

The authors managed to reoxidize the Co(II) salt to Co(III) by molecular oxygen:

$$2Co(CF_3COO)_2 + 1/2O_2 + 2CF_3COOH \longrightarrow 2Co(CF_3COO)_3 + H_2O. \qquad \text{(X)}$$

One can see that the sum of these two reactions leads to the catalytic oxidation of methane by molecular oxygen:

$$CH_4 + 1/2O_2 + 2CF_3COOH \longrightarrow CF_3COOCH_3 + H_2O. \qquad \text{(XI)}$$

The insufficiently high yield of methyl trifluoroacetate (4 mol based on the oxidative equivalent of Co) is associated by the authors with the formation of insoluble cobalt fluorides. Carbon dioxide was detected in the gas phase, and its yield was found to be independent of the methane pressure. Carbon dioxide is most likely to form via the decarboxylation of TFAA and its anion.

In the $Pd(OAc)_2$–$Cu(OAc)_2$ system considered in the preceding section, $K_2S_2O_8$ can be replaced by molecular oxygen. At 80°C and pressures of CH_4, CO, and O_2 of 2.0, 1.5, and 1.5 MPa, respectively, the turnover number in methane carbonylation to acetic acid was 2.4 for 20 h [40]. Methane carboxylation to acetic acid by carbon dioxide in the system $Pd(OAc)_2$–$Cu(OAc)_2$–$K_2S_2O_8$–CF_3COOH, reported in the same paper, is doubtful because this reaction is thermodynamically unfavorable.

Let us consider another example from Shilov chemistry. It has recently been found that the Pt(II)–Pt(IV)–Cl^- system can be replaced by Pt(II)–Cu(II)–Cl^- [46]. At 150°C and P_{O_2} = 8.26 MPa, the following substrates were oxidized to the corresponding oxygenates in an aqueous solution with H_2SO_4 additives: methane-, ethane- and propanesulfuric acids, propionic acid, and ethanephosphoric acid. For 4 h, the turnovers based on Pt were 8, 53, 28, 35, and 16, respectively. The low reactivity of CH_3SO_3H is explained by the strong electron-acceptor effect of the sulfo group. The oxidation of ethane and propane derivatives mostly affects the methyl group. According to the authors, this fact suggests the electrophilic two-electron mechanism rather than a radical one. It was demonstrated that in the competitive oxidation of ethane and ethanesulfonic acid the ratio of reaction products remains practically the same when one replaces the Pt(II)–Pt(IV)–Cl^- system by Pt(II)–Cu(II)–Cl^-. This is further evidence for the two-electron mechanism.

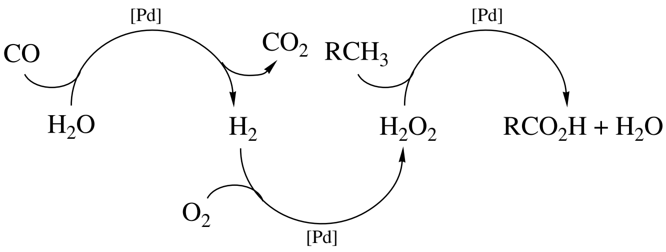
Interestingly, deuterium exchange between the substrates and the medium occurs both in the presence and in the absence of oxygen. In the presence of oxygen the extent of exchange is higher, which can be explained by the constant generation of catalytically active species. In this case, rather intensive exchange of methylene groups is observed in, for instance, the third position of *n*-butanesulfonic acid. In the absence of oxygen, the ratio of intensities of CH_3 and CH_2 groups in the third position in this substrate is higher. Some nonselective pathway may be effective to a small degree in this case.

Thus, in the cited paper, the principle used in the design of the catalytic systems palladium–reoxidant for olefin oxidation [47] is applied to alkane oxidation.

2.2. Alkane Oxidation with the Participation of Reducing Agents

Here we consider publications by Sen's group on the oxidation of methane, ethane, butane, and several saturated organic compounds containing functional groups in the presence of Pd/C or systems based on Pd/C (or K_2PdCl_4) and $CuCl_2$ [18, 48–50]. Carbon monoxide was used as a reducing agent. The use of hydrogen was less efficient, because hydrogen peroxide, which was rapidly formed in the system, also decomposed into H_2O and O_2 very rapidly.

It was found that, in D_2O in the presence of DCl and Pd/C, ethane is efficiently oxidized to ethanol and acetic acid is also efficiently oxidized to formic acid [48]. At the pressures (MPa) $P_{C_2H_6} = 3.4$, $P_{CO} = 0.68$, and $P_{O_2} = 0.68$, a change in the temperature from 70 to 100°C leads to an increase in the yield for 20–24 h from 221 to 1138 mol CH_3COOH/g-atom Pd as determined from hydrogen chemisorption. In the experiment at 70°C, the formation of ethanol was detected, which is an intermediate species in the authors' opinion. The yield of formic acid passes through a maximum with an increase in the temperature. Most probably, this is due to the decomposition of formic acid into CO and H_2O. The reaction does not occur in the absence of CO or DCl. It was shown using ^{13}CO that all of the CO_2 is formed from CO. In the absence of substrate, the catalyzate contained up to 0.002 M of hydrogen peroxide. The use of Pt/C was less efficient because of the higher reactivity of platinum in the decomposition of hydrogen peroxide. This is supported by experiments with hydrogen. Thus, at 25°C and pressures (MPa) $P_{H_2} = 1.0$ and $P_{O_2} = 2.0$, 0.024 M H_2O_2 was formed on Pt/C after 6 h, and 1.4 M H_2O_2 was formed on Pd/C. The intermediate formation of H_2O_2 was proven in independent experiments. Thus, at 30°C, ethane was slowly oxidized to ethanol and the acetic acid was slowly oxidized to formic acid upon the addition of hydrogen peroxide as an oxidant. Because the formation of acetic acid $CH_3{}^{13}COOH$ was not observed in the experiments with ^{13}CO, $CH_3^{\bullet}$ was not assumed to be an intermediate. The authors concluded that the process occurs via the two-electron mechanism (Scheme 11).



Scheme 11.

We believe that the probability of H_2O_2 formation from H_2 formed by the water-gas shift reaction is low. Even if this reaction occurs, H_2 activation is barely possible under the conditions of the great concentration of CO in the initial gaseous mixture. The authors should have observed a long induction period associated with the transformation of a considerable portion of CO via the water-gas shift reaction. Moreover, data are available on the direct interaction of CO with oxygen to form H_2O_2 [51, 52]:

$$CO + O_2 + H_2O \longrightarrow CO_2 + H_2O_2. \qquad \text{(XII)}$$

Methane is oxidized with lower efficiency than ethane. The main product is formic acid [49]. The replacement of water by TFAA as a solvent did not result in an increase in the efficiency, but the addition of $CuCl_2$ to a TFAA solution gave an active and selective catalytic system for methane oxidation to methyl fluoroacetate [49].

As follows from Table 1 (runs 1, 2), an increase in the amount of Pd/C from 1 to 6 mg at a constant concentration of $CuCl_2$ did not affect the overall yield of reaction products, but the rate of product formation per Pd/C amount decreased. This is possibly due to the fact that, together with an increase in the amount of Pd/C, the authors should have increased the concentration of $CuCl_2$ accordingly. The addition of $Cu(CF_3COO)_2$ and NaCl was equivalent to adding $CuCl_2$ as an initial component. The replacement of Pd/C by K_2PdCl_4 led to a drastic increase in the reaction rate (run 4). Ethane and butane showed higher reactivities than methane (runs 5–7). Furthermore, in the case of ethane and butane, C–C bond activation and cleavage were observed. We believe that the experimentally high activity of the K_2PdCl_4–$CuCl_2$ system is due to the effect of colloidal palladium. Most likely, in a long experiment, colloidal palladium particle will be enlarged and the activity of the system will decrease. Moreover, if the palladium complex were effective, one should expect the carbonylation reaction to occur as well. It is known that palladium complexes are the most active catalysts in olefin carbonylation [53]. However, the formation of CH_3COOH was not reported in [49]. Some regularities of the process were studied in the presence of K_2PdCl_4–$CuCl_2$. The linear Arrhenius dependence in the range of 85–150°C with $A = 2 \times 10^4$ s^{-1} and $E_{eff} = 15.3$ kcal/mol was observed, and the steady-state value of the rate is achieved at $P_{CH_4} > 4.8$ MPa. It was assumed that the catalytic systems studied act according to the two-electron mechanism. The main reason behind that is that, in the oxidation of methane via a radical mechanism in the presence of CO, one should have observed the formation of acetic acid. Carbon monoxide is an efficient trap for methyl radicals. The rate constant of this reaction in water is 2×10^6 l mol^{-1} s^{-1} [54].

The catalytic system Pd/C–$CuCl_2$ in the absence of O_2 and CO in a medium of aqueous TFAA was also efficient for the oxidation of distant C–H bonds and the cleavage of C–C bonds in functionalized hydrocarbons: propionic and *n*-butyric acids, ethane- and *n*-propanesulfonic acids, ethanephosphoric acid, 1-chloropropane, cumene, and isopropylbenzoic acid [50]. Thus, propionic acid (1.34 mmol) transformed into 3-oxypropionic (0.22–0.29 mmol), acetic (~0.20 mmol) and formic (0.44–0.71 mmol) acids for 18 h in a solution of 11.5 ml TFAA and 0.5 ml H_2O in the presence of 3 mg 5% Pd/C and 3.5–15 mg $CuCl_2$ (anhydrous) at 75°C and pressures (MPa) of $P_{N_2} = 6.4$, $P_{CO} = 1.36$, and $P_{H_2} = 0.68$. The addition of mercury inhibits the oxidation process. This shows that heterogeneous palladium acts upon the system. The following evidence was provided for the two-electron mechanism. A rather high degree of attack on the stronger primary C–H bond is observed. Moreover, 1-chloropropane chlorination (a radical reaction) targets position 2, whereas oxidation affects the methyl group. In the competitive oxidation of ethane and cumene (or *p*-isopropylbenzoic acid), the main product was ethanol, although the concentration of ethane was much lower.

Interestingly, when hydrogen peroxide was gradually added by a high-pressure pump, the hydroxylation of *n*-propanol to 1,3- and 1,2-propanediol occurred in the presence of $CuCl_2$ but did not occur on Pd/C. At the same time, Pd/C, as well as $CuCl_2$, catalyzes the cleavage of C–C bonds. That is, the formation of acetic and formic acids was observed. Based on these observations, the authors concluded that the components of the

Table 1. Oxidation of methane, ethane, and butane in palladium-containing catalytic systems at T = 85–95°C [49]

No.	5% Pd/C, mg	$[K_2PdCl_4] \times 10^5$, M	$[CuCl_2] \times 10^3$, M	$[NaCl] \times 10^3$, M	Alkane (P, MPa)	P_{CO}, MPa	P_{O_2}, MPa	τ, h	Activity, mol $(CH_3OH + CF_3COOCH_3)$ (g-atom Pd)$^{-1}$ h^{-1}
1	1.0	–	25.0	–	CH_4 (6.12)	1.36	0.68	50	0.64[1]
2	6.0	–	25.0	–	″	″	″	50	0.10[1]
3	3.0	–	25.0[2]	25.0	″	″	″	48	0.21[1]
4	–	3.0	7.4	–	CH_4 (6.8)	″	″	6	1890
5	3.0	–	25.0	–	C_2H_6[3] (2.7)	0.68	0.34	16	1.67[1, 4]
6	–	3.0	7.4	–	″[3]	″	″	18	4040[5]
7	–	3.0	7.4	–	*n*-C_4H_{10}[6] (0.2)	″	″	20	1430[7]

Note: In runs 1–3 and 5 the medium is 3 ml TFAA and 1 ml H_2O; in runs 4, 6, and 7 the medium is 1.5 ml TFAA and 0.5 ml H_2O.

[1] Based on Pd determined from H_2 chemisorption.

[2] $Cu(CF_3COO)_2$.

[3] N_2 added (2.72 MPa).

[4] From the sum of the products formed $(CH_3OH + CF_3COOCH_3) = 0.30$ M, $(C_2H_5OH + CF_3COOC_2H_5) = 0.75$ M, and $CH_3COOH = 0.14$ M.

[5] From the sum of products formed $(CH_3OH + CF_3COOCH_3) = 0.22$ M, $(C_2H_5OH + CF_3COOC_2H_5) = 0.72$ M, and $CH_3COOH = 0.15$ M.

[6] N_2 added (5.44 MPa).

[7] From the sum of products formed $(CH_3OH + CF_3COOCH_3) = 0.14$ M, $(C_2H_5OH + CF_3COOC_2H_5) = 0.14$ M, and $CH_3COOH = 0.15$ M.

catalytic system distribute their functions among each other. The role of Pd/C consists in the transformation of CO and O_2 into hydrogen peroxide in the presence of water, and $CuCl_2$ catalyzes alkane hydroxylation in the presence of H_2O_2. If one takes into account that the dependence of the activity of the Pd/C–$CuCl_2$ system on the concentration of $CuCl_2$ passes through a maximum, then it is possible to draw the following assumption. The surface palladium atoms are in equilibrium with $CuCl_2$. Palladium atoms are substantially blocked, and this affects the catalytic activity. An alternative (and, in our opinion, more probable) pathway of hydrogen peroxide formation consists of a sequence with the following steps:

$$2\mathrm{CuCl} + \mathrm{O_2} + 2\mathrm{H^+} \longrightarrow 2\mathrm{CuCl^+} + \mathrm{H_2O_2}, \tag{XIII}$$

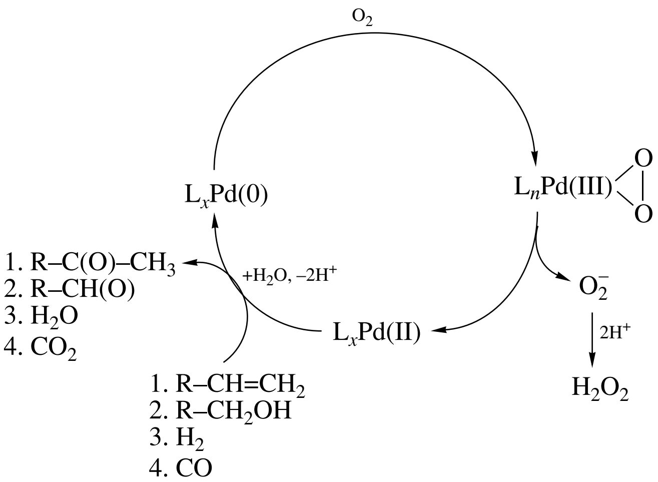
$$2\mathrm{CuCl^+} + \mathrm{CO} + \mathrm{H_2O} \xrightarrow{\mathrm{Pd}} 2\mathrm{CuCl} + \mathrm{CO_2} + 2\mathrm{H^+}. \tag{XIV}$$

It is known that in several cases the oxidation of copper(I) by molecular oxygen in protic media occurs with the formation of both water and hydrogen peroxide [55–57]. The regeneration of Cu(I) occurs in the palladium-catalyzed reduction of Cu(II) by carbon monoxide.

The difference in the reaction products of *n*-propanol oxidation by hydrogen peroxide in the presence of Cu(II) and Pd/C suggests that the mechanisms of C–H and C–C bond activation are very different. As noted above, methyl group hydroxylation occurs on Cu(II), and the cleavage of C_1–C_2 and C_2–C_3 bonds occurs on Pd/C.

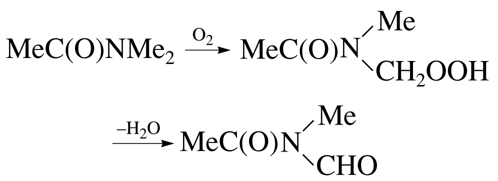
Note that alkane oxygenation reactions with hydrogen as a reducing agent are notable. Thus, in the presence of Pd/Al_2O_3 and cocatalysts (iron and vanadium compounds), cyclohexane is oxidized to cyclohexanol and cyclohexanone in a ratio of ~3 : 1 [58]. The reaction was carried out in a solution of propionic acid at 36°C and pressures of H_2, O_2, and N_2 equal to 0.64, 0.64, and 6.4 MPa, respectively. Nitrogen was added for explosion safety reasons. The role of the palladium catalyst is hydrogen generation according to Scheme 12, whereas iron- or vanadium-containing compounds catalyze cyclohexane oxygenation. The specific activity based on iron or vanadium under the cited conditions is 25–38 turnover/h.

Taking into account the data reported in [34] on alkane oxygenation by hydrogen peroxide in the presence of vanadium catalysts, this reaction apparently occurs via the two-electron mechanism. Studies by V.A. Likholobov and co-workers were devoted to alkane oxidation by a mixture of H_2 and O_2 via the one-electron mechanism. They are considered in section 3.



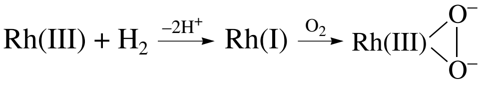
Scheme 12.

An interesting example of =N–CH_3 group oxidation in dimethylacetamide was reported by Gamage and James [59]. The reaction is catalyzed by $RhCl_3(DMSO)_3$ in a substrate solution at 50°C and P_{O_2} = 260 Torr and P_{H_2} = 500 Torr. *N*,*N*-dimethylacetamide hydroperoxide, which is initially formed, is dehydrated to form *N*-methyl-*N*-formylacetamide during experiments or during operations necessary for GC analyses via the following sequence of steps:



$$\mathrm{MeC(O)NMe_2} \xrightarrow{\mathrm{O_2}} \mathrm{MeC(O)N}\begin{array}{l}\diagup\mathrm{Me}\\ \diagdown\mathrm{CH_2OOH}\end{array}$$
$$\xrightarrow{-\mathrm{H_2O}} \mathrm{MeC(O)N}\begin{array}{l}\diagup\mathrm{Me}\\ \diagdown\mathrm{CHO}\end{array} \tag{XV}$$

It was assumed that molecular oxygen is activated by oxidative addition to rhodium(I):

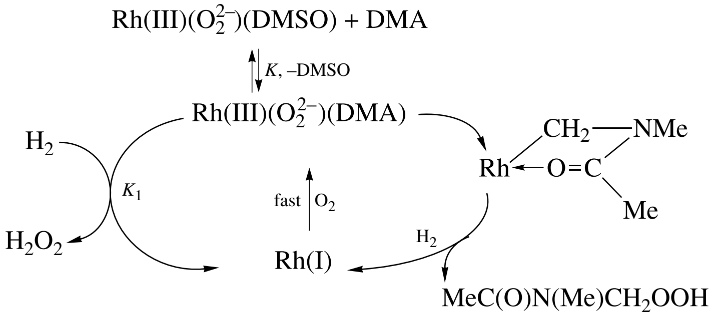


$$\mathrm{Rh(III)} + \mathrm{H_2} \xrightarrow{-2\mathrm{H^+}} \mathrm{Rh(I)} \xrightarrow{\mathrm{O_2}} \mathrm{Rh(III)}\begin{array}{l}\diagup\mathrm{O^-}\\ \;\;|\\ \diagdown\mathrm{O^-}\end{array} \tag{XVI}$$

Without H_2, no oxidation occurs. If a solution that had contact with oxygen is treated with hydrogen for some time, the absorption of the mixture of H_2 and O_2 starts over again. The addition of H_2O_2 or *t*-BuO_2H instead of the mixture of H_2 and O_2 leads to a decrease in the reaction rate by a factor of 5–8. According to the authors, the role of hydrogen consists in the primary reduction of rhodium(III) to rhodium(I) and in the prevention of the formation of inactive polynuclear complexes. Kinetic data agree with the proposed mechanism (Scheme 13).

Thus, it was assumed in this case that hydrogen is not a necessary reducing agent, and hydrogen oxidation to H_2O and H_2O_2 is an inevitable side process.

There is an example of using zinc powder as a reducing agent. As this takes place methane is selectively oxidized by molecular oxygen to methanol (methyl trifluoroacetate) in the presence of $EuCl_3$ at room temperature and atmospheric pressure in a medium of TFAA [60, 61]. As follows from the figure, other substances are also oxidized. Ethane is oxidized



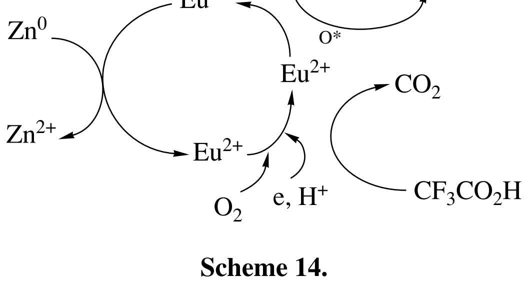
Scheme 13.

mostly to ethyl trifluoroacetate and acetaldehyde and propane is oxidized to *n*-isopropyl trifluoroacetate, acetone, and propionic aldehyde. In the course of alkane oxidation, CO_2 is formed in a substantial amount. With an increase in alkane pressure, the rate of CO_2 formation decreases. According to the results obtained, the only pathway to CO_2 is TFAA decarboxylation. The oxidation of ethane and propane is also observed in acetic acid, but the efficiency of this process is lower. According to the UV spectroscopic data, there is a substantial difference between a compound formed by initial Eu^{3+} reduction with zinc (presumably Eu^{2+}) and Eu^{2+} treated with oxygen.

The proposed mechanism is shown in Scheme 14.

Europium(III) is reduced by zinc to europium(II). The latter activates molecular oxygen by transforming it to an “electrophilic” state, which has a poorly defined nature. According to the authors [60, 61], the electrophilicity of this state follows from the higher reactivity of the secondary C–H bond compared to that of the primary C–H bond. It was assumed that the alkane is activated by this electrophilic oxygen state. A variant of the one-electron process, which may begin with the generation of $CF_3^{\bullet}$ in TFAA decarboxylation was not considered.

2.2.1. Catalytic systems for the oxidation and oxidative carbonylation of alkanes based on rhodium complexes and cocatalysts. In 1994, Lin and Sen found an interesting catalytic system for the oxidative functionalization of methane [62]. This system contained $RhCl_3$, KI, and NaCl or DCl in D_2O. At 95°C, $P_{CH_4} = 6.9$, $P_{CO} = 1.36$, and $P_{O_2} = 0.68$ MPa, the main product of the reaction is acetic acid (27.6 mol/mol Rh for 420 h). Methanol and acetic acid were observed in very small amounts. When analyzing these data, we assumed that the process rate can be increased by replacing water by aqueous–organic media, specifically by aqueous–carboxylic acid solutions. Such examples for carbonylation reactions in the presence of metal complexes have been known [63, 64]. Indeed, it was found that the replacement of a certain portion of water by heptafluorobutyric [65], acetic [66, 67], or trifluoroacetic [68, 69] acid leads to a considerable increase in the efficiency of the rhodium–iodide–chloride system.



Scheme 14.

In a solution of heptafluorobutyric acid ($C_3F_5COOH : D_2O = 6 : 1$), oxidation and oxidative carbonylation of methane, ethane, propane, and *n*-butane were studied [65]. Under standard conditions (80–85°C, P_{CH_4} = 6.8 MPa, P_{CO} = 0.2 MPa, P_{O_2} = 0.07 MPa, $[RhCl_3] = 5 \times 10^{-3}$ M, KI = 1.7×10^{-3} M, NaCl = 7×10^{-2} M), the formation of acetic acids occurs at a rate of 0.45 mol (mol Rh)$^{-1}$ h^{-1}. Using ^{13}C-labeled compounds, it was proven that the carbonyl group in acetic acid is from carbon monoxide. Most of the CO_2 is also formed from CO rather than from CH_4. It was shown in the competitive runs ($^{13}CH_4 + {}^{12}CH_3OH$) that methane is more reactive than methanol, and acetic acid is only formed from methane. Thus, the process mechanism differs strongly from the mechanism of the Monsanto process of methanol carbonylation, which involves the formation of CH_3I and its oxidative addition to Rh(I) [70, 71]. Interestingly, if a part of heptafluorobutyric acid is replaced by $(CF_3)_2CHOH$ and if one carries out an experiment at a volume ratio $C_3F_5COOH : (CF_3)_2CHOH : D_2O = 4 : 2 : 1$, then acetic acid becomes the main product of the reaction. As concerns the mechanism of the process, the authors did not consider the step of methane activation, and the apparent ratio of the reaction products is explained by the ratio of the rate constants k_{Nu} and k_{CO} depending on the properties of the reaction medium (Scheme 15).

The role of the iodide cocatalyst is not explained. It was assumed that the active oxygen is formed by reaction (XVII), and the hydrogen needed for this reaction is formed by the water-gas shift reaction (XVIII):

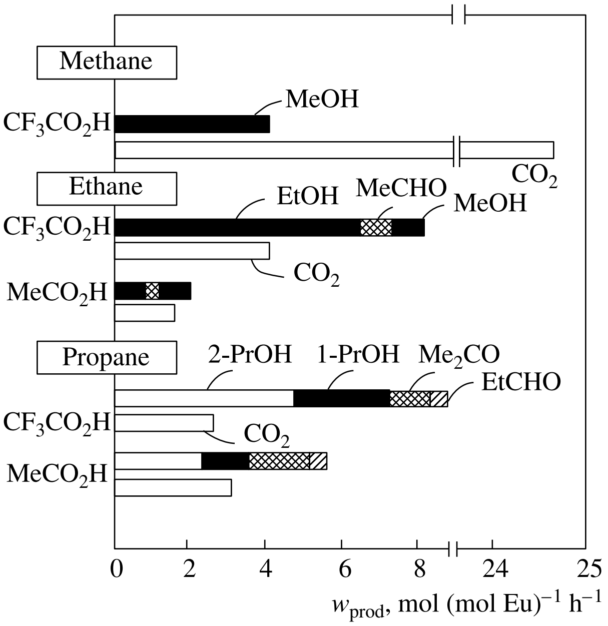
$$H_2 + O_2 \longrightarrow H_2O + O^*, \qquad \text{(XVII)}$$

$$CO + H_2O \longrightarrow CO_2 + H_2. \qquad \text{(XVIII)}$$

Ethane in this system showed a higher reactivity than methane. The products of ethane functionalization are methanol, ethanol, their esters, and acetic acid. Propionic acid was found in trace amounts. This is explained by the fact that the ethyl complex is much more inclined to the nucleophilic attack than the methyl one, and the carbonylation step does not occur. It was shown using ^{13}CO that 80% of the acetic acid is formed from ethane, and 20% is probably formed by the cleavage of the C–C bond in ethane, further formation of the CH_3–Rh species, and its carbonylation. Labeled ethane $^{13}C_2H_6$ only produces labeled methanol and methyl heptafluorobutyrate. The same result was obtained with the simultaneous introduction of $^{13}C_2H_6$ and $^{12}C_2H_5OH$; that is, methanol is not produced from ethanol. Propane mostly produces *iso*-propyl and *n*-propyl heptafluoroacetate in a ratio of 5 : 1, acetone, and a noticeable amounts of methanol, ethanol, and acetic acid.

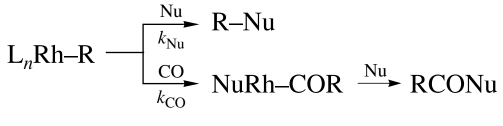
A striking example of C–C bond functionalization was demonstrated for *n*-butane. Virtually all products were obtained with the cleavage of the C–C bonds. Thus, 0.61 mmol of *n*-butane gave the following products after 20 h: ethanol and its ester (0.18 mmol), acetic acid (0.34 mmol), acetaldehyde (0.04 mmol), methanol and its ester (0.17 mmol), and formic acid (0.63 mmol). The overall yield based on *n*-butane was 85%. 2-Methylbutane and 2,3-dimethylbutane also react with C–C bond cleavage, and the yield based on substrate carbon was 87 and 40%, respectively.

Using various literature data and their own data, the authors of [65] assumed that the two-electron mechanism is more probable than the radical one. Specifically, methane appears to be five times more reactive than methanol despite the low energy of homolytic C–H bond cleavage in the latter substance. Using simultaneous functionalization of C_2H_6 and C_2D_6, the primary isotope effect was found for the formation of methyl heptafluorobutyrate ($k_H/k_D = 2.65$). This fact conflicts with the one-electron mechanism where one can expect only a moderate secondary isotope effect. According to the authors, in the presence of excess I^- in the reaction medium, one should not expect the appearance of a more reactive radical than $I^\bullet$ and a stronger oxidant than I_2. None of these reactants can react with methane. Thus, the activation of a C–H-bond in alkanes is most likely to occur in the coordination sphere of the rhodium complex. Two mechanisms were proposed for the functionalization of C–C bonds. The first of them is the primary activation of the C–H bond with the formation of an Rh–alkyl species. Then, a poorly understandable β-abstraction step takes place, which leads to the cleavage of the C–C bond. According to the second mechanism, alkane and the rhodium complex form an alkoxy complex. Its homolytic decomposition leads to an alkoxy radical whose fragmentation may lead to the products observed.



The rates of product formation in oxidation of methane, ethane, and propane in the presence of the system $EuCl_3$–O_2–Zn–CF_3CO_2H (or $MeCO_2H$) at 40°C, $P_{CH_4} = 10$ atm, $P_{C_2H_6} = 10$ atm, and $P_{C_3H_8} = 8$ atm.

A series of papers devoted to an increase in the efficiency of the rhodium-containing catalytic system and to the elucidation of some aspects of the mechanism of its action was published by the authors from the Institute of Structural Macrokinetics, Russian Academy of Sciences [66–69, 72, 73]. Somewhat earlier than the paper [65] appeared, we reported on the possibility of oxidation and oxidative carbonylation of methane in the presence of the rhodium–iodide–chloride catalytic system in CD_3COOD–D_2O–DCl [66, 67]. As in water, the main product of the reaction was acetic acid. In addition to that, we found methanol, methyl trifluroacetate and formic acid. The overall efficiency was 5–6 times higher than in water under comparable condi-



$Nu = OH^-, C_3F_7CO_2^-.$

Scheme 15.

Table 2. Comparison of the initial rates and the solvent kinetic isotope effect for the rhodium–iodide–chloride and rhodium–copper chloride catalytic systems in the course of oxidation and oxidative carbonylation of methane [69, 73]

Reaction products	$RhCl_3$–KI–NaCl[1]			$RhCl_3$–CuO–NaCl[2]		
	$w \times 10^2$, mol l^{-1} h^{-1}		k_H/k_D	$w \times 10^2$, mol l^{-1} h^{-1}		k_H/k_D
	CF_3COOH–H_2O	CF_3COOD–D_2O		CF_3COOH–H_2O	CF_3COOD–D_2O	
Methyl trifluoroacetate + methanol	36.0	18.0	2.0	25.9	25.6	~1.0
Acetic acid	4.5	9.0	2.0	5.3	5.0	~1.0
Formic acid	6.0	3.5	1.7	3.2	3.0	~1.0
Carbon dioxide	650	320	~ 2.0	995	622	~1.6

Reaction conditions: $T = 95°C$, initial pressures at room temperature; MPa: $P_{CH_4} = 6.00$, $P_{CO} = 1.84$, $P_{O_2} = 0.58$.

[1] $[RhCl_3] = 5 \times 10^{-3}$ M, $[KI] = 2 \times 10^{-2}$ M, $[NaCl] = 5 \times 10^{-2}$ M, $m_{water} = 0.67$.

[2] $[RhCl_3] = 2.5 \times 10^{-3}$ M, $Cu(II) = 5 \times 10^{-2}$ g-ion/l, $[NaCl] = 7.5 \times 10^{-3}$ M, $m_{water} = 0.62$.

tions, and comprised ~0.6 mol (mol Rh)$^{-1}$ h^{-1}. We assumed that the intermediate oxidant was hypoiodous acid formed by reaction (XIX). Reaction (XX) is thermodynamically favorable ($\Delta G = -5$ kcal/mol).

$$2DI + O_2 \longrightarrow 2DOI, \quad (XIX)$$

$$CH_4 + CO + OI^- \longrightarrow CH_3COOH + I^-. \quad (XX)$$

It was also found that methanol and methyl iodide, under conditions of methane conversion, are not carbonylated. Methanol transforms into methyl acetate, and methyl iodide transforms into methyl chloride. Thus, as in [65], the process mechanism differs from that found for the Monsanto process. Note than the latter requires very high concentrations of HI [70, 71].

When analyzing data on both the catalytic functionalization of alkanes and for the fine synthesis of oxygen-containing compounds [74], one can see that one of the best solvents is trifluoroacetic acid. Its use led to a decrease in the efficiency of the rhodium–iodide–chloride system in the oxidation and oxidative carbonylation of methane compared to the results obtained in the presence of heptafluorobutyric and acetic acids. A higher rate of the reaction allowed us to replace quantitative ^{1}NMR analysis by GC and carry out kinetic studies [72, 73].

It was found that, in the presence of the system studied, the product yield (CH_3OD, CF_3COOCH_3, HCOOD, and CH_3COOD) passes through a maximum depending on the concentration of iodide ions and CO pressure. With an increase in the concentration of NaCl to 0.2 M, the yield of CH_3COOD grows and the yield of other products somewhat decreases. A further increase in the concentration of NaCl leads to the inhibition of formation of all products.

A kinetic isotope effect associated with the solvent (k_H/k_D) was equal to ~2.0 for the formation of methanol, methyl trifluoroacetate, acetic acid, and carbon dioxide and ~1.7 for formic acid (Table 2).

It is interesting that in the course of the oxidation and oxidative carbonylation of methane, metallic titanium is also oxidized. The maximum of intensity in titanium oxidation is observed at the same concentration of water as the yield of organic products from methane. It is likely that methane and titanium oxidation occur under the action of the same oxidant, which is formed from molecular oxygen and the components of the medium. We suppose that such an oxidant can be hydrogen peroxide or its equivalents: HOI or CF_3COOOH. It is known that titanium is oxidized due to degrading the protective oxide film according to the reaction [75]

$$TiO_2 + H_2O_2 \longrightarrow H_2TiO_4. \quad (XXI)$$

Taking into account iodine volatility, the high corrosion activity of the hydrochloric acid, and the possibility of RhI_3 precipitation at a low CO pressure in the rhodium–iodide–chloride system, the design of a iodide-free system is very important. If hydrogen peroxide can be a true oxidant, then under certain conditions it can be generated by copper(I) oxidation to copper(II) [57–60] (see reaction (XIII)).

Indeed, it was found that the $RhCl_3$–Cu_2O(CuO)–NaCl system in aqueous trifluoroacetic acid catalyzes oxidation and the oxidative carbonylation of methane [72, 73]. The introduction of copper oxides as initial cocatalysts is stipulated by the convenience in carrying out experiments and the necessity of the study of the process regularities at low chloride ion concentrations. Under experimental conditions, copper oxides rapidly transform into trifluoroacetates and probably in part to chlorides. The rhodium–copper and rhodium–iodide–chloride systems are similar in their main features: the same products are observed and there are similar dependences of the product yields on the concentration of chloride ions and CO pressure. None of these systems catalyze the isotopic exchange of methane with the reaction medium, but they are both capable of oxidizing metallic titanium. The apparent differences are as follows. The rhodium–copper–chloride system is approximately 1.5 times more active in methane conversion than the rhodium–iodide–chloride system, it is less sensitive to the concentration of water, and it is more corrosive toward titanium. There is also a difference in the solvent isotopic effects.

The oxidation of metallic titanium can be considered as a test for the presence of H_2O_2. Therefore, it was assumed that the primary intermediate in the interaction of molecular oxygen with the medium is hydrogen peroxide. The latter oxidizes HI to HOI in the rhodium–iodide– chloride system. A narrow interval of the activity of this system can be due to limited HOI stability depending on the concentration of water.

The kinetic isotope effect for the solvent (k_H/k_D) in CO oxidation to CO_2 in both catalytic systems is most probably due to the equilibrium deprotonation of the aqueous–carbonyl rhodium(III) complex [76] in the reaction

$$[Rh(CO)_2(H_2O)Cl_3] \longleftrightarrow [Rh(CO)_2(OH)Cl_3]^- + H^+. \qquad (XXII)$$

The $Rh(CO)_2(H_2O)Cl_3$ complex is a weak acid, and the dissociation constants of weak acids in D_2O are 2–3 times lower than in H_2O [77]. It is common to assume that if the solvent kinetic isotope effect is >1 there is a dissociation step with the formation of a proton (or D) and an anionic species and this step precedes the first irreversible step or is the first irreversible step itself. Examples of such reactions are known from homogeneous metal-complex catalysis: ethylene oxidation to acetaldehyde in the presence of aqueous solutions of palladium chloride (the kinetic isotope effect is ~4) [78], the water-gas shift reaction in the presence of phosphine palladium complexes in TFAA (the kinetic isotope effect is ~3) [79], and the oxidative carbonylation of acetylene in alcohol solutions of palladium complexes (the kinetic isotope effect is ~1.7–1.8) [80]. It is assumed that a kinetic isotope effect of ~ 1 for the formation of organic products in the rhodium–copper chloride system and a kinetic isotope effect of ~ 2 in the rhodium–iodide–chloride system (Table 2) are associated with the following circumstances. The formation of H_2O_2 according to reaction O_2 with Cu(I) in an acidic medium (reaction (XIII)) is not associated with the dissociation of the H–anion bond. At the same time, in the iodide system the generation of two-electron oxidants requires the dissociation of HI, which may be a rather weak acid in the excess of TFAA. It is important that the inhibitors of radical reactions (chloranil and ionol) do not affect the rate of oxidation and oxidative carbonylation of methane in the presence of both systems, and according to [65], the mechanism is most probably the two-electron one.

At least two mechanisms can be proposed for these catalytic systems. The first mechanism is associated with the intermediate formation of a rhodium complex where rhodium is in a high oxidation state according to the following reactions:

$$[Rh(CO)_2Cl_2]^- \xleftrightarrow{HCl} [HRh(CO)_2Cl_3]^- \xrightarrow{O_2} [HOO\text{–}Rh(CO)_2Cl_3]^- \xrightarrow{H^+} [O{=}Rh(CO)_2Cl_3] + H_2O, \qquad (XXIII)$$

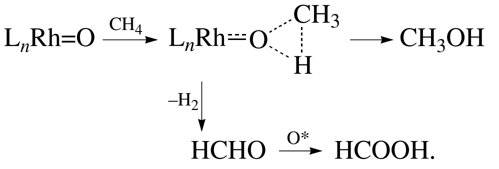
$$[Rh(CO)_2Cl_3L] + H_2O_2 \xrightarrow[-L]{} [O{=}Rh(CO)_2Cl_3] + H_2O. \qquad (XXIV)$$

Certain evidence in favor of the oxene mechanism can be the formation of CO_2 from labeled O_2 presumably via the following reactions:

$$L_nRh(C^{16}O)(^{18}O{=}^{18}O) \longrightarrow L_nRh{=}^{18}O + C^{16}O^{18}O, \qquad (XXV)$$

$$L_nRh{=}^{18}O + CO \longrightarrow L_nRh + C^{16}O^{18}O. \qquad (XXVI)$$

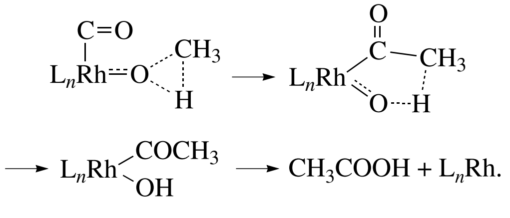
It has been shown using a number of examples that an oxygen atom bound with a metal atom in a high oxidation state may undergo insertion into C–H bonds in alkanes via the intermediate formation of complexes with five-coordinated carbon atom (such reactions were considered in [5]). As a result of this reaction, methane forms methanol (XXVIIa). Biooxidation of methane to methanol is likely to include analogous reaction in which a catalytically active species is a binuclear iron(IV) complex. According to [5], oxo complexes are also capable of mediating the reaction of hydrogen molecule abstraction from methane with the formation of formaldehyde. Fast oxidation of formaldehyde leads to the formation of formic acid (XXVIIb).



(XXVIIa)

(XXVIIb)

According to the hypotheses on the possibility of the existence of complexes with five-coordinated carbon, one may propose the following mechanism for the formation of acetic acid:

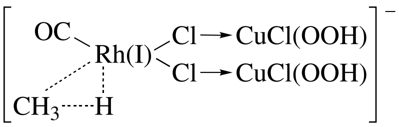


(XXVIII)

There are reasons to assume that, when the concentration of O_2 is low, an alternative mechanism is possible. This is a mechanism with the participation of coordinatively unsaturated Rh(I) complexes. Such complexes may form as a result of redox reactions inside the coordination sphere like this one [76]:

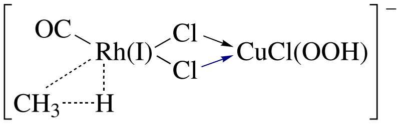
$$[Rh(CO)_2(OH)Cl_3]^- \longrightarrow [Rh(CO)Cl_2]^- + CO_2 + HCl. \qquad (XXIX)$$

We have found that the rhodium–copper–halide system does not catalyze the isotopic deuterium exchange of methane with the medium. Thus, for a system containing 0.01 M $RhCl_3$, 0.03 M NaCl, and 0.2 M CuO in aqueous CF_3COOD (the molar fraction of water is $m_{D_2O} = 0.62$) at $P_{CH_4} = 6$ MPa, $P_{O_2} = 0.2$ MPa, $P_{CO} = 0.5$ MPa, and 95°C after 25 h, the mass spectra did not indicate the presence of deuterium-exchange products of methane above the background amount. Moreover, the use of the $[Rh(CO)_2Cl_2]_2$ complex in the absence of oxygen and carbon monoxide at $P_{CH_4} = 6$ MPa and $T = 95°C$ for 15 h did not lead to the products of deuterium exchange between methane and the medium. Therefore, the formation of a rhodium methyl–carbonyl complex (an intermediate for the synthesis of acetic and formic acids) is likely to occur under the action of the oxidant. It was assumed that methane initially forms a weak associate with a coordinatively unsaturated complex. Then, two electrons are transferred from Rh(I) via a chloride bridge and a copper atom to a hydroperoxo group attached to copper. This facilitates the cleavage of the C–H bond. Then, we can consider the following variants of transformations. The transfer of two electrons from the C–H bond would result in the formation of a carbocation and proton, but the synchronization of such a process would be unlikely according to the authors [4]. The more probable is the heterolytic cleavage of the C–H bond under the action of a base, e.g., CF_3COO^-. In that case, methyl trifluoroacetate and rhodium(III) hydride, which is immediately oxidized with the elimination of a proton and the transfer of two electrons onto the second peroxy group. The overall process can be described by the following reaction.



$$\xrightarrow[CF_3COOH]{2HCl} [Rh(III)(CO)Cl_4]^- + CF_3COOCH_3 + 2H_2O + 2CuCl(OH). \qquad (XXX)$$

In another pathway, the transfer of two electrons is sufficient with the formation of the Rh(III)–CH_3 bond and the evolution of a proton, which participates in water formation:



$$\xrightarrow{HCl} [CH_3Rh(III)(CO)Cl_3]^- + CuCl(OH) + H_2O. \qquad (XXXI)$$

If the methyl–carbonyl complex has enough time to coordinate the second carbon monoxide molecule, then the rest of the reactions occur as in the case of the Monsanto process [70, 71]: the insertion of a carbonyl group into an Rh–CH_3 bond with the formation of an acyl complex. Then, acetic acid is formed by reductive elimination and hydrolysis. The double action of an oxidant on the methyl–monocarbonyl complex leads to a formyl derivative of rhodium and formic acid:

$$[CH_3–Rh(CO)Cl_3]^- + 2O^*$$

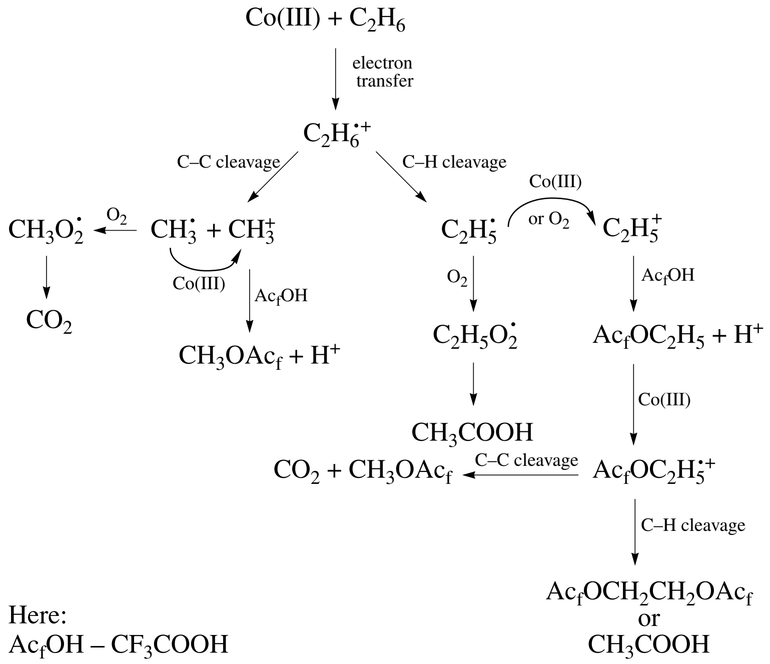
$$\longrightarrow \left[H–\overset{\overset{\displaystyle O}{\|}}{C}–Rh(CO)Cl_3 \right]^- + H_2O. \qquad (XXXII)$$

Thus, the probability of the mechanism of the process studied with the formation of an intermediate oxo complex is based on the fact of $C^{16}O^{18}O$ formation when $^{18}O_2$ is used. The possibility for the formation of coordinatively unsaturated rhodium complexes stems from the fact that in the reactions of their formation most of the oxygen atoms enter carbon dioxide formed from water and trifluoroacetic acid. Experimental dependences of the yield of products of methane conversion on the concentration of chloride ions and carbon monoxide pressure also agree with the possible participation of coordinatively unsaturated rhodium(I) complexes in methane activation.

ONE-ELECTRON PROCESSES

One-electron oxidation of alkanes in the presence of hydroperoxides was discovered by Fenton at the end of the 19th century [81]. Fenton's reagent contains iron(II) sulfate and hydrogen peroxide. Recently, a new system has been developed for benzene oxidation to phenol [82]. This system is based on Fenton's reagent and also includes water, trifluoroacetic acid, an organic solvent, and a heterocyclic amino acid. One-electron processes have been considered in detail in a recent review paper by Shul'pin [17] and in [4, 5].

We restrict ourselves here to the analysis of studies that are the closest to the topic of this review and that were not considered in [17]. Moiseev and co-workers [83] showed that ethane and propane are oxidized to



Scheme 16.

TFAA by cobalt (III) trifluoroacetate or in the presence of Co(II)– O_2. The main products are ethyl and isopropyl trifluoroacetates, respectively. The reactions were carried out at 130–200°C, $P_{\text{alkane}} = 0.5\text{–}4.0$ MPa and $P_{O_2} = 0\text{–}1$ MPa. The formation of isopropyl trifluoroacetate is not due to the regioselectivity of the reaction, but rather to the isomerization of *n*-propyl trifluoroacetate, which is initially formed. This was supported by special experiments. Other substances are also formed in minor amounts: ethane produces $CF_3COOCH_2\text{–}CH_2\text{–}OOCCF_3$, CH_3COOH, and CF_3COOCH_3 in a ratio of 5 : 3 : 2, and propane produces CF_3COOCH_3, $CF_3COOC_2H_5$, CH_3COOH, $CH_3C(O)CH_3$, $CF_3COOCH(CH_3)CH_2OOCCF_3$. These compounds are the products of further oxidation of ethyl and *n*-propyl trifluoroacetates. It was assumed that these processes occur via the one-electron mechanism according to Scheme 16 proposed for ethane oxidation.

The process begins with the formation of a radical cation from ethane, which transforms via two pathways. In the first pathway, the C–C bond is cleaved and CH_3^+ forms methyl trifluoroacetate, while $CH_3^{\bullet}$ forms CO_2 in the presence of O_2.

In the second pathway a C–H bond is cleaved in $C_2H_6^{+\bullet}$ to form a proton and an ethyl radical. The latter reacts with O_2 and produces $C_2H_5O_2^{\bullet}$ and then CH_3COOH. Another variant is the formation of $C_2H_5^+$ and then ethyl trifluoroacetate. Ethyl trifluoroacetate is oxidized by cobalt(III) to give a radical cation, which transforms into the corresponding diether of ethylene glycol or acetic acid due to the cleavage of another C–H bond. In general, the cleavage of C–C bonds in alkanes and the formation of glycols from alkanes has not previously been observed.

It sounds surprising that the catalytic carbonylation of methane to acetic acid occurs in the presence of $CaCl_2$ and $K_2S_2O_8$ as an oxidant [84]. The best conditions are: $T = 85°C$, $P_{CO} = 4.0$ MPa, $P_{CH_4} = 0.5$ MPa, and TFAA as a solvent. The yield of acetic acid for 15 h is 25.7% based on methane. If the reaction is carried out for 140 h and trifluoroacetic anhydride is added before a run for binding water contained in $CaCl_2$, the yield of acetic acid is as high as 93.8%. The use of calcium compounds (oxide, acetate, acetylacetonate, sulfate, carbonate, and dihydroxide), other solvents (methylene chloride), or other oxidants (NaClO and H_2O) was inefficient. The application of labeled compounds $^{13}CH_4$ and ^{13}CO supports the fact that acetic acid is formed by methane carbonylation. The activation parameters (low ΔH^* and negative ΔS^*) and the positive kinetic isotope effect $k_H/k_D = 1.82$ suggest that the process includes direct interaction of methane with metal resulting in the generation of methyl radicals. According to the IR spectroscopic data, $CaCl_2$ initially transforms into $Ca(CF_3COO)_2$. According to the authors, the active species that accepts hydrogen from methane is $(Ca\text{–}O)^*$. This species is generated from $Ca(CF_3COO)_2$ under the action of $K_2S_2O_8$ and CO. The one-electron mechanism of the process is supported by its inhibition with free radical traps, such as 2,4,6-tri-*t*-butylphenol, tetrachloro-*p*-benzoquinone, and 2,2,6,6-tetramethylpiperidine. Still, it remains unclear what prevents the above inactive calcium compounds from converting into calcium trifluoroacetate under the reaction conditions.

Moiseev and co-workers showed that, in the system V(V)–H_2O_2–RCOOH (R = CH_3, CF_3) at 3.0–3.5 MPa and 20°C, methane is oxidized to methanol and its products [85]. Under conditions of 10^{-4} mmol $VO(Acac)_2$ or K_2VO_3 in 0.3 ml TFAA, 2.5 mmol CH_4, and 9.94 mmol H_2O_2, the following products are formed after 2–20 h: 9.3×10^{-3} mmol methyl trifluoroacetate, 3×10^{-3} mmol methanol, and ~0.1 mmol CO_2. It was assumed that the relatively low yield of products from methane and a high yield of CO_2 point to the fact that the complete oxidation of methane dominates the process. Under the conditions studied, methanol and methyl trifluoroacetate are probably oxidized more rapidly than methane. It was shown in [86] that, in the presence of $(NBu_4)VO_3$ and pyrazine-2-carboxylic acid as a cocatalyst in an acetonitrile solution, methane (4.0–7.5 MPa) is oxidized by air (1 MPa) at 23–75°C to methyl hydroperoxide, formaldehyde, and formic acid. The reaction also requires adding hydrogen peroxide, which is a promoter in this case. To analyze methyl hydroperoxide, it is preliminarily reduced by triphenylphosphine:

$$\begin{aligned} &CH_3OOH + P(C_6H_5)_3 \\ &\longrightarrow CH_3OH + O{=}P(C_6H_5)_3. \end{aligned} \qquad \text{(XXXIII)}$$

In cyclohexane oxidation by labeled oxygen $^{18}O_2$, up to 75% of the cyclohexanol (upon reduction by triphenylphosphine) contains ^{18}O. This oxygen isotope was also found in triphenylphosphine oxide. This confirms that alkane oxidation in this case is due to molecular oxygen. In our opinion, the formation of methyl hydroperoxide is an unfavorable process because an additional step of its reduction is needed.

The one-electron mechanism is assumed. The $OH^{\bullet}$ radical formed accepts a hydrogen atom from the alkane. The alkyl radical rapidly reacts with molecular oxygen with the formation of a hydroperoxy radical, which produces alkyl hydroperoxide in the reaction medium.

In another study, the same authors reported the carboxylation of alkanes by carbon monoxide and dioxide [87]. In the presence of sodium vanadate in an aqueous solution with pH 7.3 at T = 80–100°C, P_{CH_4} = 5 MPa, and P_{CO} = 1.5 MPa, acetic acid, methanol, and formaldehyde are formed. Air is an oxidant. In the catalytic system sodium vanadate–pyrazine-2-carboxylic acid in the presence of hydrogen peroxide at T = 25–60°C, P_{CH_4} = 5.0 MPa, and P_{CO} = 0.5–3.0 MPa, the reaction products are acetic acid and methyl hydroperoxide. No doubt, these reactions occur via the one-electron mechanism.

If carbon dioxide is used as a carboxylating agent, then CO_2 is initially reduced by alkyl and/or hydroxyl radicals to form carbon monoxide. Then, the reaction occurs as in the case of carbon monoxide: hydrogen abstraction from methane and methyl radical interaction with CO to form an acetyl radical. Acetyl radical reacts with molecular oxygen and produces peroxyacetic acid under the action of the reaction medium.

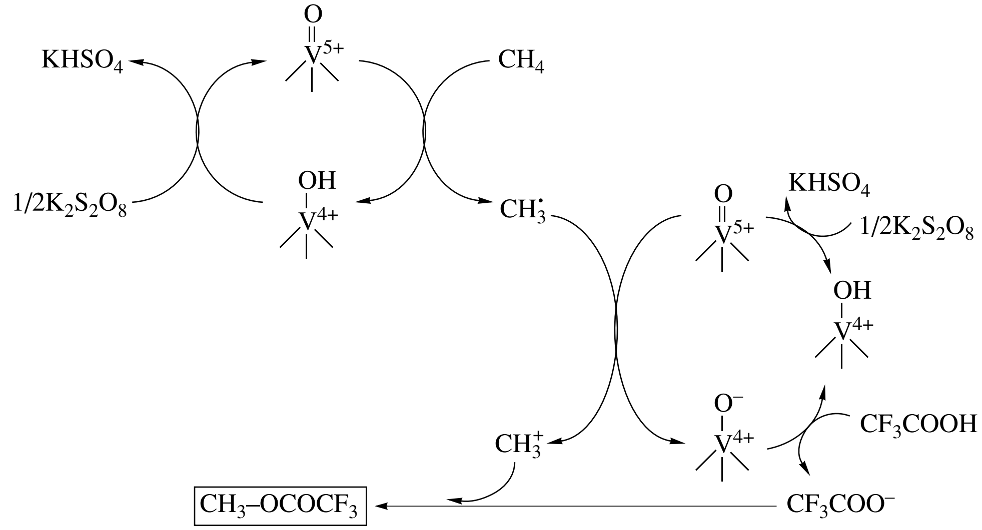
It has been recently reported that the salts of tetra-*n*-butylammonium with the anions of phosphomolybdovanadium heteropoly acids $[PMo_{11}VO_{40}]^{4-}$ and $[PMo_6V_5O_{39}]^{12-}$ efficiently catalyze ethane, *n*-octane, *cyclo*-octane, adamantane, and decalin oxygenation by hydrogen peroxide in a solution of acetonitrile [88]. The main products are the corresponding alkyl hydroperoxides, which steadily decompose into aldehydes and ketones in the course of the reaction. For instance, at 60°C, *cyclo*-octane is oxidized with an oxygenate yield of 30% after 9 h, and the overall number of catalytic cycles is ~1000. It was assumed that the first H_2O_2 molecule reduces V(V) to V(IV), and the second H_2O_2 molecule reacts with V(IV) and generates a hydroxyl radical. The latter abstracts a hydrogen atom from an alkane. The alkyl radical formed transforms into a hydroperoxide.

It was found in 1999 that Keggin-structure heteropoly acids are efficient in the reaction of methane oxidation to methyl trifluoroacetate and methyl acetate [89]. The highest activity was observed in the case of $H_5PV_2Mo_{10}O_{40}$, $H_5SiVW_{11}O_{40}$, and $H_5PV_2W_{10}O_{40}$. At T = 80°C and P_{CH_4} = 2.0 MPa, the use of $K_2S_2O_8$ as an oxidant and trifluoroacetic anhydride additive made it possible to obtain a product yield of 3.5–4.6% based on methane. The product yield has a maximum depending on the amount of trifluoroacetic anhydride added. The maximum corresponds to the turnover number of 490 for 20 h.

The mechanism proposed is shown in Scheme 17 and involves the formation of the methyl radical by the reaction of a V(V)=O fragment, which is formed by V(IV) oxidation by potassium persulfate. Then, V(V)=O abstracts a proton from a methyl radical, and CH_3^+ formed in the reaction with CF_3COO^- produces methyl trifluoroacetate. It was not explained how methyl acetate can be formed under these conditions.

In 1995 Fujiwara and co-workers reported a new interesting reaction of alkanes: their aminomethylation by trimethyl-*N*-oxide in the presence of copper acetate as a catalyst and a small amount of potassium persulfate as a cooxidant [90]. Reactions of ethane and propane were studied. Methane does not enter this reaction. Propane produces *N*,*N*-dimethylisobutylamine, isopropyl trifluoroacetate, and a small amount of dimethylamine:

$$\begin{aligned} &C_3H_8 + (CH_3)_3N{\rightarrow}O + CF_3COOH \\ &\longrightarrow (CH_3)_2CHCH_2N(CH_3)_2 \qquad \text{(XXXIV)} \\ &+ (CH_3)_2CHOCOCF_3 + (CH_3)_2NH + H_2O. \end{aligned}$$



Scheme 17.

Under optimal conditions ($P_{C_3H_8}$ = 1.0 MPa, T = 150°C, 5.0 mmol $(CH_3)_3NO$, 5.0 mmol TFAA, 0.05 mmol $Cu(Ac)_2$, 1.0 mmol $K_2S_2O_8$), the yield of reaction products based on trimethyl-*N*-oxide is 14% *N*,*N*-dimethylisobutylamine and 5.2% isopropyl trifluoroacetate. Under these conditions, amine formation is the most selective. Propane also reacts with *N*-oxides of *N*-methylpiperidine, pyrrolidone, and *N*-methylmorpholine.

The mechanism is not known in detail, but since inhibition by free-radical traps was observed, the process occurs via a one-electron mechanism. The intermediate formation of alkylcopper and Mannich bases from *N*-oxides and TFAA was suggested.

Sen and co-workers used potassium persulfate and mercury sulfate in 27–33% oleum as initiators of the one-electron oxidation of methane [91]. At a methane pressure of 6.4 MPa and 90°C, the main product was methanesulfonic acids. At 160°C, methanesulfonic acid was isomerized to form methyl sulfate, which is the main product. It was assumed that the process occurs according to Scheme 18.

According to this scheme, persulfate decomposes into two radicals, which abstract hydrogen atoms from methane molecules. Chain propagation occurs by the reaction of a methyl radical with SO_3. $CH_3SO_3^{\bullet}$ formed by the reaction with methane produces methanesulfonic acid and a methyl radical.

Then, it was found that ethane is efficiently functionalized by oxidation with hydrogen peroxide in trifluoroacetic anhydride [92]. The reaction occurs in the presence of olefin traces with the formation of propionic acid, its mixed anhydride with TFAA, and trifluromethyl ethyl ketone. An olefin is not needed if the initiator is metachloroperbenzoic acid, azobisbutironitrile and tetraethyllead. The reaction occurs most readily in the presence of $PbEt_4$. For each equivalent of this substance, up to 500 equivalents of the products are formed. Methane practically does not react under the reaction conditions, and propane undergoes simple stoichiometric oxidation to isopropanol and acetone. The dependences of the product yield on the concentration of trifluoroacetic anhydride, propylene, and hydrogen peroxide were studied. The reaction with ethane is usually carried out in the presence of 0.2 ml 30% aqueous H_2O_2 (1.8 mmol) in 3 ml (21.2 mmol) $(CF_3CO)_2O$ at 2 MPa ethane, 1600 ppm ethylene, 2 MPa N_2, and T = 75–80°C for a day and 1.85 mmol of propionic acid and its mixed anhydride together with 0.68 mmol of trifluoromethyl ethyl ketone are formed.

The process is assumed to occur according to Scheme 19.

Likholobov and co-workers [93–96] used a mixture of H_2 and O_2 for cyclohexane oxidation. The authors motivated such a choice by the fact that the use of hydrogen peroxide often leads to a low selectivity of the process. The difference of these studies from [58] is that the mixture H_2/O_2 forms a hydroxyl radical coordinated by platinum rather than hydrogen peroxide. Catalysts of two types were studies. The first of these is a

$$\left.\begin{array}{l} K_2S_2O_8 \longrightarrow 2KSO_4^{\bullet}, \\ KSO_4^{\bullet} + CH_4 \longrightarrow KSO_4H + CH_3^{\bullet}, \end{array}\right] \text{Initiation}$$

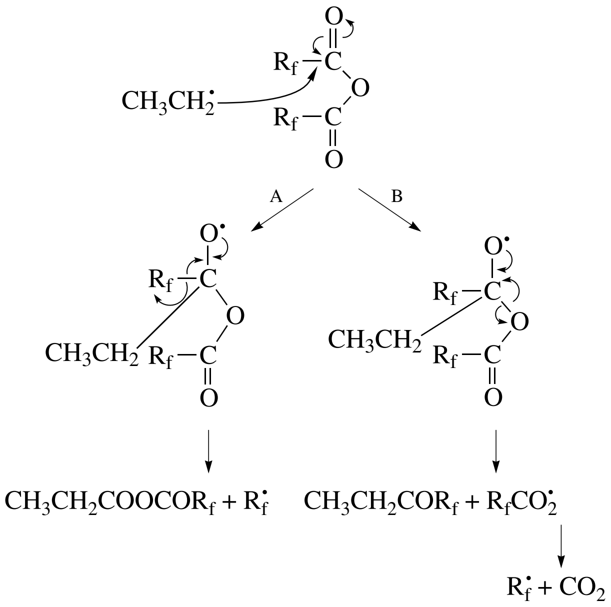
$$\left.\begin{array}{l} CH_3^{\bullet} + SO_3 \longrightarrow CH_3SO_3^{\bullet}, \\ CH_3SO_3^{\bullet} + CH_4 \longrightarrow CH_3SO_3H + CH_3^{\bullet}. \end{array}\right] \text{Propagation}$$

Scheme 18.

Initiation

$$R^{\bullet} + CH_3CH_3 \longrightarrow RH + CH_3CH_2^{\bullet}.$$

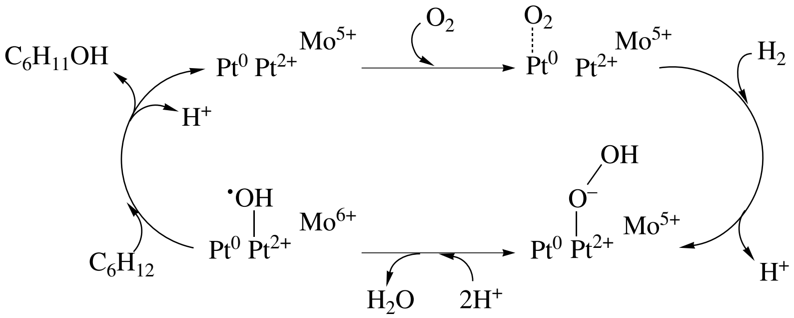
Chain propagation



$$CF_3^{\bullet} + CH_3CH_3 \longrightarrow CF_3H + CH_3CH_2^{\bullet} \quad (\Delta H = -5 \text{ kcal/mol at 298 K})$$

Here R_f is the fluorinated fragment

Scheme 19.



Scheme 20.

catalytic system Pd/SiO_2 or Pt/SiO_2 and heteropoly acids. The activity of heteropoly acids increases in the series $H_6[P_2Mo_{18}O_{62}] < H_4[PMo_{11}VO_{40}] < H_4[PMo_{10}V_2O_{40}]$. It was assumed that the catalytically active species is formed due to the adsorption of heteropoly acids from the solution by the Pd/SiO_2 and Pt/SiO_2 catalysts. In this connection, an example of preparation of a solid two-component catalyst from a complex salt $[Pt(NH_3)_4] \cdot [H_2PMo_{12}O_{40}]_2 \cdot 7H_2O$ by calcination and further reduction is interesting. It was assumed the process mechanism is of the radical nature (Scheme 20).

CONCLUSION

The oxidative functionalization of methane may occur via both one- and two-electron mechanisms. Hydrogen peroxide, potassium persulfate, and molecular oxygen are the most frequent oxidants. In most cases the mechanisms proposed for these processes are conjectural. This is especially the case of reactions at elevated pressures.

At the present state of the art, we see the accumulation of knowledge on the reaction mechanisms, and in the near future a breakthrough in technological solutions is expectable. According to Crabtree [15], the study by Periana *et al.* [30] is the closest to the technology-scale solution [30]. We assume that this work has a disadvantage consisting in the use of sulfuric acid. Hydrolysis is needed for the isolation of methanol from methyl bisulfate. After methanol distillation, a very dilute sulfuric acid should be concentrated. Therefore, it is better to use trifluoroacetic acid, which is rather easy to concentrate by distillation upon methyl trifluoroacetate hydrolysis and return it to the process. When comparing the studies of Sen and Fujiwara, we would prefer the first group of studies, because Fujiwara *et al.* used potassium persulfate as an oxidant and it is unclear how to utilize the accumulated potassium sulfate.

Most interesting are the studies in which molecular oxygen is used as an oxidant. However, a reducing agent should be added to the system if one wants to create an efficient system. The best reducing agent is carbon monoxide in our opinion, because its oxidation leads to carbon dioxide, which is easy to remove from the system. Unfortunately, the yield of target products based on the reducing agent is low; that is, its consumption is unproductive. Usually, the corresponding reactions are carried out in trifluoroacetic acid. Therefore, it is topical to develop catalytic systems based on acetic acid that would be as efficient as the analogous systems based on trifluoroacetic acid.

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