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The Selective Functionalization of Saturated Hydrocarbons. Part 45. The Effect of Lower Temperature on the Rate and Efficiency of Formation of Oxidized Products in the Fe^{III}-Fe^{V} and Fe^{II}-Fe^{IV} Manifolds

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Abstract. In the Fe^{III}-Fe^{V} manifold the formation of the iron-carbon bond was found to be very fast, but the evolution to give ketone was slow at -20 °C and -40 °C. However, the efficiency at the latter temperature was good. The iron-carbon bond can be captured rapidly by I^- or by PhSeH. We have confirmed that either way to measure the iron-carbon bond gives essentially the same results. In contrast to the Fe^{III}-Fe^{V} manifold the reactions at -20 °C in the Fe^{II}-Fe^{IV} manifold are very fast for both iron-carbon bond formation and evolution to final products. In this manifold the reactions at -20 °C are more efficient than those at -5 °C.

Introduction

In the early days of Gif Chemistry we recognized that iron based activation processes required pyridine (or a suitable congener) and a carboxylic acid like acetic acid or picolinic acid.[1,2,3] Two activation processes were perceived: one based on Fe^{II}, the other on Fe^{III}. The Fe^{II} process required activation by superoxide as in Scheme 1 in which superoxide reacts with Fe^{II} to make Fe^{III}-O-OH. The Fe^{III} requires activation by H_2O_2 in a displacement reaction to make the same Fe^{III}-O-OH species as in Scheme 2. The evolution of the Fe^{III}-O-OH into the really active species is now understood with greater certainly than before. In the absence of hydrocarbon the species is relatively stable and has a half-life at room temperature of about 50 min. However, on the addition of the saturated hydrocarbon a new species is produced very rapidly.[4] This is formulated as having an Fe^{V}-CHR_2 bond. The half-life of this species for the formation of R_2CH-O-OH is also about 45 min, but on addition of iodide ion the Fe^{V}-CHR_2 species is instantly transformed into R_2CH-I. These observations have been correlated in Scheme 3 with a postulate that two Fe^{III} centers are involved.

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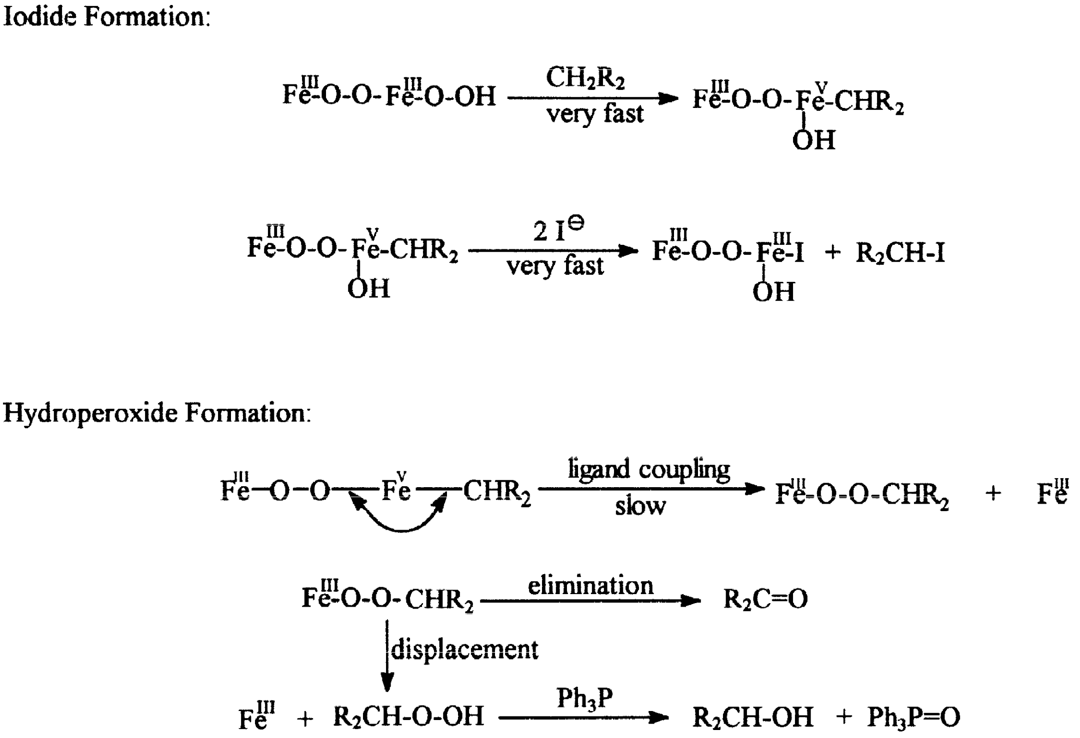
$$Fe^{II} + HO_2^{\bullet} \longrightarrow Fe^{III}\text{-O-OH} \quad \text{(addition)}$$

Scheme 1

$$Fe^{III} + H_2O_2 \longrightarrow Fe^{III}\text{-O-OH} \quad \text{(displacement)}$$

Scheme 2

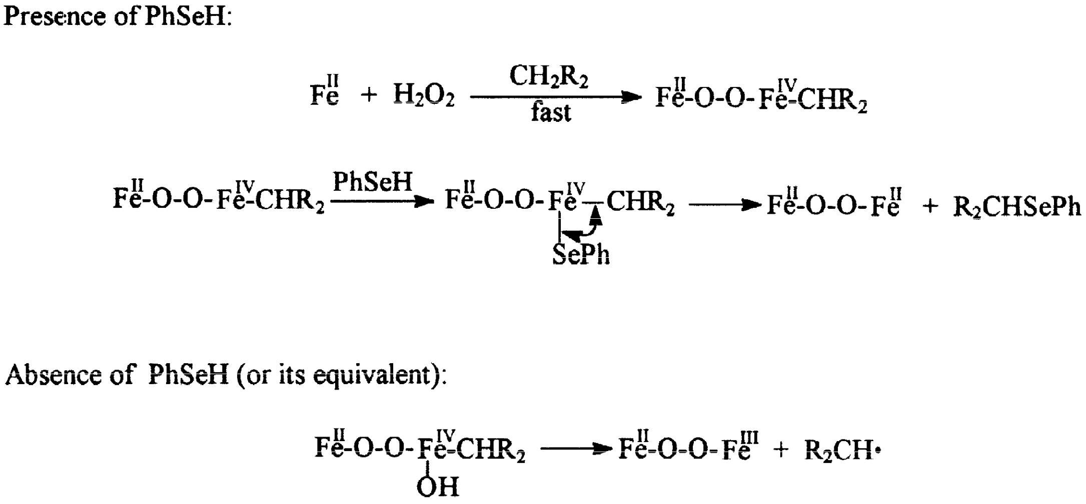


Scheme 3

In Scheme 1, 2 and 3 we have indicated the valence states of the iron species, but we have not added the carboxylic acid species involved and the number of pyridines complexed to the iron. For picolinic acid we are certain, from NMR measurements,[5,6] that there are two picolinic acids (PA) per Fe^{III} and at least one pyridine. In the Fe^{III} species there is, of course, the appropriate carboxylate bridging to hold the two Fe^{III} together. The reaction of this species with the saturated hydrocarbon is , as we mentioned above, very fast. We have postulated that it is the saturated hydrocarbon which activates the Fe^{III} species to an Fe^{V} oxenoid species that immediately reacts with the activating hydrocarbon. This idea was originally introduced to explain ***'The Sleeping Beauty Effect'***. This was based on the observations that Ph_2S and Ph_3P did not react, as expected with the iron species. However, the Ph_3P did reduce the ultimately formed hydroperoxide to alcohol in competition with elimination to give ketone.[2]

Recent work on the phenylselenation of saturated hydrocarbons in the presence of phenylselenol, a perfect trap for radicals, has confirmed that radicals cannot be present and that the activation of the hydrocarbon by Fe^{II}-H_2O_2 is *not* inhibited by the very easily oxidized phenylselenol or by *n*-Bu_3P.[7]

The reactions summarized in Schemes 1 through 3 take place in what we have called the Fe^{III}-Fe^{V} manifold[3]. On the other hand we have shown that the phenylselenation reaction takes place in a different manifold which we have called the Fe^{II}-Fe^{IV} manifold.[3] In scheme 4 we summarize the reactivity of this manifold. The rate of the reaction is much faster in this manifold than in the Fe^{III}-Fe^{V} manifold. Both manifolds require the carboxylic acid function and pyridine (or an appropriate congener) for the hydrocarbon activation. If we assume that the carboxylate function permits bridging then we can again involve a two iron species which reacts as depicted in Scheme 4.



Presence of PhSeH:

$$\overset{II}{Fe} + H_2O_2 \xrightarrow[\text{fast}]{CH_2R_2} \overset{II}{Fe}\text{-O-O-}\overset{IV}{Fe}\text{-}CHR_2$$

$$\overset{II}{Fe}\text{-O-O-}\overset{IV}{Fe}\text{-}CHR_2 \xrightarrow{PhSeH} \overset{II}{Fe}\text{-O-O-}\underset{SePh}{\overset{IV}{Fe}}\text{-}CHR_2 \longrightarrow \overset{II}{Fe}\text{-O-O-}\overset{II}{Fe} + R_2CHSePh$$

Absence of PhSeH (or its equivalent):

$$\overset{II}{Fe}\text{-O-O-}\underset{OH}{\overset{IV}{Fe}}\text{-}CHR_2 \longrightarrow \overset{II}{Fe}\text{-O-O-}\overset{III}{Fe} + R_2CH\bullet$$

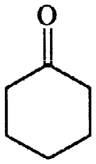
Scheme 4

In the presence of PhSeH which could act as a special ligand, it is postulated that the hydrocarbon reacts with the activated iron species and affords the selenide PhSe-CHR_2 by ligand coupling. The formation of carbon radicals can be diminished due to the excess of PhSeH. Recently we have shown that chloride R-Cl can also be formed by ligand coupling. However, in the absence of any special ligand, the active Fe^{IV} species, Fe^{IV}-CHR_2, can undergo homilytic bond cleavage to give carbon radicals and Fe^{III}. The radicals react with pyridine (under argon) or with oxygen to furnish the expected radical products.

A factor of importance in the oxidation of saturated hydrocarbons is the yield with respect to the hydrogen peroxide, or other oxidant that was used. Another consideration is the temperature at which this yield is optimal. Within the basic theory of the two manifolds we have examined systematically the effect of temperature on yield for the first time.

Results and Discussion

Table 1 shows the reactions in the Fe^{III}-Fe^{V} manifold (Scheme 3) at varying temperatures. Cyclohexanone **1** and cyclohexanol **2** are formed. However, the addition of iodide to an aliquot furnished cyclohexyl iodide **3** which was a measure of the amount of iron-carbon bond will respect to time. Entry 1 showed that at -40 °C the reaction to give the iron-carbon bond was fast. However, as expected, the evolution to give ketone and alcohol was very slow. After 16 hr the efficiency of the reaction was a commendable 86%, but the presence of the iron-carbon bond was indicated as shown by the formation of cyclohexyl iodide. In Entry 2 the reaction temperature was raised to -20 °C. The efficiency of the reaction decreased after 13hr comparing with Entry 1. The effect of the amount of H_2O_2 added was studied in Entry 4. There was a pleasing linear relationship between the amount of H_2O_2 added and the amount of iron-carbon bond formed after 1 minute, although the efficiency was only about 25%. The total amount of products after 13hr was close to the amount at 1 min, but still showed a significant amount of iron-carbon bond. When the concentration of $FeCl_3 \cdot 6H_2O$ was again doubled to 4 mmol, the efficiency was reduced (Entry 5). When LiI was introduced into the reaction system from the beginning, the major product was the expected cyclohexyl iodide **3**. Table 1 shows that a low concentration of Fe^{III} was preferable for increased efficiency as well as a lower temperature. The formation of the iron-carbon bond was demonstrated in each experiment. At zero degree (Entry 3) the initial formation of the iron-carbon bond and then its steady conversion into ketone was clearly demonstrated with an efficiency near to 60%.



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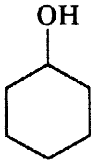

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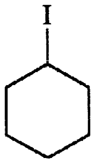

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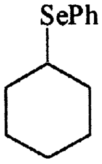

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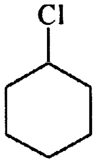

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Table 1. Gif Reactions at Low Temperature within the Fe^{III}-Fe^{V} Manifold

Entry	**Temp.**	**H_2O_2 (mmol)**	**Reaction time**	**1 (mmol)**	**2 (mmol)**	**3 (mmol)**	**Efficiency[e] (%)**
1[a]	-40°C	4	1min	n.d.	n.d.	0.73	18.3
			10min	0.04	0.03	0.88	25.5
			30min	0.04	0.02	1.04	29.0
			1h	0.04	0.03	0.92	26.5
			16h	1.26	0.06	0.74	84.5
2[a]	-20°C	4	1min	tr.	n.d.	0.90	22.5
			13h	0.47	0.13	0.60	45.0
3[a]	0 °C to R.T.	4	1min	0.12	0.04	0.91	30.8
			10min	0.15	0.05	0.95	33.8
			30min	0.25	0.07	0.90	38.5
			1h	0.47	0.11	0.72	47.0
			2h	0.93	0.10	0.19	56.3
			4h	1.14	0.03	n.d.	58.5
			6h	1.10	0.03	n.d.	56.5
4[b]	-20°C	1	1min	n.d.	n.d.	0.22	22.0
		2	1min	n.d.	n.d.	0.56	28.0
		4	1min	tr.	n.d.	1.06	26.5
		8	1min	0.06	tr.	2.06	27.3
		8	13h	1.10	0.23	0.48	39.3
5[c]	-20°C	4	30min	0.05	0.05	0.36	14
			1h	0.06	0.05	0.40	15.5
			1h30	0.11	0.07	0.39	18.8
			2h	0.26	0.09	0.35	26.3
			2h30	0.32	0.10	0.26	27.5
			4h	0.47	0.08	0.05	28.8
6[d]*	0°C to R.T.	4	1min	n.d.	n.d.	0.30	7.5
			15min	n.d.	n.d.	0.69	17.0
			40min	n.d.	n.d.	0.95	23.8
			1h	n.d.	n.d.	1.02	25.5
			1h30	tr.	n.d.	1.09	27.3
			2h	0.04	n.d.	1.11	29.8
			4h	0.05	n.d.	1.10	30.0
	-20°C	4	15min	0.05	0.02	0.21	8.8
			30min	0.05	0.02	0.82	24.0
			1h	0.05	0.02	0.92	26.5
			2h	0.05	0.02	0.98	28.0
			4h	0.05	0.02	0.98	28.0

For entries 1 to 5, an aliquot of the reaction mixture was quenched with a solution of LiI (0.4 mmol) in pyridine (2 mL) at room temperature. The products were analyzed by GC with naphthalene as internal standard.

[a] $FeCl_3 \cdot 6H_2O$ (1 mmol), PA (4 mmol), Cyclohexane (50 mmol), Pyridine (30 mL).

[b] $FeCl_3 \cdot 6H_2O$ (2 mmol), PA (8 mmol), Cyclohexane (50 mmol), Pyridine (30 mL).

[c] $FeCl_3 \cdot 6H_2O$ (4 mmol), PA (8 mmol), Cyclohexane (20 mmol), Pyridine (33 mL).

[d] $FeCl_3 \cdot 6H_2O$ (4 mmol), PA (8 mmol), Cyclohexane (20 mmol), LiI (2 mmol), Pyridine (33 mL).

* Lithium iodide was added to the reaction mixture before H_2O_2 addition.

[c] With respect to H_2O_2 (1-8 mmol). Calculated considering that 2 mmol of H_2O_2 is consumed for each 1 mmol of ketone and alcohol and 1 mmol of H_2O_2 is consumed for 1 mmol of cyclohexyl iodide.

In comparing Entries 1, 2 and 3 it would seem that there is an advantage in carrying out the initial stages at lower temperatures and then allowing the reaction to warm slowly to 0 °C or room temperature. The results at -40 °C and -20 °C present no special advantage with respect to the formation of ketone and alcohol on the time scale chosen.

We postulated some years ago that the remarkably efficient phenylselenation reaction of saturated hydrocarbons was due to capture of the iron-carbon bond.[8] We now know that this is within the Fe^{II}-Fe^{IV} manifold. Recently the role of iodide ion in the capture of the iron-carbon bond has been demonstrated[4] as in the examples in Table 1. If these two reagents are capturing the same iron-carbon bond efficiently then both reagents should afford comparable yields of products on aliquots drawn from the same experiments. Table 2 presents the results on an experiment carried out at -20 °C with aliquots quenched with either I^- or PhSeH. The PhSeH was generated by reaction of PhSeSePh with a 50% excess of *n*-Bu_3P. The excess of the latter reagent guarantees that any PhSeH that is oxidized to PhSeSePh will be at once reduced back to PhSeH again.

Table 2. Gif Reactions at Low Temperature with Detection of the Iron-Carbon Bond

Entry	Temp.	H_2O_2 (mmol)	Reaction time	1 (mmol)	2 (mmol)	3 (mmol)	4 (mmol)	Efficiency* (%)
1	-20°C	2	1min	0.04	tr.	0.68	0.64	38
			1h	0.03	tr.	0.64	0.60	35
			3h	0.07	0.03	0.60	0.54	40
			6h	0.10	0.04	0.58	0.49	43
			19h	0.25	0.06	0.36	0.27	49
			22h	0.26	0.05	0.35	0.24	49

All the products were analyzed by GC with naphthalene as internal standard. The reaction was carried out at -20°C under an argon atmosphere. $FeCl_3 \cdot 6H_2O$ (2 mmol), PA (4 mmol), Cyclohexane (50 mmol), Pyridine (30 mL), H_2O_2 (2 mmol). Two aliquots of the reaction mixture were quenched, separately, with both solutions of LiI (0.4 mmol) and PhSeSePh/*n*-Bu_3P (0.3/0.45 mmol) in pyridine (2 mL) at room temperature.

* With respect to H_2O_2 (2 mmol). Calculated considering that 2 mmol of H_2O_2 is consumed for each 1 mmol of ketone and alcohol and 1 mmol of H_2O_2 is consumed for 1 mmol of cyclohexyl iodide or cyclohexylphenyl selenide.

As expected, at 1 min after the addition of 2 mmol of H_2O_2, separate quenching, by either iodide ion or PhSeH showed essentially the same amount of products coming from the iron-carbon bond. The reaction again demonstrates the fast rate at which the iron-carbon species is formed. With time there was, as expected at -20 °C, a slow evolution to furnish ketone and alcohol. Even after 22 hr about half of the originally formed iron-carbon bond was still present. The amounts of iodide 3 and of phenylselenide 4 formed were nearly the same and the efficiency varied only from 38 to 49%. Also noteworthy was the fact that the Fe^{III}-H_2O_2 ratio was chosen as 1:1. According to our theory the formation of iodide 3 takes place in the Fe^{III}-Fe^{V} manifold and as iodide does not reduce Fe^{III} to Fe^{II} under the conditions used. However, the formation of the phenylselenide 4 was shown to take place in the Fe^{II}-Fe^{IV} manifold. As PhSeH reduces Fe^{III} to Fe^{II}, we conclude that the formation of 4 depends on reduction of the Fe^{V}-carbon bond in the Fe^{III}-Fe^{V} manifold to the Fe^{IV}-carbon bond with ligation of the PhSeH with the Fe^{IV} species. Then the usual ligand coupling process affords phenylselenide 4 and Fe^{II}. It is reasonable that this extra complication leads to a slightly lower yield of selenide 4 than of iodide 3.

We then turned to a study of Gif Chemistry in the Fe^{II}-Fe^{IV} manifold (Table 3). As already mentioned the reaction which gives cyclohexyl chloride is much faster in this manifold. Also reactions were more efficient at -20 °C than at -5 °C. In Entry 1 an aliquot was quenched with iodide ion at room temperature whereas Entries 2 through 5 the iodide quenching was carried out at -20 °C. Both Entries 1 and 2 showed that the reaction was almost complete in 1 min at -20 °C. The amount of residual iron-carbon bond was very small (as shown by the iodide 3). A striking fact was that both chlorides originally attached to Fe^{II} were efficiently incorporated into the cyclohexyl chloride 5. In Entry 3 an excess of chloride ion (20 mmol) was present before the H_2O_2 was added. Again the reaction was fast with only a trace of the iron-carbon bond left after 1 min which related to an increase in chloride formation (2.58 mmol) and in efficiency (70.5%) after 30 min. The amount of LiCl showed no significant difference (Entry 4). Substituting $FeCl_2{\bullet}4H_2O$ for $Fe(ClO_4)_2{\bullet}6H_2O$ with addition of LiCl (10 mmol) before the addition of the H_2O_2 showed a significant diminution in the amount of cyclohexyl chloride 5 that was formed. This is support for the chloride arising from ligand coupling. In Entry 6 the amount of $FeCl_2{\bullet}4H_2O$ was increased to equal the amount of H_2O_2, the reaction temperature increased to -5 °C, and the quenching with iodide was carried out at room temperature. Here the reaction was much less efficient and almost only chloride was formed. Although the amount of cyclohexane used was reduced to 20 mmol this should not have a great effect. When varying amounts of lithium iodide were added before the addition of H_2O_2, a large effect on the product distribution was noted. When 1 mmol of lithium iodide was added the major product was cyclohexyl chloride 5 (Entry 7). In contrast only cyclohexyl iodide 3 was formed when a large excess (8 mmol) of lithium iodide was added, but in both cases the efficiency was much lower as usual.

Table 3. Gif Reactions at Low Temperature within the Fe^{II}-Fe^{IV} Manifold

Entry	Temp.	H_2O_2 (mmol)	Reaction time	**1** (mmol)	**2** (mmol)	**3** (mmol)	**5** (mmol)	Efficiency[i] (%)
1[a]	-20°C	4	1min	0.10	0.05	0.13	2.08	62.8
			10min	0.13	0.06	0.14	1.99	62.8
			30min	0.19	0.08	0.12	2.00	66.5
2[b]	-20°C	4	1min	0.17	0.07	0.10	1.91	62.3
			10min	0.15	0.06	0.15	2.01	64.5
			30min	0.20	0.07	0.10	1.82	61.5
3[c]	-20°C	4	1min	0.09	n.d.	0.07	1.93	54.5
			10min	0.10	n.d.	n.d.	2.13	58.3
			30min	0.12	n.d.	n.d.	2.58	70.5
4[d]	-20°C	4	1min	0.07	n.d.	0.09	1.47	42.5
			10min	0.07	n.d.	n.d.	1.81	48.8
			30min	0.16	n.d.	n.d.	2.47	69.8
5[e]	-20°C	4	1min	0.10	0.06	0.14	0.50	24.0
			10min	0.11	0.04	0.15	0.50	23.8
			30min	0.12	0.04	0.13	1.14	39.8
6[f]	-5°C	4	1min	0.07	n.d.	n.d.	0.80	23.5
			15min	0.06	n.d.	n.d.	0.84	24.0
			30min	0.06	n.d.	n.d.	0.84	24.0
			16h	0.06	n.d.	n.d.	0.84	24.0
7[g]**	-5°C	4	1min	0.04	tr.	0.28	0.63	24.8
			15min	0.04	tr.	0.28	0.65	25.3
			30min	0.04	tr.	0.29	0.66	25.8
			16h	0.05	tr.	0.32	0.75	29.3
8[h]**	-5°C	4	1min	0.03	tr.	0.74	n.d.	20.0
			15min	tr.	tr.	0.73	n.d.	18.3
			30min	tr.	tr.	0.72	n.d.	18.0
			16h	tr.	tr.	0.75	n.d.	18.8

For the entries 1 to 6, an aliquot of the reaction mixture was quenched with a solution of LiI (0.4 mmol) in pyridine (2 mL). The products were analyzed by GC with naphthalene as internal standard. All the reactions were carried out under an argon atmosphere.

[a] $FeCl_2 \cdot 4H_2O$ (1 mmol), PA (3 mmol), Cyclohexane (50 mmol), Pyridine (30 mL). Quenching at room temperature.

[b] $FeCl_2 \cdot 4H_2O$ (1 mmol), PA (3 mmol), Cyclohexane (50 mmol), Pyridine (30 mL). Quenching at -20°C.

[c] $FeCl_2 \cdot 4H_2O$ (1 mmol), PA (3 mmol), Cyclohexane (50 mmol), Pyridine (30 mL), LiCl (20 mmol). Quenching at -20°C.

[d] $FeCl_2 \cdot 4H_2O$ (1 mmol), PA (3 mmol), Cyclohexane (50 mmol), Pyridine (30 mL), LiCl (6 mmol). Quenching at -20°C.

[e] $Fe(ClO_4)_2 \cdot 6H_2O$ (1 mmol), PA (3 mmol), Cyclohexane (50 mmol), Pyridine (30 mL), LiCl (10 mmol). Quenching at -20°C.

[f] $FeCl_2 \cdot 4H_2O$ (4 mmol), PA (8 mmol), Cyclohexane (20 mmol), Pyridine (33 mL). Quenching at room temperature.

** The lithium iodide was in the reaction mixture.

[g] $FeCl_2 \cdot 4H_2O$ (4 mmol), PA (8 mmol), Cyclohexane (20 mmol), LiI (1 mmol), Pyridine (33 mL).

[h] $FeCl_2 \cdot 4H_2O$ (4 mmol), PA (8 mmol), Cyclohexane (20 mmol), LiI (8 mmol), Pyridine (33 mL).

[i] With respect to H_2O_2 (4 mmol). Calculated considering that 2 mmol of H_2O_2 is consumed for each 1 mmol of ketone and alcohol and 1 mmol of H_2O_2 is consumed for 1 mmol of cyclohexyl chloride and iodide.

The results confirm that hydrogen peroxide, Fe^{III}, the saturated hydrocarbon (cyclohexane) and the correct ligands form an active species rapidly even at low temperature. For the Fe^{III}-Fe^{V} manifold the species evolves to products at it but is much slower at depressed temperature. The Fe^{II}-Fe^{IV} manifold is also entered rapidly at low temperature to give the active species which forms products rapidly and is difficult be intercepted by other halides or phenylselenol.

Experimental

Chemicals were purchased from the Aldrich Chemical Co., except for pyridine, diethyl ether, magnesium sulfate and hydrogen peroxide (30%) from EM Science.

Gas Chromatography (GC) analysis was performed on a Hewlett-Packard 5890 series II instrument equipped with a flame ionization detector and a Hewlett-Packard 3396A integrator. Purified N_2 was used as the carrier gas. The capillary columns used were a DB-WAX (Polyethylene glycol, 30m x 0.32mm i.d., 25μm film thickness) and DB-5 (Chemically bonded methyl silicone, 30m x 0.32mm i.d., 25μm film thickness) from J&W Scientific.

The routinely employed temperature program for GC was: initial temperature: 50°C, initial time: 5 min, rate: 20°C/min, final temperature: 220°C, final time: 10 min. Injector and detector temperatures were 245°C and 280°C or 300 °C, respectively.

Gas Chromatography-Mass Spectrometry (GC-MS) analysis was carried out on a Hewlett-Packard 5890A series II gas chromatography coupled with a Hewlett-Packard 5971 series quadrupole mass-selective detector (40eV, electron impact). Helium was used as the carrier gas. The capillary column used in the GC-MS was a HP-5MS (Cross-linked 5% phenyl methyl silicone, 30m x 0.32mm i.d., 25μm film thickness).

The routinely employed temperature program for GC-MS was: initial temperature: 50°C, initial time: 2 min, rate: 20°C/min, final temperature: 210°C, final time: 10 min. Injector and detector temperatures were 250°C and 280°C respectively.

Typical quenching with lithium iodide (LiI). An aliquot (1 mL) was taken from the reaction mixture and quenched at the temperature reported in the appropriate table with 0.4 mmol of LiI in 2 mL of pyridine. After stirring 5 min, the mixture was analyzed by the typical quantification procedure.

Typical quenching with diphenyldiselenide (PhSeSePh). PhSeSePh (0.3 mmol) was dissolved under argon in 2 mL of pyridine. After complete solubilization, Bu_3P (0.45 mmol) was added and the mixture was stirred for 2 hr at room temperature under argon. An aliquot (1 mL) was taken from the reaction mixture and quenched at room temperature by the solution (PhSeSePh/Bu_3P/pyridine) and the resulting mixture was stirred 30 minutes under argon before the typical quantification procedure.

Typical quantification procedure. The quenched mixture was diluted with 5 mL of water and extracted with diethyl ether (3x5 mL). The combined organic extracts was added with naphthalene solution (1 mL, 0.01M or 0.08M in diethyl ether) as internal standard and dried over $MgSO_4$, The products were analyzed by gas chromatography. All products had identical retention times with authentic samples.

Typical Fe^{III}-H_2O_2 experiment in the Fe^{III}-Fe^{V} manifold. Variable amounts (see Tables) of $FeCl_3{\bullet}6H_2O$ (1-4 mmol) and picolinic acid (4-8 mmol) were dissolved in 30-33 mL of pyridine. The mixture was stirred for 30 min before adding the amount of substrate as reported in the appropriate table. The reaction mixture was cooled to the working temperature (0°C to -40°C): 30% aqueous hydrogen peroxide (2-8 mmol) was then added dropwise to the stirred solution. The products formed were quantified at different times (see Table 1 and 2) by the general work-up procedure.

Typical Fe^{II}-H_2O_2 experiment in the Fe^{II}-Fe^{IV} manifold. Reactions were typically carried out under an argon atmosphere. Variable amounts (see Tables) of $FeCl_2{\bullet}4H_2O$ or $Fe(ClO_4)_2{\bullet}6H_2O$ (1-4 mmol) and picolinic acid (3-8 mmol) were dissolved in 30-33 mL of pyridine. The mixture was stirred for 30 min before adding the amount of substrate as reported in the Table 3. The reaction mixture was cooled to the working temperature (0°C to -40°C): 30% aqueous hydrogen peroxide (4 mmol) was then added dropwise to the stirred solution. The products formed were quantified at different times (see Table 3) by the general work-up procedure.

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