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The Functionalization of Saturated Hydrocarbons. Part 34.[†] A Study on the Mechanism of Tempo Trapping in GIF-Type Systems

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Abstract: The photolysis of Barton PTOC esters (radical reaction) in presence of Tempo produces alkyl-Tempo in very good yield. Good results are also obtained with Fe^{II}-H_2O_2 system (pyridine, Picolinic Acid, hydrocarbon). In this case the Fe^{II}-Fe^{IV} manifold is responsible for the formation of the adduct. Using Fe^{III}-H_2O_2, Tempo adduct is formed at the same rate as the oxidation products. Mechanistic studies suggest the oxidation of Tempo by the Fe^{V} to give an oxoamonium salt and an Fe^{IV} species. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The selective functionalization of saturated hydrocarbons under mild conditions remains a problem of contemporary interest.[1,2] Oxidation using, for example, H_2O_2 and Fe^{III} in pyridine-acetic acid (Gif-type chemistry) affords selectively at room temperature under neutral conditions nearly quantitative yields of ketones on conversions of up to 20-30 %. At higher attempted conversions ketones are further oxidized, but never in the α-position.[3,4]

We have postulated the formation of an Fe^{V}-carbon bond and its evolution in an Fe^{III}-Fe^{V} manifold into ketone. Carbon radicals do not play a role except when certain tertiary positions are involved.

Recently we recognized the existence of a second Fe^{II}-Fe^{IV} manifold.[5] Here H_2O_2 oxidizes Fe^{II} to an Fe^{IV} species in a very fast reaction. The Fe^{IV} species attacks saturated hydrocarbons selectively at secondary positions. An Fe^{IV}-carbon bond is postulated which breaks into carbon radicals which react with anions attached to the Fe^{III} species resulting from the fragmentation. In this way chlorides, bromides, azides etc. are produced with coformation of the Fe^{II} species. As usual in pyridine, hydroxyl radicals do not play any role in the chemistry and are not produced in significant amount.[6] The rate of reaction of hydroxyl radicals with pyridine is very fast (about 1.7×10^{9} M^{-1} sec^{-1} for pyridine and 2.1×10^{7} for protonated pyridine).[7]

With the two manifolds, radical (Fe^{II}) and non-radical (Fe^{III}) there is the possibility of a transfer from one to the other. Indeed it is surprising that all the valence states of iron do not interconvert by one electron transfer. Fortunately, this is not in general the situation. In the Fe^{III}-Fe^{V} manifold, C-Cl bond formation is never seen however must chloride is added. However, addition of reducing agents like triphenylphosphine in

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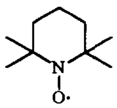
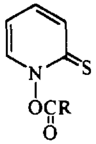
the presence of H_2O_2 converts Fe^{III} to Fe^{II} and the much faster Fe^{II}-Fe^{IV} manifold takes over to make chloride.[5,8] Accurate titration for Fe^{II} and Fe^{III} makes an important contribution.[9]

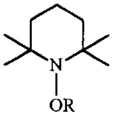
During the course of our work on the detection of hydroperoxides as intermediates in the formation of ketones in the Fe^{III}-H_2O_2 reaction[10] we noted that Tempo (**1**) was able to trap an intermediate. We considered this to be a property of an Fe^{V}-carbon bond and not indicative of radical chemistry.[11, 12] There were other stronger arguments against radical chemistry.

Now we have examined again the behavior of the Fe^{III}-H_2O_2 system in comparison with that of the Fe^{II}-H_2O_2 system toward Tempo-trapping.


Tempo (**1**)


(R = Cyclohexyl or Adamantyl)

Barton PTOC esters (**2**)


Alkyl-Tempo (**3**)

RESULTS AND DISCUSSION

Genuine radical reactions: photolysis of Barton PTOC esters

Table 1: Photolysis of Barton PTOC esters.

Entry	Conditions	Products (mmol)		
		R-Tempo	R-Spy	R-X
1	A, RT, Ar	0.39	0.10	---
2	A, RT, O_2	0.39	0.09	---
3	B, -30°C, Ar	---	0.37	-Cl (0.23) [(a)]
4	C, -40°C, Air	0.38	0.09	n.d.
5	A*, 0°C, Air	0.08	0.10	-Br (0.30)
6	A**, 0°C, Air	0.16	0.10	-Br (0.19)
7	D, 0°C, Air	0.18	0.06	-Br (0.22)
8	A#,0°C, Air	0.38	0.10	n.d

Except as specified, these reactions were carried out by dissolving Barton PTOC esters in 15 ml of pyridine, then photolysis with an 'MM' lamp[13]. Ar refers to Argon. (a) 0.36 mmol of cyclohexyl carboxylic acid was formed by hydrolysis of Barton PTOC ester. (A) Cyclohexyl Barton ester: 0.5 mmol, AcOH: 1.5 ml, Tempo: 2.5 mmol. * $CBrCl_3$: 2.5 mmol. ** $CBrCl_3$: 1.0 mmol. # CCl_4: 2.5 mmol. (B) $Fe^{III}Cl_3 6H_2O$: 1 mmol, Cyclohexyl Barton ester: 2 mmol, LiCl: 10 mmol. (C) $Fe^{III}Cl_3 6H_2O$: 0.1 mmol, Cyclohexyl Barton ester: 0.5 mmol, LiCl: 2.5 mmol, Tempo: 1 mmol. (D) $Fe^{III}(NO_3)_3.6H_2O$: 0.1mmol, Cyclohexyl Barton ester: 0.5 mmol, AcOH: 1.5 ml,Cyclohexane: 5 mmol, TBHP: 5mmol, $CBrCl_3$: 1 mmol, Tempo: 2.5 mmol.

In genuine carbon radical reactions which were carried out by photolysis of Barton PTOC esters (**2**), Tempo is a superior trap. With or without O_2, another good radical trap, the ratio of products does not change. The alkyl-Tempo adduct (**3**) is always the major product (**Table 1**, entries 1 and 2). When $FeCl_3$ is present, cyclohexyl chloride and Fe^{II} is formed by radical attacking $FeCl_3$ (entry 3) , which is one of the steps in the Fe^{II}-Fe^{IV} manifold. Again, this reaction is suppressed by Tempo trapping (entry 4). In the presence of Tempo and $CBrCl_3$, a competition between Tempo and $CBrCl_3$ trapping occurs. Both cyclohexyl-Tempo adduct and cyclohexyl bromide are formed, the amount of them depends on the ratio of Tempo to $CBrCl_3$ added (entries 5,6 and 7). Cl_3CCCl_3 is observed as the byproduct of $CBrCl_3$ trapping, which is consistent with the radical nature of this reaction. Apparently, CCl_4 is not able to compete with Tempo to trap cyclohexyl radicals so cyclohexyl chloride is not detected in entry 8 when Tempo and CCl_4 are present.

Tempo trapping using Fe^{II} systems

Table 2: Fe^{II} systems

Entry	Conditions	Products(mmol)			
		R-Tempo	R=O	R-X	Ox./R-Tempo
1	A+H_2O_2 (3mmol), Air	---	n.d.	-p-Pyr (0.52) -o-Pyr (0.83)	---
2	A**+H_2O_2 (3mmol), Air	---	trace	-Cl (1.07)	---
3	A*+H_2O_2 (3mmol), Air	1.60	trace	n.d.	---
4	A*+H_2O_2 (3mmol), Ar	2.03	n.d.	n.d.	---
5	A***+H_2O_2 (3mmol), Air	1.06	n.d.	n.d.	---
6	B+H_2O_2 (5mmol), Ar	1.89	0.53	---	0.28
7	C+H_2O_2 (4mmol), Ar	0.48	0.18	---	0.38
8	D+H_2O_2 (4x3mmol), Ar	3.49	1.27	---	0.36
9	E+H_2O_2 (15x1mmol), Ar	4.23	0.23	-p-Pyr (0.80) -o-Pyr (0.53)	0.05

Except as specified, these reactions were carried out with 40 mmol cyclohexane in 30 ml pyridine overnight.The Ox./R-Tempo ratio is defined as the total oxidation products divided by total alkyl-tempo products. PA refers to picolinic acid. (A) $Fe^{II}(ClO_4)_2 6H_2O$: 3 mmol, AcOH: 3 ml, RT.* with Tempo: 5 mmol. ** with, LiCl: 10mmol. *** with Tempo: 5 mmol.. (C) $Fe^{II}(ClO_4)_2 6H_2O$: 1 mmol, PA: 3 mmol, Tempo: 2 mmol, 0°C to RT., LiCl: 10mmol. (D) $Fe^{II}(ClO_4)_2 6H_2O$: 3 mmol, PA: 9 mmol, Tempo: 3 mmol, 0°C to RT. (B) $Fe^{II}(ClO_4)_2 6H_2O$: 3 mmol, PA: 9 mmol, Tempo: 5 mmol, Ascorbic acid: 1.5 mmol, 0°C to RT. (E) $Fe^{II}(ClO_4)_2 6H_2O$: 0,25 mmol, AcOH: 3 ml, Zn: 20 eq, 0°C to RT, Tempo:6x1 mmol.

The experiments using Fe^{II}-H_2O_2 are summarized in **Table 2**. Without addition of Tempo, the only products formed are the cyclohexyl-pyridine coupling products (entry 1) or cyclohexyl chloride when LiCl was present (entry 2). The formation of these compounds is characteristic of carbon radicals formed by the Fe^{II}-Fe^{IV} manifold. In presence of Tempo, the major product is the cyclohexyl-Tempo (entries 3,4, and 5) which is formed by the reaction between the carbon radical and Tempo. Fe^{II} and H_2O_2 is a very fast reaction which ceased when all the Fe^{II} has been oxidized to Fe^{III}. Then an excess of oxidant, permits the formation of ketone slowly (entries 6 and 7). The formation of the Tempo adduct increases in the presence of ascorbic acid which reduces Fe^{III} to Fe^{II} (entry 8).[9] Using Zn-acetic acid as reductant gave a better result (entry 9): starting with only 0.25 mmol of Fe^{II} we obtained 4.23 mmol of Tempo adduct.

A blank experiment with only $Fe^{II}(ClO_4)_2$ and Tempo in pyridine, shows that Fe^{II} is converted to Fe^{III} in less than two minutes. The fact that we still find a large amount of cyclohexyl-Tempo proves that the rate of the Fe^{II}-Fe^{IV} manifold is even faster.

Tempo trapping using Fe^{III} systems

It has been demonstrated that Gif type Chemistry does not involve the formation of carbon radicals when Fe^{III}-H_2O_2 is used. We show in **Table 3** that in the presence of Tempo, cyclohexyl-Tempo can be formed (entry 1) at the same rate as the oxidation products (T½ = 90 min). If we increase the amount of Tempo, the ratio of oxidation products to cyclohexyl-Tempo decreases (entry 2). Without a carboxylic acid as ligand, no reaction takes place, and only oxygen is formed (entry 3).

The possibility that the Tempo is coordinated to Fe^{III} to give Fe^{IV} has been considered. This can not be true, the formation of an Fe^{IV} species should generate a sequence similar to the Fe^{II}- Fe^{IV} manifold. A blank experiment was made without oxidant and no reaction occured (entry 4). However, the rates of these two reactions producing cyclohexyl-Tempo were very different, T½ Fe^{III} = 90 min and T½ Fe^{II} < 2 min respectively. The experiment carried out with an excess of LiCl and a small amount of Tempo does not produce alkyl chloride, and only some traces of Fe^{II} have been detected (entry 5). A reaction without hydrocarbon, using Fe^{III}: 1 mmol, Tempo: 0.5 mmol and H_2O_2: 1 mmol in 30ml of pyridine was carried out to see if the Tempo could reduce the Fe^{III} to Fe^{II} . No Fe^{II} was detected and only 0.22 mmol of oxygen was formed.

Also, when we increased the amount of oxidant, the ratio of oxidation products and cyclohexyl-Tempo was constant (entries 6 and 7). Similar results were obtained when the experiments were carried out in a mixture of pyridine and acetic acid (10 to 1 ratio) instead of using picolinic acid as ligand (entries 9 and 10). Ketone, or a mixture of ketone and alkyl-Tempo if Tempo was used,were the only major products, while alkyl chloride was not detected in a significant amount.

In the presence of a small amount of $CBrCl_3$, both cyclohexyl bromide and cyclohexyl-Tempo as well as cyclohexanone were formed (entry 11). The fact that CO_2, instead of Cl_3CCCl_3 or $CHCl_3$, was formed as the by-product when trapping with $CBrCl_3$, suggests this reaction is non-radical in nature, which is consistent with the proposed mechanism for Gif systems. Again CCl_4 did not give any significant amount of trapping products (entry 12).

When the reactions with Tempo and Fe^{III} were run under argon or under oxygen, there was a difference. More Tempo trapping was seen under argon (entries 13 and 14). Insertion into an Fe^{III}-carbon bond of oxygen would change the ratio.[10]

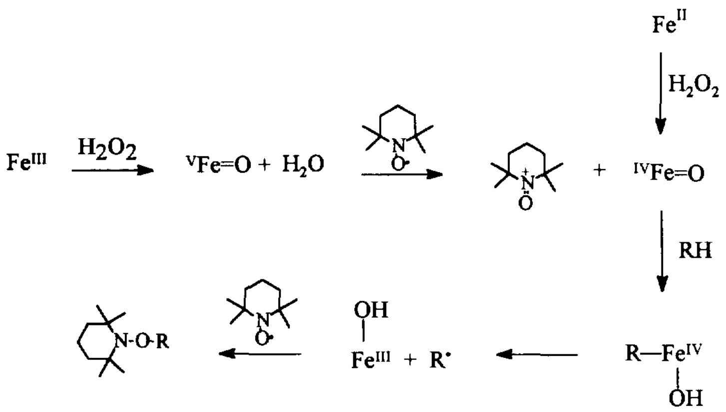
Table 3: Fe^{III} systems

Entry	Conditions	Products(mmol)				
		R-Tempo	R=O	R-OH	R-X	Ox./R-Tempo
1	A+H_2O_2 (5 mmol), Ar	0.29	0.91	n.d	n.d.	3.14
2	A*+H_2O_2 (5mmol), Ar	0.76	0.54	0.02	n.d.	0.73
3	B+H_2O_2 (1mmol), Air	n.d.	n.d.	n.d.	n.d.	---
4	A* no H_2O_2; Ar	n.d.	n.d.	n.d.	n.d.	---
5	C+H_2O_2 (2mmol), Ar	0.22	0.28	n.d.	n.d.	1.27
6	D+H_2O_2 (1mmol), Ar	0.36	0.20	0.01	n.d.	0.74
7	D+H_2O_2 (3mmol), Ar	0.63	0.47	0.02	n.d.	0.77
8	D+H_2O_2 (5mmol), Ar	0.48	0.64	0.03	n.d.	1.39
9	E+H_2O_2 (30mmol), Air	---	5.16	n.d.	-Cl (trace)	---
10	E*+H_2O_2 (30mmol), Air	2.36	2.25	n.d.	-Cl (n.d.)	0.95
11	F*+H_2O_2 (10mmol), Air	0.38	0.69	---	-Br (0.50)	---
12	F**+H_2O_2 (10mmol), Air	0.10	0.53	---	-Cl (0.04)	---
13	D+H_2O_2 (2mmol), O_2	0.16	0.44	0.16	n.d.	2.81
14	D+H_2O_2 (2mmol), Ar	0.30	0.27	n.d.	n.d.	0.93

Except as specified, these reactions were carried out with 20 mmol cyclohexane in 15 ml pyridine at 0°C to room temperature for 24 hours. (A) $Fe^{III}(PA)_2Cl_2HPyr_2$: 0.3 mmol, Tempo: 1 mmol. * Tempo 2 mmol. (B) $Fe^{III}Cl_3 6H_2O$: 0.5 mmol, Tempo: 1 mmol. (C) $Fe^{III}(PA)_2Cl_2HPyr_2$: 0.5 mmol, LiCl: 20 mmol, Tempo: 0.5 mmol. (D) $Fe^{III}(PA)_2Cl_2HPyr_2$: 0.5 mmol, Tempo: 1 mmol.(E) $Fe^{III}Cl_3.6H_2O$: 3 mmol, Pyridine: 30 ml, AcOH: 3 ml, Cyclohexane: 50 mmol, LiCl: 1 mmol, -20°C to RT, H_2O_2: 30 mmol (3 mmol/15 min). * Tempo: 5 mmol. (F) $Fe^{III}Cl_3 6H_2O$: 0.2 mmol, PA: 0.6 mmol, Pyridine: 30 ml, AcOH: 3 ml, Cyclohexane: 50 mmol, Tempo: 2.5 mmol, RT. * $BrCCl_3$: 1 mmol. .** CCl_4: 10 mmol.

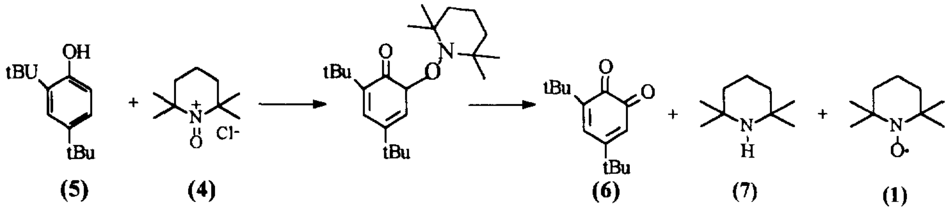
Characterization of the intermediate: 2,2,6,6-tetramethyl-1-oxopiperidium (4)

The oxidation of Tempo by the Fe^{V} to give the 2,2,6,6-tetramethyl-1-oxopiperidium and an Fe^{IV} species, can explain the formation of a radical which is trapped by another molecule of Tempo (**Scheme 1**).



Scheme 1. Proposed mechanism for the Tempo trapping in Fe^{II} and Fe^{III} system using H_2O_2

The oxoammonium salt **(4)** is known to be a good oxidizing agent which can convert ketones to α-diketones [14] and alcohols to ketones.[15] If the mechanism proposed in **Scheme 1** is correct, it should be possible to quench the reaction by trapping the oxoammonium salt **(4)** using a phenol like 2,4-di-*tert*-butylphenol **(5)** as described in **Scheme 2**.



Scheme 2

First, we used the salt in the conditions already described.[14] Using one equivalent of phenol **(5)** with two equivalents of salt **(4)** in CH_2Cl_2 at -80°C to RT under argon, 13% of 3,5-di-*tert*-butyl-*o*-benzoquinone **(6)** was isolated by column chromatography. The same reaction carried out with the Gif system (**Table 4**, entry 1), also showed formation of the quinone **(6)**. The presence of Tempo was necessary to produce **(6)** (entry 2). Some unexpected results were obtained when the blank experiments were carried out without the Fe salt or without H_2O_2 (entries 3 and 4): in both cases some quinone **(6)** was isolated. Later we discovered that, in the presence of oxygen and after purification by column chromatography, the phenol **(5)** was oxidized to the quinone (**6**). These experiments were repeated using a deoxygenated solution and quantified by GC (see experimental part).

Table 4: Reactions with the oxoammonium salt (**4**)

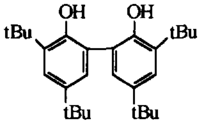
Entry	Conditions	Products (mmol)			
		1	**5**	**6**	**7**
1	A	n.q.	0.80	0.15	n.q.
2	A without Tempo	n.q.	0.86	n.d.	n.q.
3	A without Fe salt	n.q.	0.94	0.10	n.q.
4	A without H_2O_2	n.q.	0.95	0.09	n.q.
5	B	1.14	0.78	0.09	0.29
6	C	0.38	---	0.18	0.25
7	B without Tempo	---	0.94	n.d.	n.d.
8	B without Fe salt	1.98	0.99	traces	n.d.
9	B without H_2O_2	2.08	1.10	n.d.	n.d.
10	D	1.88	0.05	0.14	0.15

(A) 2,4-di-*tert*-butylphenol: 1 mmol, $Fe^{III}(PA)_2Cl_2HPyr_2$: 0.5 mmol , Tempo: 2 mmol, H_2O_2: 3× 1 mmol in 15 ml of pyridine, 0°C to RT, under argon, overnight. The products were isolated by chromatography column (hexane: 20/ CH_2Cl_2: 80), the structures were checked by ^1H NMR. (B) 2,4-di-*tert*-butylphenol: 1 mmol, $Fe^{III}(PA)_2Cl_2HPyr_2$: 0.5 mmol, Tempo: 2 mmol, H_2O_2: 5×1 mmol in 15 ml of pyridine, 0°C to RT, under argon, overnight. (C) 3,5-di-*tert*-butyl-*o*-quinone: 0.5 mmol, $Fe^{III}(PA)_2Cl_2HPyr_2$: 0.5 mmol, Tempo: 1 mmol, H_2O_2: 5×1 mmol in 15 ml of pyridine, 0°C to RT, under argon, overnight. (D) 2,4-di-*tert*-butylphenol: 1 mmol, oxoammonium salt: 2 mmol in 15 ml of pyridine at 0°C to RT, under argon, overnight. In B,C,D, the reaction mixture was deoxygenated before adding H_2O_2.and the products were quantified by GC after different workup (see experimental part). N.q. refers to not quantified.

Entries 8 and 9 showed that when we worked without oxygen, quinone (**6**) and 2,2,6,6- tetramethyl piperidine (**7**) were not formed. The same results were obtained without Tempo (entry 7). The reaction carried out in the Gif system (entry 5) produced, as we expected, the quinone (**6**) and the piperidine (**7**) The formation of (**7**) can be explained only by a mechanism using the salt as intermediate. Owing to a poor mass balance, we conducted a blank experiment to verify the stability of the quinone (**6**) under these conditions (entry 6): the quinone (**6**) was wholly and Tempo only partially consumed. Different unknown peaks appeared in the GC spectrum which were not identified.

We also needed to verify, how the salt (**4**) would react with the phenol (**5**) in the Gif solvent: pyridine (entry 10). Almost identical quantities of quinone (**6**) and piperidine (**7**) were detected thus showing the relationship between these two compounds. A blank experiment was made to check the stability of the quinone (**6**) in this system: the total amount of quinone (**6**) used was recovered at the end of the reaction. The mass balance toward Tempo was correct, but this was not the case for the phenol (**5**). Two unknown compounds were observed by GC and TLC. One of these was isolated from the reaction mixture and identified as the 4,4',6,6'-tetra-*tert*-butyl-*o,o'*-biphenol (**8**) dimer formed by phenolate radical oxidative coupling[16] (electron transfer between the salt (**4**) and the phenol (**5**)); the second, which was not identified, arose from the oxidation of the dimer (**8**).

A blank experiment carried out with only the oxoammonium salt (**4**) in pyridine showed than only a few hours are necessary to reduce the salt (**4**) back to Tempo. This can be explained by an electron transfer between the salt (**4**) and the pyridine.



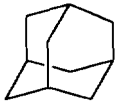
(8)

Adamantane selectivity

Table 5: Selectivity of Adamantane (**9**)

Entry	Conditions	Products (mmol)							
		R-H	R-Tempo secondary	R-Tempo tertiary	R=O	R-OH tertiary	R-Pyr tertiary	C_2/C_3	Mb (%)
1	A	8.58	0.44	0.28	nd	0.02	o- 0.04 p- 0.05	1.2	102
2	B	9.88	0.17	0.17	0.12	0.07	nd	1.2	104

These reactions were carried out with 10 mmol of adamantane, 3 mmol of Tempo, 3 mmol of H_2O_2 in 30 ml pyridine, under an argon atmosphere, at 0°C to room temperature for 24 hours. The C_2/C_3 ratio is defined as an the total secondary products divided by total tertiary products. Mb is mass balance.
(A) $Fe^{II}(ClO_4)_2 \cdot 6H_2O$: 3 mmol, PA: 9 mmol. (B) $Fe^{III}(PA)_2Cl_2HPyr_2$: 1mmol



Adamantane (**9**)

Table 5 shows the reactivity of adamantane (**9**) towards the Fe^{II} and Fe^{III} systems. Starting with Fe^{II} (entry 1), we obtain two times more of adamantyl-Tempo in secondary position than in tertiary position, with a total ratio C_2/C_3 of about 1.2. This value is very close to the one found with the system Fe^{II} / H_2O_2 / LiCl.[5] It is the same for the K.I.E [17]: 2.1 in the case of LiCl experiment and 1.95 in the case of the reaction of Tempo. The mechanism involves the formation of an Fe^{IV} oxenoid, followed by an insertion of hydrocarbon and an iron-carbon bond radical fragmentation. We obtained very similar results using Fe^{III} salts (entry 2). The ratio

C_2/C_3 is the same but with little selectivity for Tempo trapping . Here, as in the other Gif systems, the activation of adamantane involves a species different from a carbon radical.

CONCLUSION

The role of Tempo in the trapping of radicals in the Fe^{II}-Fe^{IV} manifold fits in well with our prior investigations.[5] All the Fe^{II}-H_2O_2 reactions are very fast, even faster than the reaction of the Fe^{II} and Tempo to afford Fe^{III} and TempoH. In contrast, the reactions of Fe^{III}-H_2O_2 are slow and Tempo trapping does not dominate the reaction products. Significant amounts of ketone are formed.

We consider that these facts are explained by the mechanism given in **Scheme 1**. The reaction of Fe^{II} and H_2O_2 gives the Fe^{IV} oxenoid species which reacts rapidly and selectively with the saturated hydrocarbon to furnish an Fe^{IV} species which fragments into Fe^{III} and carbon radicals. These are preferentially trapped by Tempo but also by chloride ion bound to Fe^{III}.[5]

For the Fe^{III}-H_2O_2 manifold we consider that the Fe^{V} oxenoid species oxidizes Tempo to the 2,2,6,6-tetramethyl-1-oxopiperidium **(4)**, a known species,[15,16] with formation of Fe^{IV}. In this way a less efficient production of carbon radicals results.

EXPERIMENTAL

Unless otherwise stated, all chemicals were purchased from commercial sources and, after verification, used without further purification. Gas chromatographic analyses were performed on a Hewlett-Packard 5890 series II gas chromatograph using a DB-Wax or a DB-5 capillary column (30 meters long, film thickness 0.25 μm, J&W scientific). GC-MS analyses were carried out on a Hewlett-Packard 5890 series II gas chromatograph coupled to a Hewlett-Packard 5791 mass selective detector using a DB-5 column (30 meters long, film thickness 0.25 μm). ^1H and ^{13}C NMR experiments were carried out at room temperature on a Varian XL-200 or a Gemini-200 NMR spectrometer. Chemical shifts are reported relative to TMS ($\delta = 0.00$ ppm). Infrared spectra were recorded on a Perkin-Elmer 881 infrared spectrophotometer. UV-visible spectra were recorded on a Beckmann Du-7 spectrophotometer.

The *cyclohexyl-Tempo* adduct **(3)**, *sec-* and *tert-adamantyl- Tempo*[6a] adducts were prepared by photolysis of the N-hydroxypyridine-2-thione derivatives of the corresponding carboxylic acids[18] and Tempo. The authentic samples of the *ortho-* and *para-cyclohexylpyridines*, *sec-* and *tert-adamantylpyridines*[19] were obtained by same method in pyridine-trifluoroacetic acid. ^{1}H and ^{13}C NMR, mass spectra and infrared spectra were in agreement with their structures.

1,2-Diacetoxy-3,5-di-tert-butylbenzene. A solution of 1,2-dihydroxy-3,5-di-*tert*-butylbenzene (4 mmol) in a mixture of dry ether (50ml) and dry pyridine (2 ml) was stirred at 0°C under argon. Acetyl chloride (17 mmol) was added slowly and the solution was allowed to reach room temperature. The reaction mixture was stirred at room temperature until the reaction was complete (the reaction was following by TLC).The mixture was washed with water and brine and extracted with ether. The combined organic layers were dried over $MgSO_4$ and gave the diacetate (98%). The ^{1}H NMR was in agreement with the data already reported.[20]
^{1}H NMR ($CDCl_3$), δ (ppm): 7.2-7.3 (d, 1H); 7.0-7.1 (d, 1H); 2.3 (s, 3H); 2.3 (s,3H); 1.4 (s, 9H); 1.3 (s, 9H).
^{13} C NMR ($CDCl_3$), δ (ppm): 168.3; 148.6; 142.4; 141.9; 138.5; 121.3; 118.4; 35.0; 34.8; 31.3; 30.3; 20.9; 20.8.

General work-up procedure.

(a) An aliquot of the reaction mixture (1.0 ml) was acidified with cold 20% H_2SO_4 (2.0 ml). The mixture was then extracted with ether (3x5 ml). The combined ether extracts were washed with saturated $NaHCO_3$ (2 ml) and dried ($MgSO_4$). The appropriate internal standard (naphthalene in ether) was then added. The products were quantified by gas chromatography. (b) Another aliquot of the reaction mixture (1.0 ml) was made alkaline by the addition of 5% NaOH (2 ml) and the basic products were extracted with ether (3x5 ml). The work-up procedure followed as in (a).

General procedure for radical reactions.

The N-hydroxypyridine-2-thione derivative of cyclohexyl carboxylic acid (0.5 mmol) was dissolved in a solution of pyridine (15 ml) and acetic acid (1.5 ml). The reaction was then irradiated under air or argon atmosphere using a 'Max Million" lamp at room temperature for 30 min. After work-up, the products were quantified by gas chromatography using naphthalene as internal standard.

General procedure for Gif-type reactions with Fe^{II} salts.

$Fe^{II}(ClO_4)_2 \cdot 6H2O$ (3 mmol), picolinic acid (9 mmol), LiCl (10 mmol) and cyclohexane (40 mmol) were dissolved in a mixture of pyridine (30 ml) and acetic acid (3 ml). The reaction was initiated by the addition of 3 mmol of 30 % H_2O_2 (or 90% TBHP) at 0°C. The reaction mixture was stirred at room temperature overnight. General work-up procedure was followed to quantify the products by gas chromatography.

General procedure for Gif-type reactions with Fe^{III} salts.

$Fe^{III}Cl_3 \cdot 6H2O$ (1 mmol), picolinic acid (4 mmol) and cyclohexane (40 mmol) were dissolved in pyridine

(33 ml). The flask was closed with rubber septum with a needle inlet. The reaction was initiated by the addition of 4 mmol of 30% H_2O_2. The reaction mixture was stirred at room temperature overnight. After work-up, the products were quantified by gas chromatography.

General procedure for the reactions with oxoamonium salt **(4)**.

2,4-di-*tert*-butylphenol (1 mmol) was dissolved in pyridine (15 ml) and the reaction was deoxygenated and kept under argon. The oxoamonium salt was added at 0°C and the solution was allowed to reach slowly room temperature and stirred overnight under argon.

Quantification of the different products.

- An aliquot of the reaction mixture (1 ml) with a naphthalene solution in ether (1 ml) was washed with a NaOH solution (10%) saturated with NaCl and extracted two times with 5 ml of ethyl acetate. The combined organic layer were dry under $MgSO_4$ and Tempo, 2,4-di-tert-butylphenol and 2,2,6,6- tetramethyl piperidine were quantified by GC.
- The remaining solution was reduced by adding Zn (1 g) and AcOH (2 ml) under argon. After 30 mn, an other aliquot (1 ml) was taken and added to 2 ml of acetic anhydride. The aliquot was stirred under argon for 3h and worked up as described previously with a naphthalene solution (1 ml). The 3,5-di-*tert*-butyl-*o*-benzoquinone **(6)** was transformed into 1,2-diacetoxy-3,5-di-*tert*-butyl benzene and quantified by GC.

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