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Catalytic Version of and Reuse in Hypervalent Organo-λ^3- and -λ^5-iodane Oxidation

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Keywords: Catalytic oxidation / Iodine / Hypervalent / Polymer / Reuse

Hypervalent organoiodanes are one of the most valuable classes of oxidants for use in oxidative transformations of various kinds of functionalities in modern organic synthesis. This microreview provides an overview of the recently developed aryl iodide-catalyzed oxidations, in which hypervalent organoiodanes(III and V) generated in situ serve as the actual oxidants. We also summarize recent attempts to improve the efficiency of recyclable hypervalent organoiodanes in oxidations, updating Togo's and Sakuratani's 2002 review.

1. Introduction

Hypervalent organoiodanes (aryl-λ^3- and aryl-λ^5-iodanes with heteroatom ligands) enjoy a rich chemistry, in particular as reagents for oxidation reactions.[1] They would seem to occupy pole position among the most valuable oxidants in modern organic synthesis, because of their excellent selectivity, reactivity, and applicability, their ready and commercial availability, their stability towards atmospheric oxygen and moisture, their high tunability in molecular design, their mild reaction conditions, and, most importantly, their low toxicity. Aryl-λ^3-iodanes – ArILL′ (L, L′ = heteroatom ligands) – effect oxidative transformations of a variety of functional groups including olefins, alkynes, carbonyl compounds, alcohols, phenols, ethers, amines, amides, sulfides, sulfoxides, alkyl iodides and bromides, aromatic compounds, etc., with high regio-, stereo-, and chemoselectivity under mild conditions. The two heteroatom ligands L and L′ on iodine(III) are essential for the oxidation reactions as leaving groups, one being used in the ligand exchange step and the other being used in the reductive elimination step.[1d] The ease of ligand exchange on iodine(III) with a low-energy barrier makes it possible to prepare a wide range of hypervalent aryliodanes, which has in turn allowed the easy molecular design of new hypervalent iodanes with intended functions.

These oxidations use stoichiometric, or often excess, amounts of aryl-λ^3-iodanes, and so produce large amounts of aryl iodides as inevitable waste products. Additionally,

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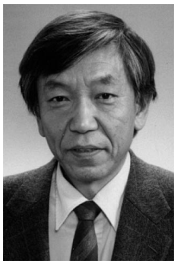

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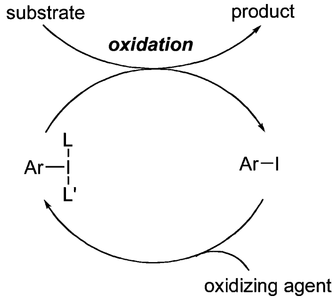
the stoichiometric aryl-λ^3-iodane oxidants are quite expensive for large-scale applications. When, however, the aryl iodide is selectively reoxidized to a hypervalent aryl-λ^3-iodane under the reaction conditions, the oxidation needs only a catalytic amount of aryl-λ^3-iodane or aryl iodide (Scheme 1). The catalytic use of aryl iodide in oxidations opens up new areas of research in hypervalent organoiodane chemistry. The focus of this review is on the aryl iodide-catalyzed oxidations developed in the past few years.[2]



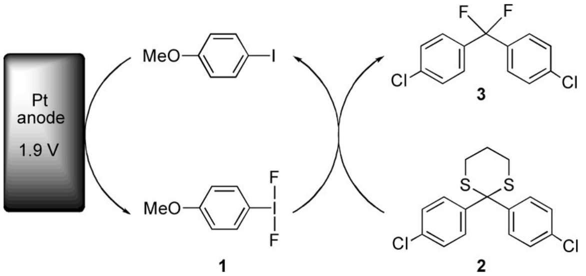
Scheme 1.

A possible alternative to these catalytic oxidations is the reuse of hypervalent organoiodanes(III or V) that can easily be recovered from reaction mixtures as the reduced iodides or λ^3-iodanes, respectively, and can then be reoxidized to the original oxidation state without loss of activity over several reuses. Recent progress in waste-free recycling protocols involving polymeric and molecular hypervalent species is also summarized in the concluding part of this review.

2. Catalytic Oxidation

2.1 Electrochemical Methods

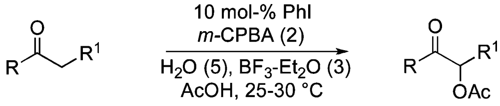
In 1994, Fuchigami and Fujita reported a pioneering study of iodobenzene-catalyzed oxidations based on an electrochemical method (Scheme 2).[3] They carried out the anodic *gem*-difluorination of cyclic dithioacetal **2** in the presence of a catalytic amount (5 mol-%) of *p*-methoxyiodobenzene and $Et_3N{\cdot}3HF$. *p*-Methoxyiodobenzene is selectively anodically oxidized at 1.9 V (vs. SCE) and generates the difluoro-λ^3-iodane **1** as a reactive species, because of the higher oxidation potential of the cyclic dithioacetal **2** relative to that of the iodoarene. The catalytic reaction quantitatively afforded the *gem*-difluoride **3**. Catalytic anodic oxidation involving the formation of active chloro(fluoro)(*p*-methoxyphenyl)-λ^3-iodane also gives the difluoride **3** in 61% yield.[3b] Electrochemical oxidation of *tert*-butyl acetoacetate with 50 mol-% of *p*-iodotoluene results in α-monofluorination of a β-dicarbonyl compound in a high yield.[4]



Scheme 2.

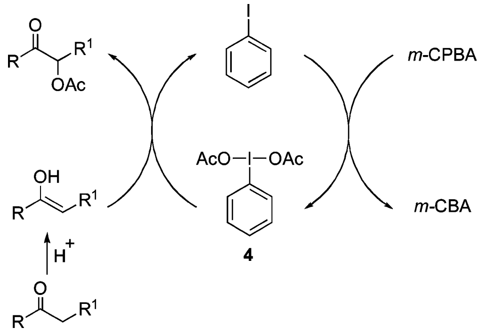
2.2 Chemical Method: Catalytic Oxidation Generating λ^3-Iodanes in situ

The first example of an iodobenzene-catalyzed oxidation that generates active hypervalent phenyl-λ^3-iodanes in situ as real oxidants by a chemical method was found at Tokushima and is shown in Scheme 3.[5] Introduction of oxygen functionalities onto α-carbons in carbonyl compounds with the aid of stoichiometric amounts of aryl-λ^3-iodanes is a well established process and has found a broad range of utility in synthetic organic chemistry.[1,6] The reaction provides an efficient route for the synthesis of a variety of carbonyl compounds α-substituted with a hydroxy, methoxy, acetoxy, tosyloxy, mesyloxy, or phosphoryloxy group. Catalytic versions of some of these α-functionalizations have been achieved. In all of the reactions shown in the Schemes and Tables here, numbers in parentheses show molar equivalents of a reagent.



Scheme 3.

m-Chloroperbenzoic acid (*m*-CPBA) acts as a stoichiometric terminal oxidant in the catalyzed α-acetoxylation of ketones (Scheme 3) and oxidizes iodobenzene to (diacetoxy)iodobenzene (**4**) in acetic acid at room temperature. The hypervalent λ^3-iodane **4** undergoes ligand exchange on the iodine(III) with an enol derived from a ketone, and the subsequent S_N2 displacement of the resulting α-λ^3-iodanyl ketone (not shown) by acetic acid affords an α-acetoxy ketone with regeneration of iodobenzene, which reenters a catalytic cycle (Scheme 4). Only 5–10 mol-% of iodobenzene was thus required in this reaction. The presence of water slows down the rate of oxidation of iodobenzene by *m*-CPBA to λ^3-iodane **4**; however, addition of water was found to be crucial to the success of the catalyzed α-acetoxylation of acetophenone.



Scheme 4.

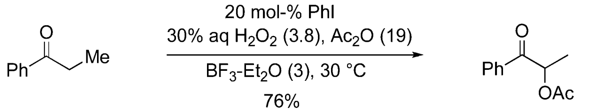
Table 1 shows the electronic effects of substituents on iodobenzene in the oxidation of acetophenone. Introduction both of slightly electron-donating (*p*-methyl) and of electron-withdrawing substituents (*p*-chloro) afforded comparable results, with formation of the α-acetoxy ketone in more than 80% yields (Table 1, Entries 2 and 3). In contrast, use of *p*-methoxy- and *p*-nitroiodobenzene significantly decreased the catalytic efficiency of iodoarenes, and a large amount of acetophenone was recovered. *m*-CPBA oxidizes ketones directly under the conditions: when the reaction was carried out without iodobenzene, no formation of α-acetoxyacetophenone was observed, but the reaction instead produced large amounts of the Baeyer–Villiger product phenyl acetate. These results indicate that the oxidation of iodobenzene with *m*-CPBA under the conditions is faster than that of acetophenone.

Table 1. Catalysts for oxidation of acetophenone to α-acetoxy ketone.

Entry	Catalyst	Yield of product (%)
1	PhI	84
2	p-MeC$_6$H$_4$I	84
3	p-ClC$_6$H$_4$I	81
4	p-MeOC$_6$H$_4$I	67
5	p-NO$_2$C$_6$H$_4$I	58

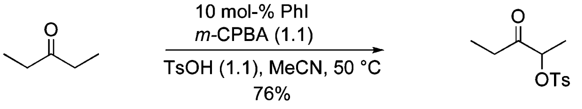
A variety of dialkyl and alkyl aryl ketones are smoothly oxidized at their α-positions to afford α-acetoxy ketones in moderate to good yields. In cases of unsymmetrical ketones, the regioselectivity for α-acetoxylation is probably determined by the preferred direction of acid-catalyzed enolization of ketones.

At the beginning of our study we used peracetic acid prepared from 34% aqueous hydrogen peroxide and acetic anhydride as a stoichiometric oxidant, instead of *m*-CPBA; however, the attempted iodobenzene-catalyzed oxidations with peracetic acid did not give reproducible results. Recently, Huang and co-workers reported the catalytic α-acetoxylation of ketones with peracetic acid.[7] An example is shown in Scheme 5.



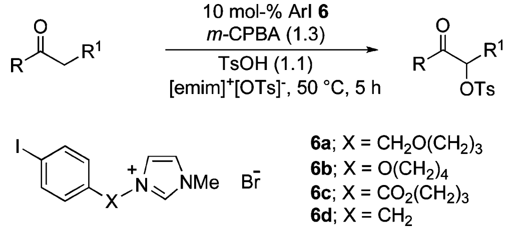
Scheme 5.

A recent extension of this reaction shows that *m*-CPBA also serves as a terminal oxidant in the iodobenzene-catalyzed α-tosyloxylation of ketones (Scheme 6);[8] here, *p*-toluenesulfonic acid acts both as a Brønsted acid and also as a ligand on iodine(III) to generate PhI(OH)OTs (Koser's reagent, **5**) in situ. The catalytic cycle involves initial generation of the λ^3-iodane **5**, which in turn reacts with the enols derived from ketones to give α-tosyloxy ketones. Togo and co-workers further improved the method to allow recycling of the iodobenzene catalyst.[9] They prepared ionic liquid-supported iodobenzene catalysts **6a–d** and carried out the catalytic α-oxygenation of ketones in an ionic liquid – 1-ethyl-3-methylimidazolium tosylate ([emim]$^+$[OTs]$^-$) – at 50 °C, to obtain α-tosyloxy ketones in good yields (Table 2). After extraction of α-tosyloxy ketones and *m*-CBA byproduct with ethyl acetate, the recovered ionic liquid containing the dissolved catalyst **6** could be reused for further oxidation, good yields of the products being maintained until the third time. After catalytic α-tosyloxylation of acetophenone with **6a** in the ionic liquid at 50 °C, addition of thioacetoamide and thiobenzamide, followed by heating at 80 °C, directly produced thiazoles. This thiazole synthesis can be repeated three times efficiently without changing the catalyst.



Scheme 6.

Table 2. Catalytic oxidation with ionic liquid-supported iodobenzenes **6**.

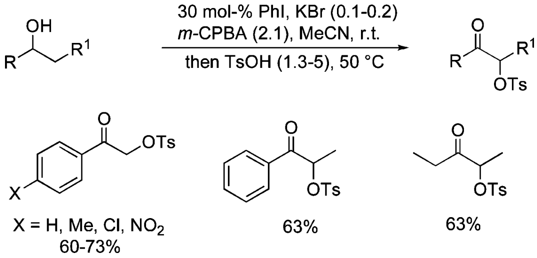


	Ketone		Yield (%)			
Entry	R	R^1	**6a**	**6b**	**6c**	**6d**
1	Ph	Me	82	83	80	70
2	p-ClC$_6$H$_4$	Me	77	76	67	67
3	p-NO$_2$C$_6$H$_4$	Me	65	70	72	71
4	Ph	Et[a]	83	75	63	70
5	Ph	n-C$_8$H$_{17}$[a]	81	75	52	56
6	n-C$_5$H$_{11}$	n-C$_5$H$_{11}$	57	66	62	53

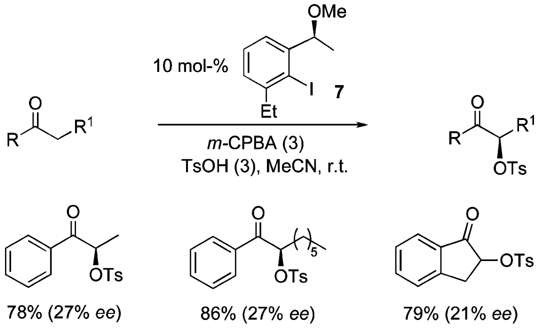
[a] TsOH (5 equiv.).

A one-pot method for catalytic oxidation of alcohols to α-tosyloxy ketones has been developed (Scheme 7):[8b] the excellent procedure developed by Kita and Tohma[10] for oxidation of alcohols to carbonyl compounds with an aryl-λ^3-iodane in the presence of KBr was modified to a catalytic reaction with respect to the aryliodane. Treatment of 1-phenylethyl alcohol with iodobenzene (30 mol-%), KBr (10 mol-%), and *m*-CPBA (2.1 equiv.) in acetonitrile at room temperature, yielding acetophenone, followed by the addition of *p*-toluenesulfonic acid and warming to 50 °C, thus directly afforded α-tosyloxyacetophenone in 73% yield. 2,2,6,6-Tetramethylpiperidine-*N*-oxyl (TEMPO) also serves as a catalyst in place of KBr in this oxidation.

Wirth and co-workers reported the first attempted iodobenzene-catalyzed enantioselective α-tosyloxylation of ketones (Scheme 8).[11a] Use of the chiral iodobenzene catalyst **7** afforded oxygenated ketones in good yields but with modest enantioselectivities, which is the same as observed in the stoichiometric reaction.[11b]

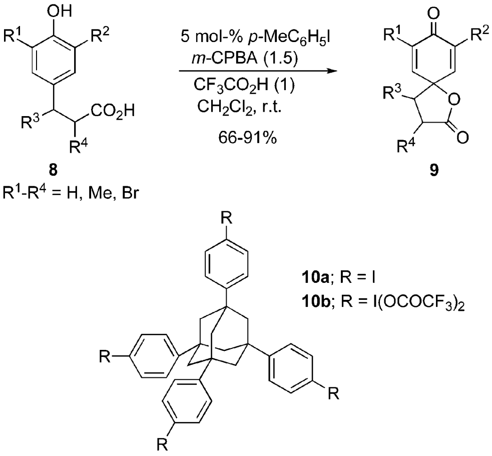


Scheme 7.



Scheme 8.

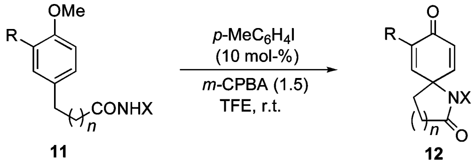
A catalyzed oxidative spirocyclization reaction of phenols, yielding spirodienones, was developed by Kita and coworkers (Scheme 9).[12] Use of p-methyliodobenzene as a catalyst and m-CPBA as a stoichiometric reagent in the presence of a Brønsted or a Lewis acid ($BF_3\cdot Et_2O$) results in oxidation of p-substituted phenols **8** and affords lactones **9** in good yields. Catalytic use of the hypervalent tetrakis(trifluoroacetoxy-λ^3-iodane) **10b** in place of p-methyliodobenzene gave a similar result. After oxidation, the iodide **10a** was recovered quantitatively by taking advantage of its insolubility in methanol.

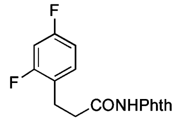
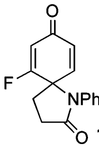
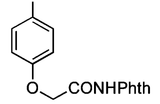
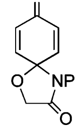


Scheme 9.

Table 3 shows similar catalytic spirocyclizations of amides **11** with m-CPBA as a terminal oxidant.[13] The spirolactamization of N-phthalimide and N-methoxy amides **11** was carried out in the presence of p-methyliodobenzene (10 mol-%) in 2,2,2-trifluoroethanol (TFE) at room temperature to produce four- to six-membered lactams **12**. TFE is moderately acidic, with a pK_a value of 12.9, so no external acid additive was required in the reaction. 4-Fluorophenyl propanamides also undergo the catalytic cyclization in good yields (Entries 6 and 7). As proposed by Kikugawa and co-workers,[14] this catalytic reaction probably involves the generation of active N-acyl-N-methoxynitrenium ion, followed by cyclization and hydrolysis with water, from the commercial wet m-CPBA.

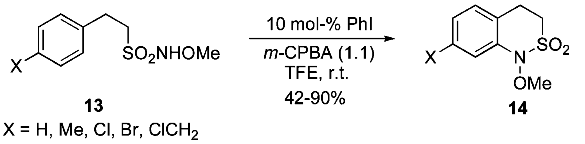
Table 3. Catalytic spirolactamization of amides **11**.



Entry	Amide 11			Lactam	
	n	R	X	**12**	Yield (%)
1	1	H	NPhth[a]	**12a**	83
2	1	H	OMe	**12b**	86
3	1	Ac	OMe	**12c**	53
4	0	H	OMe	**12d**	84
5	2	H	OMe	**12e**	64
6				 **12f**	89
7				 **12g**	79

[a] NPhth: N-phthalimide.

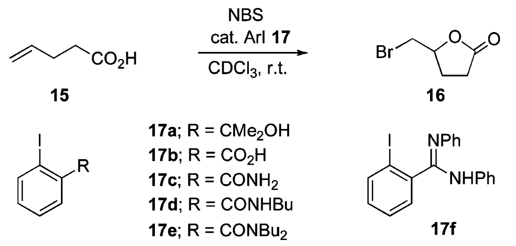
TFE was also found to be a solvent of choice in a similar catalyzed cyclization of N-methoxysulfonamides **13**, yielding cyclic amides (sultams) **14**, as shown in Scheme 10.[15] Use of acetonitrile instead of TFE required further addition of p-toluenesulfonic acid to increase the rate of cyclization, as well as the use of large excess amounts of m-CPBA (3 equiv.) to obtain a comparable result. In comparison with p-methyl-, p-chloro-, and p-methoxyiodobenzenes, 4,4′-diiodobiphenyl, and 1-iodonaphthalene, iodobenzene showed a higher catalytic efficiency in the reaction.



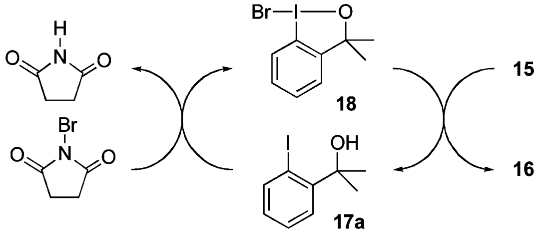
Scheme 10.

Some $ortho$-substituted iodobenzenes act as catalysts for transfer of electrophilic bromine from N-bromosuccinimide (NBS) to alkenes (Table 4).[16] Without any catalyst (Entry 1), the extent of bromolactonization of pent-4-enoic acid (**15**) with NBS in $CDCl_3$ is insignificant (20%). The use of dimethylcarbinol **17a** as a catalyst (25 mol-%) resulted in the quantitative conversion of **15** into bromolactone **16**. A catalytic cycle invoking the intermediacy of bromo-λ^3-iodane **18** is proposed (Scheme 11).

Table 4. Catalytic bromolactonization of pent-4-enoic acid (**15**).



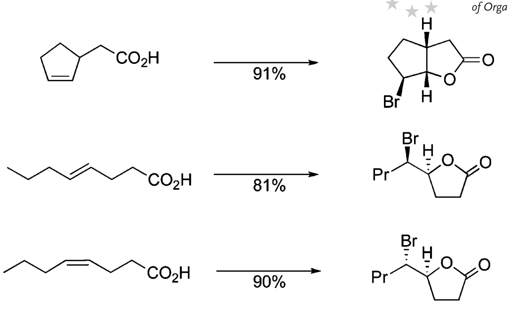
Entry	ArI **17**	mol-%	Time [h]	% Conversion
1	–		15	20
2	**17a**	25	15	100
3	**17b**	10	6	100
4	**17c**	10	2	72
5	**17d**	10	0.5	100
6	**17e**	10	0.33	100
7	**17f**	10	<0.5	100



Scheme 11.

2-Iodobenzoic acid (**17b**) proved superior as a catalyst (10 mol-%), while none of iodobenzene, benzoic acid, and 3-iodobenzoic acid showed any catalytic activity, consistently with the intermediacy of a cyclic bromo-λ^3-iodane such as **18** with linear O–I–Br hypervalent bonding. Incorporation of a more nucleophilic oxygen atom as part of an amide group *ortho* to the iodo group gives even more superior catalysts (Entries 4–6). The increasing inductive effect of added alkyl groups along the primary (**17c**), secondary (**17d**), and tertiary (**17e**) amide series seem to increase catalytic efficiency. Amidine **17f** also proved to be an excellent catalyst. These results demonstrate that the pendant functional group is required to be positioned *ortho* to the iodine atom on the benzene ring, and that, for a given *ortho*-positioned functional group, increasing of its nucleophilicity results in superior catalysts.

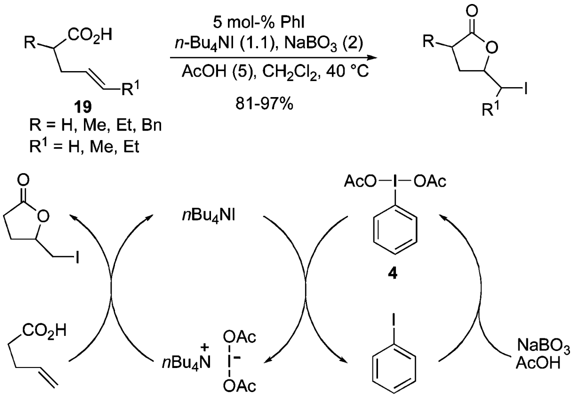
Bromolactonization of unsaturated carboxylic acids with amidine **17f** (10 mol-%) is shown in Scheme 12. The isomeric *E* and *Z* unsaturated acids give two different diastereoisomers, consistently with the stereospecific ring-opening of a bromonium ion intermediate.



Scheme 12.

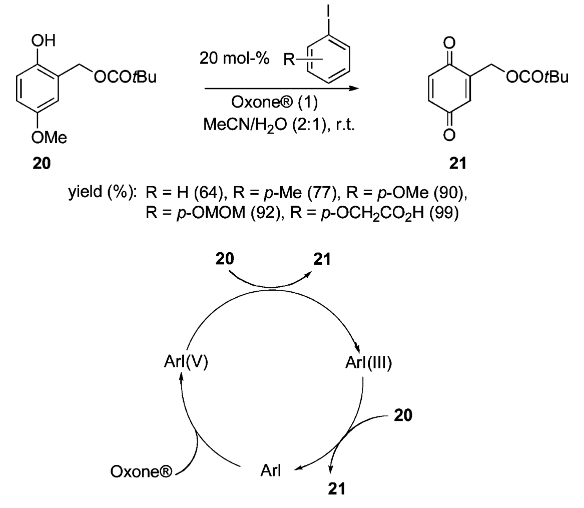
Synthesis of the bromo-λ^3-iodane **18** by treatment of dimethylcarbinol **17a** (Scheme 11) with NBS has been reported, and the structure was established by X-ray analyses.[17] In fact, the iodane **18** quantitatively promotes bromolactonization of pent-4-enoic acid (**15**) with NBS in $CDCl_3$ at room temperature.

Liu and Tan have developed a new approach for iodolactonization using iodobenzene as a catalyst (Scheme 13).[18] The active diacetoxyiodate(I) [n-$Bu_4NI(OAc)_2$] was produced from tetra-*n*-butylammonium iodide (TBAI) by treatment with (diacetoxyiodo)benzene (**4**), which was generated in situ from a catalytic amount (5 mol-%) of iodobenzene by oxidation with sodium perborate monohydrate in the presence of acetic acid. A variety of δ-pentenoic acids **19** afforded high yields of iodolactones by this methodology. This protocol was also applied to the synthesis of iodoenol lactones from δ-pentynoic acids.



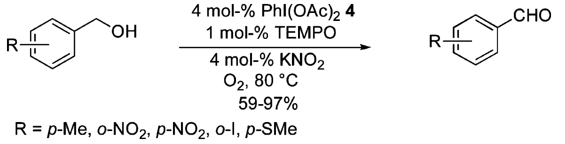
Scheme 13.

Oxidation of *p*-alkoxyphenols to quinones with aryl-λ^3-iodanes proceeds as a catalytic process.[19] Results for the oxidation of 2-substituted *p*-methoxyphenol **20** with a catalytic amount of iodobenzenes in the presence of Oxone as a co-oxidant in acetonitrile/water (2:1), yielding *p*-quinone **21**, are shown in Scheme 14. Iodobenzene showed moderate catalytic activity. Electron-donating alkoxy groups at the *para* position on the benzene ring increase the catalytic efficiency of iodoarenes. 4-Iodophenoxyacetic acid, smoothly recovered after the reaction, gave the *p*-quinone **21** in an excellent yield. A reaction mechanism involving the formation of λ^5- and λ^3-iodanes as active hypervalent reagents has been proposed.



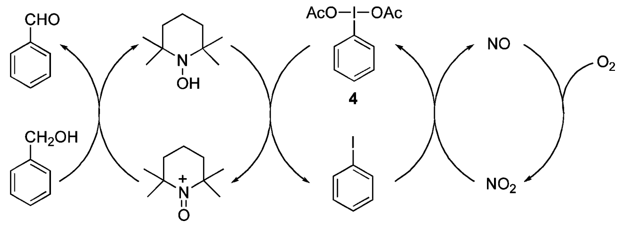
Scheme 14.

A green catalytic oxidation of benzylic alcohols to aldehydes by molecular oxygen through the use of catalytic amounts of (diacetoxy)iodobenzene (**4**)/TEMPO/KNO_2 has been developed (Scheme 15).[20] The reaction was carried out at 80 °C in the absence of a solvent, with efficient agitation of the reaction mixture under oxygen. Interestingly, the catalytic system exhibited high chemoselectivity toward the alcoholic moiety even in the presence of a sulfur heteroatom. Use of a catalytic amount of poly[4-(diacetoxyiodo)-styrene] (**25**; Scheme 19, below) led to yields comparable to those obtained with the unsupported hypervalent iodane, while offering the advantage of efficient recovery by precipitation with diethyl ether and the subsequent recycling of the hypervalent iodane.



Scheme 15.

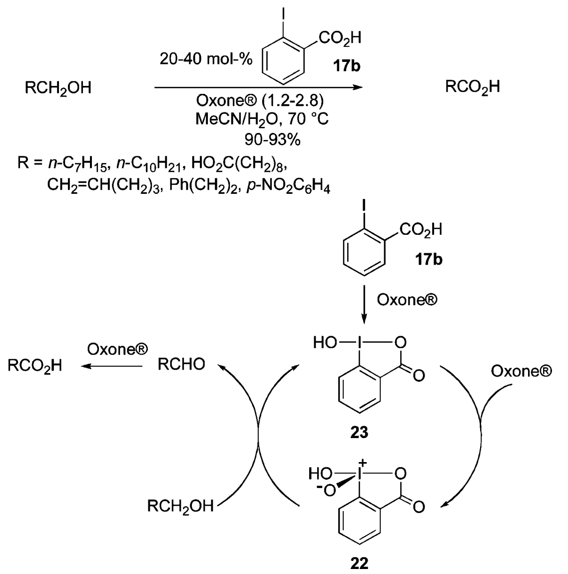
A proposed mechanism (Scheme 16) involves the generation of an oxoammonium cation, derived from TEMPO by oxidation with the λ^3-iodane **4**, as an active oxidant of benzyl alcohol.[21] Iodobenzene is reoxidized to its initial state by NO_2, and the oxidation of NO into NO_2 can be carried out with molecular oxygen, completing the catalytic cycles in the absence of any transition metal. However, the observation that several reactions utilizing iodobenzene, either alone or with different amounts of λ^3-iodane **4**, failed to display any catalytic activities does not seem to be compatible with the proposed mechanism.



Scheme 16.

2.3 Chemical Method: Catalytic Oxidation Generating λ^5-Iodanes in Situ

Pentavalent *o*-iodylbenzoic acid (IBX, **22**, Scheme 17) has emerged as a powerful yet selective oxidant that mediates a variety of oxidative transformations such as oxidation of alcohols, phenols, and amines, dehydrogenation of ketones, aldehydes, and *N*-heterocycles, and oxidative cleavage of dithioacetals.[1,22] However, IBX (**22**) has been reported to be explosive under excessive heating (>200 °C) and on impact.[23] Low solubility towards common organic solvents is an another drawback. Development of a method for in situ generation of IBX (**22**) under oxidation conditions thus seems highly desirable.

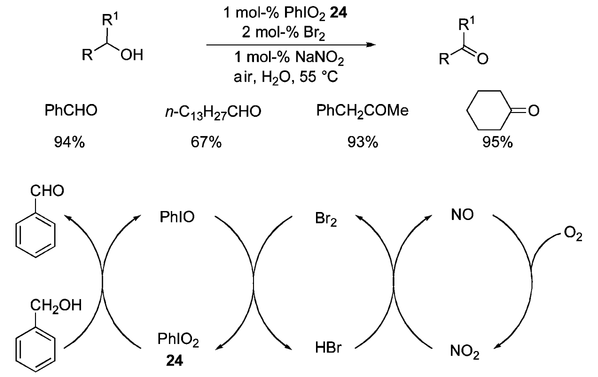


Scheme 17.

Inspired by the method for oxidation of non-explosive, commercially available 2-iodobenzoic acid (**17b**) to IBX (**22**) with Oxone in water,[24] Vinod and co-workers developed a catalytic method for oxidation of primary alcohols to carboxylic acids (Scheme 17).[25] Use of catalytic amounts of 2-iodobenzoic acid (**17b**) in the presence of Oxone as a co-oxidant in acetonitrile/water 2:1 effects oxidative transformation of primary alcohols to carboxylic acids in good yields. Oxidation of hex-5-en-1-ol provided the corresponding acid without affecting the double bond. Under these conditions, secondary alcohols produce the corresponding ketones, without this being accompanied by the formation of Bayer–Villiger oxidation products due to the presence of Oxone.

Oxidation of primary alcohols with IBX (**22**) affords aldehydes,[22] while Oxone easily oxidizes aldehydes to the corresponding acids, 2-iodobenzoic acid (**17b**) to 2-iodosylbenzoic acid (**23**), and this to IBX (**22**). All of these processes are involved in the catalytic cycle shown in Scheme 17. A similar mechanism was proposed by Giannis for a catalytic IBX-based method for the oxidation of alcohols, in which n-Bu_4NHSO_4 was used as a phase-transfer catalyst for the generation of tetra-n-butylammonium oxone.[26]

An interesting catalytic cycle using molecular oxygen as a terminal oxidant has been developed (Scheme 18).[27] A transition-metal-free aerobic oxidation of alcohols to aldehydes or ketones in water was effectively catalyzed by iodylbenzene ($PhIO_2$, **24**, 1 mol-%) as the active oxidant in the presence of Br_2 and $NaNO_2$. A proposed catalytic mechanism involves three redox cycles, similarly to that reported for TEMPO-mediated oxidation of alcohols.[28] Iodylbenzene (**24**) oxidizes alcohols to carbonyl compounds,[29] but detailed mechanistic studies seem to be required in order to establish the proposed catalytic cycles firmly.

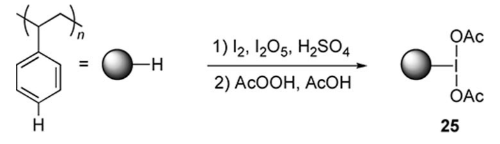


Scheme 18.

3. Reuse in Hypervalent Organo-λ^3-Iodane Oxidation

3.1 Polymer-Supported λ^3-Iodanes

Polymer-supported hypervalent organo-λ^3-iodanes are easily recovered almost quantitatively by simple filtration of the reaction mixture, and it is possible to reuse the reduced polymers (iodides) after oxidation to the original hypervalent λ^3-iodanes. Early studies on their use in organic synthesis can be found in an excellent review by Togo and Sakuratani reported in 2002.[30] In 1961, Okawara and co-workers reported the first synthesis of poly[4-(diacetoxyiodo)styrene] (**25**) through regioselective iodination of polystyrene with iodine and diiodine pentoxide, followed by oxidation with peracetic acid (Scheme 19).[31,32]

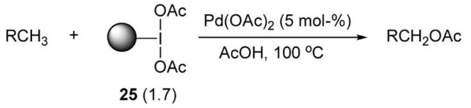


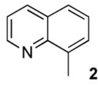
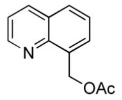
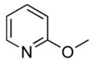
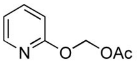
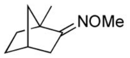
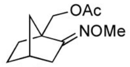
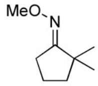
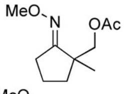
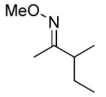
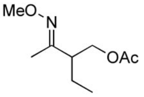
Scheme 19.

Poly(diacetoxy-λ^3-iodane) (**25**) has emerged as a reagent of choice for oxidation of alcohols to aldehydes, ketones, or carboxylic acids, oxidation of phenols, hydroquinones, and sulfides, iodination of arenes, oxidative 1,2-aryl migration of alkyl aryl ketones, oxidative spirocyclization of phenols, oxidative biaryl coupling of phenols, and α-oxygenation of ketones.[30,33] Poly-λ^3-iodane **25** or poly{4-[hydroxy(tosyloxy)iodo]styrene} effect oxidative transformation of primary alcohols to methyl esters,[34] Hofmann rearrangement of primary amides,[32a] and radical or ionic cyclization of 2-arylethanesulfonamides.[35]

In recent years, much attention has been paid to regio- and chemoselective functionalization of arenes and alkanes. Sanford and co-workers have developed an interesting palladium-catalyzed oxidative acetoxylation of alkane and arene C–H bonds based on the use of poly-λ^3-iodane **25** as a stoichiometric oxidant;[36] some representative results are shown in Table 5. Entry 5 indicates a strong preference for C–H activation of methyl relative to methylene groups via five-membered palladacyclic intermediates. Sequential Pd-catalyzed acetoxylation of 8-methylquinoline (**26**) followed by the recovery and recycling of poly(4-iodostyrene) with peracetic acid can be repeated five times with comparable yields of 8-(acetoxymethyl)quinoline and recovered **25** for each run.

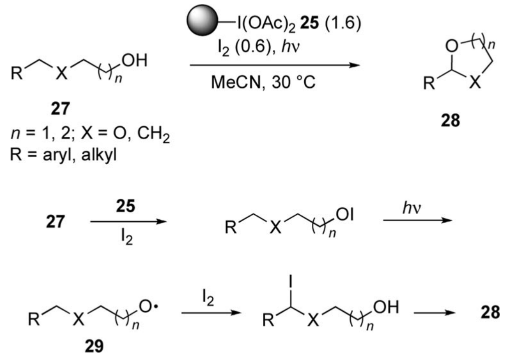
Table 5. Pd-catalyzed C–H bond acetoxylation with λ^3-iodane **25**.



Entry	Substrate	Product	Yield (%)[a]
1	 **26**		77 (88)
2			70 (68)
3			78 (75)
4			59 (61)
5			73 (78)

[a] Isolated yields. Yields in parentheses are those obtained with $PhI(OAc)_2$ (**4**).

Irradiation of alcohol **27** with a tungsten lamp in the presence of polymer-immobilized λ^3-iodane **25** and iodine in acetonitrile results in cyclization, yielding cyclic acetals or ethers **28** (Scheme 20).[37] A proposed mechanism involves the formation of an alkoxy radical **29** generated from an initially formed alkyl hypoiodite under irradiation. Subsequent 1,5- or 1,6-hydrogen shift, iodination with diiodine, and final intramolecular cyclization affords **28**.



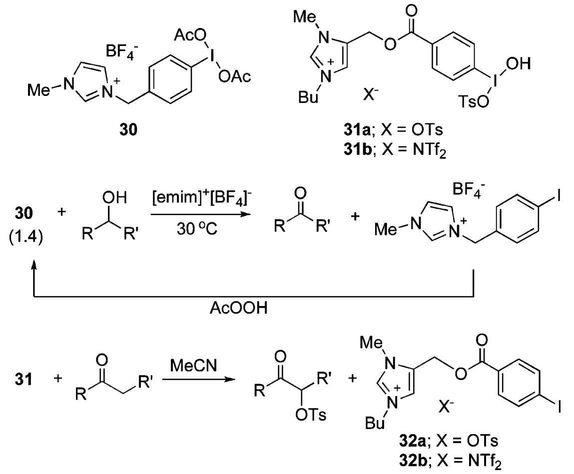
Scheme 20.

The polymer-supported hypervalent organo-λ^3-iodanes seem to be very useful for oxidative transformations of various functionalities; however, it has been pointed out that they have lower reactivities than the corresponding monomeric analogues and, moreover, that the repeated use of these polymers leads to significant degradation due to the benzylic oxidation of the polystyrene chain.[38]

3.2 Ion-Supported λ^3-Iodanes

In 2005, the ionic liquid-supported (diacetoxy)iodobenzene **30**[39] and the [hydroxy(tosyloxy)iodo]benzenes **31**[40] were synthesized as thermally stable aryl-λ^3-iodanes. These hypervalent iodanes allow easy recovery and recycling of the reduced aryl iodides either by extraction into an ionic liquid phase or by simple filtration, with subsequent reoxidation (Scheme 21). A variety of primary and secondary alcohols were oxidized to aldehydes and ketones with **30** in 1-ethyl-3-methylimidazolium tetrafluoroborate ($[emim]^+[BF_4]^-$) in the presence of a low concentration of bromide ions.[39] A proposed reaction mechanism involves a reactive Br^+ ion species, probably acetyl hypobromite or a bromate(I) ($Br(OAc)_2^-$), produced from a small amount of bromide ion remaining in the $[emim]^+[BF_4]^-$. The bromonium ion reacts with alcohols to produce the carbonyl compounds. The recyclable ion-supported λ^3-iodane **30** selectively oxidizes sulfides to sulfoxides in water under neutral conditions without overoxidation to sulfones.[41] The sulfide oxidation is tolerant of hydroxy groups and carbon–carbon double bonds.

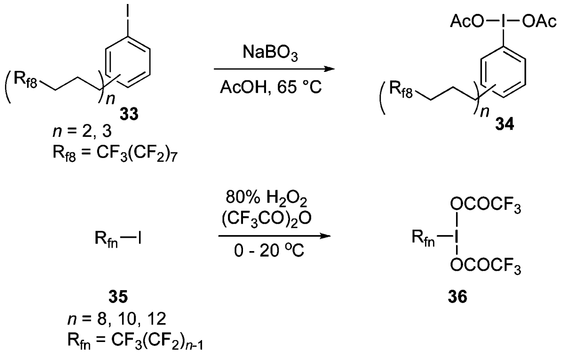
α-Tosyloxylation of ketones with the ion-supported Koser's reagent **31a** proceeds smoothly in MeCN even at 0 °C.[40] The reactions are faster than those with Koser's reagent (**5**) itself, probably due to the presence of the electron-withdrawing ester group on the benzene ring. The ability to tune the solubility/miscibility properties of the support by changing the anion facilitates its recovery. Thus, the ion-supported **32b**, with a softer, more weakly coordinating triflimide anion, is soluble in the less polar solvent diethyl ether, while **32a**, with a harder tosylate anion, is immiscible with diethyl ether and precipitates on dilution of the reaction mixture with the solvent.



Scheme 21.

3.3 Fluorous λ^3-Iodanes

Use of hypervalent fluorous aryl- and alkyl-λ^3-iodanes with electronegative perfluoroalkyl chains makes it possible to recover and reuse the reduced fluorous reagents, with high fluorous-phase affinities, through simple extraction into a fluorous phase. Gladysz and co-workers synthesized several diacetoxy(aryl)-λ^3-iodanes **34** with fluorous aryl moieties by sodium perborate oxidation of aryl iodides **33**, prepared from the corresponding aromatic aldehydes (Scheme 22).[42] Fluorous alkyl-λ^3-iodanes **36** are more readily accessible, since many aliphatic iodides **35** are commercially available.[43,44]



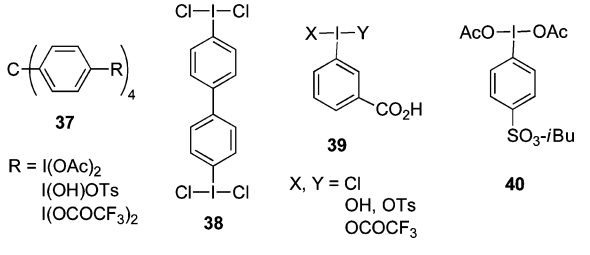
Scheme 22.

Fluorous λ^3-iodanes **34** and **36** rapidly oxidize 1,4-hydroquinones to quinones in methanol at room temperature. Subsequent addition of the fluorous solvent $CF_3C_6F_{11}$ or n-C_6F_{14} (FC-72) affords liquid/liquid biphase systems. The product quinones are generally isolated from the methanol phases in high yields, and solvent removal from the fluorous phases recovered the reduced iodides **33** and **35** in yields of over 95%. Alternatively, the very low solubility of **35** (n = 12) in MeOH allows efficient recovery by solid/liquid phase separation. These recovered iodides are reoxidized and reused. The fluorous λ^3-iodanes **36** oxidize aliphatic and benzylic secondary alcohols to ketones in the presence of aqueous KBr and the absence of organic solvents.[45]

3.4 Other λ^3-Iodanes

Because of the recently increasing demands for waste-free, environmentally benign protocols in hypervalent λ^3-iodane oxidations, much effort has been devoted to the development of simple, nonpolymeric, recyclable, hypervalent iodanes, showing reactivities similar to those of the original phenyl-λ^3-iodanes. In 2004, Kita and Tohma reported the synthesis and reactions of the interesting tetrakis(*p*-λ^3-iodanylphenyl)adamantane **10b** and its analogues (**10**; R = $I(OCOCF_3)_2$, and I(OH)OTs) as recyclable hypervalent reagents (Scheme 9).[46] As described above, the tetraiodide **10a** was easily separated from the product mixtures. As a related study, a more simple tetrakis(*p*-λ^3-iodanylphenyl)methane **37** was also synthesized.[47]

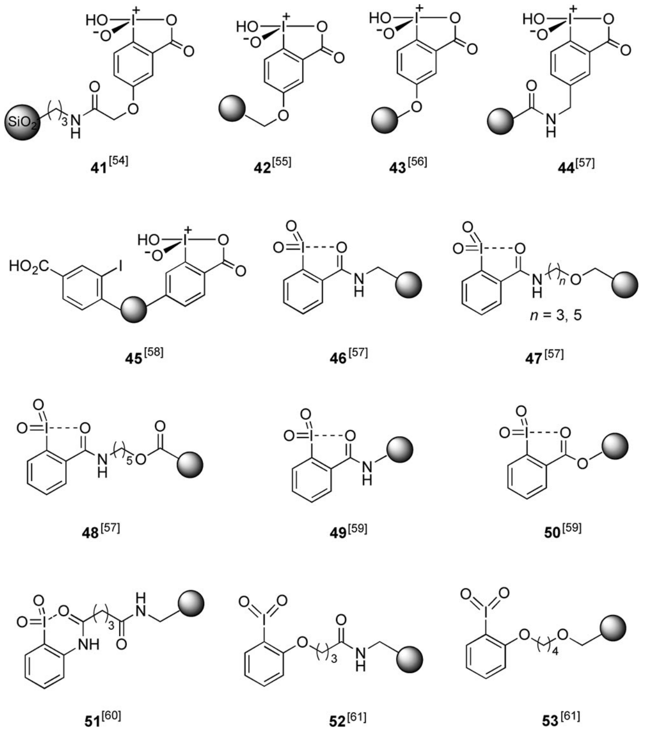
The reactivity of the bis(λ^3-iodane) **38** (Scheme 23) in the vicinal halomethoxylation of olefins is similar to that of the commonly used (dichloroiodo)benzene, and the reduced 4,4′-diiodobiphenyl was recovered by filtration of the precipitates in hexane solution and reused.[38] Yusubov, Kirschning, and Zhdankin synthesized the acidic aryl-λ^3-iodanes **39** with carboxy groups at their *meta* positions.[38,48,49] The reduced 3-iodobenzoic acids can be separated at the end of the reaction by treatment with 5% aqueous sodium hydrogen carbonate solution or with IRA-900 anionic-exchange resin. The well known analogues of **39** containing *ortho* carboxy groups generally exhibit low reactivities toward oxidations, because of the formation of stable five-membered cyclic structures.[1] On the other hand, the reactivities of the acidic λ^3-iodanes **39** are similar to those of the unsubstituted (dichloroiodo)benzene, [hydroxy(tosyloxy)iodo]benzene (**5**), and [bis(trifluoroacetoxy)iodo]benzene. It will be interesting to investigate the reactivity pattern of phenyl-λ^3-iodanes with *para* carboxy groups.[50] Kirschning and co-workers developed an interesting method for recycling protocols using a tagged hypervalent aryl-λ^3-iodane **40**.[51]



Scheme 23.

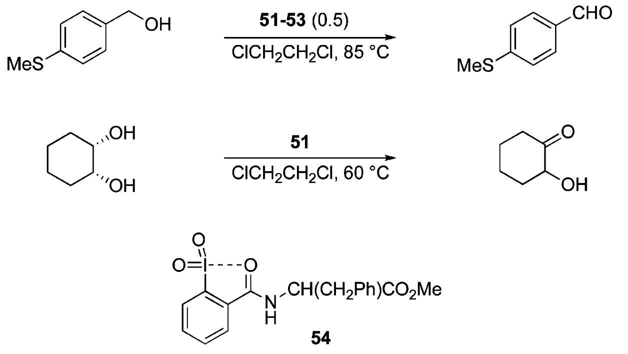
4. Reuse in Hypervalent Organo-λ^5-Iodane Oxidation

The chemistry of polymer-supported aryl-λ^5-iodanes was summarized in reviews by Togo in 2002[30] and by Zhdankin in 2006[52] and 2007.[53] In 2001, Giannis's[54] and Rademann's groups[55] reported the first syntheses of immobilized aryl-λ^5-iodanes: the aminopropylsilica gel-supported IBX **41** and the Merrifield resin-supported IBX **42**, respectively. Scheme 24 shows the structures of immobilized aryl-λ^5-iodanes prepared so far with their reference numbers. Resin **46**–**49** each incorporate the Zhdankin IBX amide. All of these polymer-supported λ^5-iodanes oxidize alcohols to carbonyl compounds, and can be recovered and reused.



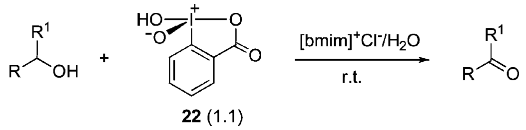
Scheme 24.

Interestingly, the polymer-supported iodanes **51**–**53** show good selectivity for oxidation of the alcohol group in the presence of the sulfide group in 4-(methylthio)benzyl alcohol (Scheme 25). Furthermore, oxidation of *cis*-cyclohexane-1,2-diol with **51** affords only the corresponding hydroxycyclohexanone, and unlike with the IBX amide **54**, no C–C bond cleavage is detected.



Scheme 25.

A green and efficient procedure for the oxidation of alcohols to carbonyl compounds with IBX **22** by use of 1-butyl-3-methylimidazolium chloride $[bmim]^+[Cl]^-$ as a solvent in the presence of a small amount of water at room temperature has been developed (Scheme 26).[62] After the extraction of a carbonyl compound from the reaction mixture with diethyl ether, 2-iodosylbenzoic acid (**23**) was recovered quantitatively by the addition of water to precipitate it. The recovered acid **23** can be reoxidized to IBX **22** with Oxone. The ionic liquid was also recovered and reused without decreasing the yields of products.



Scheme 26.

Conclusions

Developments of catalytic versions for oxidation of a variety of functionalities with hypervalent aryl-λ^3- and -λ^5-iodanes are undoubtedly consistent with the recent demands for environmentally friendly chemical processes. In the catalytic cycles reported so far, the terminal stoichiometric oxidants are mostly limited to *m*-CPBA and Oxone. The ultimate goal of this research will be to find a highly atom-economical terminal oxidant, probably molecular dioxygen or hydrogen peroxide.[63]

Acknowledgments

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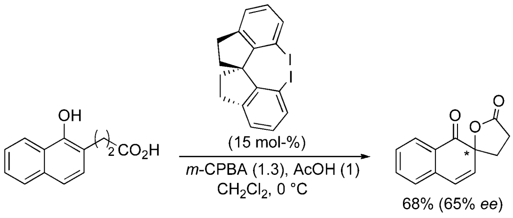

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