FULL PAPERS

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Hydroxyl Radical Promotes the Direct Iodination of Aromatic Compounds with Iodine in Water: A Combined Experimental and Theoretical Study

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Abstract: It is still a challenge to develop green, simple and effective approaches to prepare aromatic iodides. Herein, a novel and green strategy for the direct mono-iodination of aromatic compounds starting with molecular iodine has been developed. The strategy uses ceria nanocrystals to decompose hydro-

Introduction

Aromatic iodides, generally more reactive than bromides and chlorides, are important reagents to make carbon-carbon or carbon-heteroatom bonds,^[1] and find wide applications in organic synthesis.^[2] However, because of the weaker electrophilicity of iodine as compared to chlorine and bromine, the iodination of aromatic compounds starting with molecular iodine is much more difficult.^[3] To carry out a direct iodination, iodine is required to be oxidized to the more reactive intermediate such as an I⁺-type species.^[4] Various oxidizing agents have been applied for this purpose, including nitric acid, sulfuric acid, iodic acid, sulfur trioxide and heteropolyacid.^[5] However, several disadvantages prevent wide applications of these methods: the oxidizing agents are often hazardous and expensive; the reactions were carried out in organic solvents and produced toxic wastes; and homogeneous transition metal catalysts were often required, which cause inconvenience for product isolation and catalyst recycle. These limitations have encouraged chemists to develop green, simple and effective approaches to prepare aromatic iodides, yet this is still a challenge.^[6]

From a perspective of "green" chemistry, hydrogen peroxide (H_2O_2) could be an ideal oxidant candidate

gen peroxide, giving hydroxyl radicals which are demonstrated experimentally and computationally to be crucial to promote the iodinations.

Keywords: aromatic compounds; ceria nanocrystals; hydrogen peroxide; hydroxyl radicals; iodination

because water is the only side product. Direct iodination using H_2O_2 as oxidant has been extensively investigated.^[7] For example, Narender et al.^[8] studied the reaction of aromatic compounds with NH₄I and 30% H_2O_2 in acetic acid at room temperature without any catalyst. They found that more activated compounds, that is, anilines, substituted anilines, phenols, substituted phenols and methoxynaphthalenes could be converted directly into the corresponding iodinated products, while deactivated and weakly activated compounds failed to undergo iodination. Methoxybenzene derivatives, despite their marked activity in electrophilic reactions, were not iodinated. The substrate structure-dependent reactivity has also been reported by Skulski et al.^[9] To accelerate the reaction for deactivated and weakly activated arenes, strong acids and homogeneous transition metal salt catalysts were often employed. For example, Firouzabadi et al.^[10] developed a novel catalytic method using CeCl₃·7H₂O as an efficient catalyst for the iodination of arenes by NaI to their monosubstituted halides using 35% H₂O₂ in neat water as the terminal oxidant. With this protocol, the iodinations of reactive arenes such as anilines, and less reactive arenes, such as benzene, bromobenzene and chlorobenzene were found proceeded well with high regioselectivity at the para position.

On the other hand, the hydroxyl radical ('OH), a non-specific and extraordinarily strong oxidant, can react with molecules at near diffusion-controlled rates. Hydroxyl radicals can be generated *in situ via* catalytic decomposition of H_2O_2 , enhancing the oxidizing ability of the original H_2O_2 system. Although the hydroxyl radical may be an ideal green oxidant to activate iodine, a protocol for the iodination of aromatic compounds that uses hydroxyl radicals as oxidant has not been established.

It has been reported that cerium oxide (CeO₂) nanoparticles, like the Fenton reagent (a mixture of ferrous iron salts and H_2O_2 that can produce hydroxyl radicals), could facilitate the decomposition of H_2O_2 to produce hydroxyl radicals *via* the following process:^[11]

where Ce^{3+} stems from the oxygen vacancies in CeO_2 nanoparticles. The ability of the CeO_2 to generate the hydroxyl radical depends on the ease of the Ce^{3+}/Ce^{4+} redox cycle.^[11] In our previous study, we found that the Ce^{3+}/Ce^{4+} redox property could be greatly enhanced by forming larger sized oxygen vacancy clusters or by preferentially exposing some reactive crystal facets, as realized in our rod-like CeO_2 nanocrystals.^[12] We envisioned that our rod-like ceria nanocrystals [Figure 1, **a**) and **b**)] may also promote fast 'OH production from H_2O_2 , which encouraged us to explore the direct iodination of using CeO_2 nanocrys-



Scheme 1. Hydroxyl radicals facilitate the direct iodination of aromatic compounds with iodine in water.

tals/ H_2O_2 system to activate molecular iodine (Scheme 1). To our delight, we observed that aromatic compounds can be iodinated selectively and effectively.

Results and Discussion

Characterization of CeO₂ Nanocrystals

The TEM image in Figure 1, **a**) shows that the CeO_2 nanocrystals exhibit rod-like morphology, 100–300 nm in length and about 10–20 nm in diameter. Powder XRD analysis [Figure 1, **b**)] shows that CeO_2 nanorods can be indexed to the pure fluorite cubic structures. These results are consistent with our data reported previously.^[12b]

Generation of Hydroxyl Radicals *via* H₂O₂ Decomposition Catalyzed by CeO₂ Nanocrystals

EPR analysis was carried out to verify the hydroxyl radical production in the H_2O_2/CeO_2 system,^[13] and



Figure 1. a) TEM image of the fresh CeO₂ nanocrystals; b) XRD patterns of the fresh CeO₂ nanocrystals.

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Figure 2. EPR spectra of the DMPO-system aqueous: **a**) H_2O_2 ; **b**) CeO₂; and **c**) H_2O_2 and CeO²; EPR spectra of the DMPO-benzene iodination reaction system with hydroxyl radical scavengers: **d**) DMSO; and **e**) 1,3-dimethylthiourea.

the results are shown in Figure 2. It was found that no detectable hydroxyl radicals could be observed either in the pure H_2O_2 aqueous solutions [Figure 2, **a**)] or in the CeO₂ nanocrystals-water suspensions [Figure 2, **b**)]. However, four characteristic signals with a peak ratio of 1:2:2:1 could be detected once the H_2O_2 aqueous solutions and CeO₂ nanocrystals were mixed together [Figure 1, **c**)]. The *g*-value (1.992) and hyperfine coupling constant could be assigned to a DMPO-OH spin adduct,^[14] further proving the generation of hydroxyl radicals in the ceria-hydrogen peroxide system.^[15]

Iodination of Benzene under Several Control Conditions

Several control reactions (Table 1) were carried out for benzene iodination. It should be noted that the pH value strongly affects the reactivity as will be demonstrated in the next section. In all runs the pH value of the water layer is kept at 3.0 for comparison. It was found that adding either H_2O_2 or CeO₂ nanocrystals alone to the system generally did not yield any iodination product even upon increasing reaction temperature and prolonging reaction time to 24 h. In contrast, in the presence of both H_2O_2 and CeO₂, that is, when hydroxyl radicals were present, the reaction was improved remarkably and afforded the mono-iodination product in 72% yield (and 4% of the product is the 1,4-diiodobenzene). The EPR experiments

Table 1. Iodination of benzene at various conditions.^[a]

System	Product and yield ^[b] [%]
H_2O_2	none
CeO_2	none
H_2O_2 , CeO_2	72 (iodobenzene)
H_2O_2 , CeO ₂ , DMSO	none
H ₂ O ₂ , CeO ₂ and 1,3- dimethylthiourea	none
	System H_2O_2 CeO_2 H_2O_2 , CeO_2 H_2O_2 , CeO_2 , DMSO H_2O_2 , CeO_2 and 1,3- dimethylthiourea

^[a] The reaction was carried out with 1 mmol of benzene, 0.5 mmol of I₂, reaction time: 10 h; when necessary, CeO₂ nanocrystals (0.05 g), H₂O₂ (2 mL of 35 wt% H₂O₂ aqueous solution); the products were analyzed by ¹H NMR and ¹³C NMR.

^[b] The yield here is determined by GC.

show that the hydroxyl radicals were indeed generated during the process. To further verify the role of hydroxyl radicals in iodination, we performed other control experiments. Some well-known hydroxyl radical scavengers, such as DMSO or 1,3-dimethylthiourea, were added in the benzene/H₂O₂/CeO₂ iodination system. This time, no EPR signal of hydroxyl radicals [Figure 2, **d**) and **e**)] could be observed and consistently, no iodination product was produced. Apparently, this is because the hydroxyl radicals were scavenged by DMSO or 1,3-dimethylthiourea.^[13] The above experiments demonstrate that the hydroxyl radicals play a vital role in benzene iodination.

The Effects of pH Values for Benzene Iodination

If free hydroxyl radicals were involved in the system, one may reason that phenol could be produced through an intermediate aromatic radical mechanism.^[16] However, the present results show no detectable hydroxylated aromatic by-products. Walling et al.^[17] studied the hydroxylation of benzene by Fenton's reagent (a mixture of ferrous iron salts and H_2O_2 that can produce hydroxyl radicals) and found that the phenol yield was considerably pH dependent; under strongly acidic condition, only very low phenol yields were obtained. They proposed that under such conditions, most intermediate aromatic radicals could be collapsed and reduced back to benzene, preventing further hydroxylation.^[18]

To investigate the effects of the acidity on the iodination of benzene, reactions were carried out at various pH values. As mentioned in the Experimental Section, the automatically generated pH value of the water layer by the H_2O_2 aqueous solution is 3.0. For more strong acidity or basicity, it could be maintained by adding strong acids (HCl) or bases (NaOH). The EPR results at different pH values are shown in Figure 3. It can be found that OH could be generated

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Figure 3. EPR spectra of the reaction system at different pH values: **a**) pH 3.0; **b**) pH 4.5; **c**) pH 6.0.

under all the conditions. And the lower the pH value, the stronger was the ERP signal of 'OH that could be observed. When the pH value was 1.5, H_2O_2 decomposed rapidly and violently, the EPR spectrum could not be obtained.

The products were then analyzed and summarized in Table 2. When the pH value was 3.0 or less, iodobenzene was the only product; whereas at a pH value higher than 6.0, phenol was the only product. At a pH value of around 4.5, both iodobenzene and phenol were produced.

Thus the low pH value could be responsible for the high yield of iodobenzene and the absence of phenol in the present study.^[19]

Iodination of Other Arenes in the CeO₂/H₂O₂ System

The scope of the hydroxyl radical-promoted iodination was examined. Table 3 shows the results of iodi-

Table 2. Iodination of benzene at different pH values.^[a]

Entry	pH	Product and yield ^[b] [%]
1	1.5	74 (iodobenzene); 0 (phenol)
2	3.0	72 (iodobenzene); 0 (phenol)
3	4.5	12 (iodobenzene); 7 (phenol)
4	6.0	0 (iodobenzene); 12 (phenol)

^[a] The reaction was carried out with 1 mmol of benzene, 0.5 mmol of I₂, CeO₂ nanocrystals (0.05 g), H₂O₂ (2 mL of 35 wt% H₂O₂ aqueous solution) and distilled water (1 mL); the products of all these reactions were analyzed by ¹H NMR and ¹³C NMR.

^[b] the yield here is determined by GC.

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nation of other arenes under similar reaction conditions. The electron density of the aromatic ring of the arenes affects the effectiveness of the iodination. When there are electron-donating substituents, such as methyl group or methoxy group, the conversions (entries 1-3) are excellent with the yield ranging from 89% to 97%. The reactions even tolerate weakly electron-withdrawing substituents such as chlorobenzene (entry 6); the yield is nearly 70% within 10 h. However, for aromatic compounds with strongly electronwithdrawing groups (e.g. benzonitrile, entry 7) the iodination reaction is difficult; even at elevated temperature (80°C) after long reaction time (24 h) no products could be detected. The electron density-dependence is in agreement with the well-documented electrophilic aromatic substitutions.^[5,16]

Another important feature of the iodination protocol is that the substitution reactions exhibit high site selectivity. As shown in Table 3, 1,3-dimethoxybenzene (1a), 1,3-dimethylbenzene (2a), anisole (3a), methylbenzene (4a), and chlorobenzene (6a) led to almost exclusive iodination products at the *para* position (analyzed by GC and ¹H NMR). It is well known that the electron density of the aromatic ring and steric hindrance have important effects on the site selectivity of substitution reactions,^[20] and an electrondonor substituent is *ortho/para*-directing, where the electron density is relatively high.^[21] The high site selectivity here may be mainly due to the combination of high electron density at the *para*-position and the influence of steric hindrance.^[22]

The influence of the solvent should also be mentioned. It has been reported that the concentration of water had a significant effect on the rate of the iodination and the products.^[23] In the present experiments, we found that some unexpected by-products could be detected although the reaction rate could be improved by adding other organic solvents (e.g., alcohol and cyclohexane) into the system. While this process is still unclear, we observed the the adoption of water does make the products get a good selectivity in our case.^[24]

The Effect of H₂O₂ and I₂ Dosages on Iodination

The effect of H_2O_2 dosage on iodination was investigated and the results are shown in Table 4. It can be seen that the conversion of both benzene and 1,3-dimethoxybenzene increase remarkably with the increase of the dosage of H_2O_2 , although an excess amount of the H_2O_2 was employed. It is well-known that hydroxyl radicals are highly reactive and consequently short-lived. To achieve high conversion of the substrates, an excess of H_2O_2 dosage was adopted in our above experiments.

fable 3. Iodination of aromatic con	pounds using I ₂ /H ₂	O ₂ /CeO ₂ nanocrystals. ^[a]
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Entry	Substrate	Product	Time [h]	Conversion [%] ^[b]	Yield [%] ^[c]
1	MeO 1a	MeO 1b	0.5	~100	97
2	Me Me 2a	Me L 2b	1.5	~100	92
3	OMe 3a	OMe 3b	2	92	89
4	Me 4a	Me 4b	4	80	75
5	5a	5b	10	78	72 ^[d]
6	Cl 6a	Cl 6b	14	73	68
7	CN 7a	CN 7b	24	0	0

^[a] The reaction was carried out with 1 mmol of arenes, 0.5 mmol of I₂, CeO₂ nanocrystals (0.05 g), H₂O₂ (2 mL of 35 wt% H₂O₂ aqueous solution) and distilled water (1 mL); the products of all these reactions were analyzed by ¹H NMR and ¹³C NMR.

^[b] The conversion was determined by GC.

^[c] The yield here was determined by GC.

^[d] 4% of the product is 1,4-diiodobenzene.

Entry	Substrate	Dosage of H ₂ O ₂	Reaction Time [h]	Yield [%] ^[b]
1	MeOOMe	1 mmol	1	17
2	MeO OMe	5 mmol	1	92
3	MeO	20 mmol	1	97
4		5 mmol	10	33
5		10 mmol	10	57
6		20 mmol	10	72

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Table 4.	. The	effect	of H ₂ O	dosage	on our	· iodina	ation.	[a]

^[a] The reaction was carried out with 1 mmol of arene, 0.5 mmol of I₂, CeO₂ nanocrystals (0.05 g), distilled water (1 mL) and different dosages of H_2O_2 (35 wt%).

^[b] The yield here was determined by GC.

Using the iodination of 1,3-dimethoxybenzene as an example, the effect of the amounts of I_2 on the product was tested. When one equivalent of I_2 was employed, only mono-iodination of aromatic compounds (2,4-dimethoxyiodobenzene) could be obtained. If excess amounts of I_2 (with an I_2 /arene ratio of 1.2:1) were employed, at the initial stage of the reaction, only the mono-iodination product could be formed. However, once the mono-iodination was completed, the diiodination product started to form, and was the only product after a longer reaction time. These results indicate that the process of mono- and diiodination of arenes could be well separated by adjusting the amounts of I_2 .

Recovery and Reuse of CeO₂ Nanocrystals

Besides the environmentally benign feature, another clear advantage of this iodination protocol is the easy recycle of the catalyst. Due to the insolubility of CeO₂ nanocrystals in water, the CeO₂ nanocrystals can be easily recovered by centrifugation (10 min, 4000 rpm). In a typical procedure, the recovered CeO₂ nanocrystals were washed by deionized water and alcohol, and then dried in air. The recovery rates

Table 5. CeO_2 nanocrystals recycling experiments with benzene.^[a]

phology and there is no change in length and diameter.

Run	1	2	3	4	5
Conversion [%] ^[b]	78	76	76	77	78

^[a] Reaction conditions: benzene (1 mmol), I_2 (0.1270 g, 0.5 mmol), H_2O_2 (2 mL of 35 wt% H_2O_2 aqueous solution), CeO₂ nanocrystals (recycled 0.05 g), deionized water(1 mL), 80 °C, 10 h.

^[b] The conversion was determined by GC.

of CeO_2 nanocrystals were 97.8%–98.4%. Table 5 shows the five sequential runs of benzene iodination by using sequentially recycled CeO_2 nanocrystals. It can be seen that there was no change in morphology of the CeO_2 nanocrystals and they could be well reused without loss of activity.

The TEM image [Figure 4, **a**)] and the powder XRD analysis [Figure 4, **b**)] show that after the reaction the CeO₂ nanocrystals still have the rod-like mor-

Computational Results

The above experimental study indicates that both 'OH radical and acidic conditions are crucial for the benzene iodination. To gain insights into the mechanism, M05-2X^[25] DFT calculations were performed using benzene iodination as an example. The reliability of the M05-2X DFT functional has been demonstrated by calibrations and successful applications.^[26] The free energies were discussed, otherwise specified, and the enthalpy results are included in the Scheme 3 and Scheme 4 for reference.

It has been recognized that I⁺-type intermediates are important in various iodination reactions.^[20a,27] We reasoned that similar species also play a role in our reaction, according to which the first question is how hydroxyl radical activates I_2 to give the desired I⁺-







Scheme 2. Free energy (in kcalmol⁻¹) profile for I_2 activation, along with the key bond lengths in Å. The values in the square brackets are enthalpies in kcalmol⁻¹.

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type species. Our calculations unveil that I_2 can be oxidized into two IOH species *via* the mechanism shown in Scheme 2.

An 'OH radical first binds to I_2 to form the complex (I_2OH), which is exergonic by 11.7 kcalmol⁻¹. Subsequently, another 'OH attacks the I_2OH complex to give another complex [$I_2(OH)_2$]. Interestingly, the second 'OH prefers attacking the same I atom as that in the first attack, rather than the innocent I atom. This is reasonable because the first 'OH binding makes the attacked I atom electrophilic. Consequently, the I–I bond in $I_2(OH)_2$, 3.072 Å, is even shorter than the 3.428 Å in I_2OH . After passing the three-membered transition state (**TS1**), the I–I bond splits, giving the complex **IM1**. The barrier for the I–I bond



Scheme 3. Geometric and energetic results of benzene iodination of *via* IOH.

cleavage is 28.9 kcal mol⁻¹ measured from $I_2(OH)_2$, but it is only 3.1 kcal mol⁻¹ higher than $I_2 + 2$ OH. The I_2 activation is strongly exergonic by 52.0 kcal mol⁻¹. The **IM1** complex is less stable than the two IOH species in terms of free energy, so it can be dissociated into two IOH species readily.

The iodine species (IOH) has character of $I^{\delta+}$ -type species, but it is not electrophilic enough to promote iodination. No σ -complex could be located between benzene and IOH and the barrier for the reaction (IOH+C₆H₆ \rightarrow C₆H₅I+H₂O) is very high (64.8 kcal mol⁻¹, see Scheme 3).

However, under the strongly acidic condition, the IOH species can be protonated to more electrophilic IOH₂⁺. Our predicted mechanism for the IOH₂⁺-initiated iodination, together with the energetic and geometric results, are illustrated in Scheme 4. As expected, the IOH_2^+ can form a stable cationic σ -complex (IM2⁺) with benzene that is $14.1 \text{ kcal mol}^{-1}$ more stable than benzene+ IOH_2^+ . In the structure of IM2⁺, the I–O bond is elongated to 2.575 Å from 2.072 Å in the free I–OH₂⁺ species and the length of the newly formed I–C (sp^3 carbon) bond is 2.343 Å. With the σ -complex (IM2⁺) formed, another IOH then abstracts the hydrogen on the sp^3 carbon of the σ -complex by crossing a barrier (TS2⁺) of 12.8 kcal mol⁻¹. Note that a weak complex (IM3⁺) prior to $TS2^+$ can be located, but it is less stable than $IM2^+$ + IOH after thermal and entropic corrections. The hydrogen abstraction leads to the complex (IM4⁺). The



Scheme 4. Energy (in kcalmol⁻¹) profile for benzene iodination, along with optimized structures. The key bond lengths are given in Å. The values in the square brackets are enthalpies in kcalmol⁻¹.

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gradually elongated I-O (water O) distances [2.575 (IM2⁺), 2.588 (IM3⁺), 2.832 (TS2⁺), and 2.997 Å $(IM4^+)$] and the shortened I–C (sp³ carbon) bond lengths [2.343 (IM2⁺), 2.336 (IM3⁺), 2.190 (TS2⁺), and 2.127 Å (IM4⁺)], depict the leaving process of the water molecule and the forming process of the I-C bond. The process from IM2⁺+IOH to IM4⁺ is enthalpically favorable due to gaining aromaticity of the benzene ring, but nearly thermoneutral in free energy due to the cancelation of entropic penalty. Relative to the final products $(C_6H_5I + IOH_2^+ + H_2O)$, the IM4⁺ complex is enthalpically more stable, but it is 15.5 kcal mol⁻¹ less stable in terms of free energy. The entropic driving force separates the complex (IM4⁺), giving the final products. The IOH₂⁺ species released from the process can be "recycled" for the next benzene iodization, in agreement with the experimental fact that one equivalent iodine can iodize two equivalents of aromatic compound. The mechanism requiring protonation is consistent with the experimental fact that no iodobenzene could be detected under the weakly acidic conditions.

To support our proposed mechanism, we have run the iodination of methoxybenzene in the $I_2/H_2SO_4/H_2O_2$ system. It was observed that iodination of the arene occurred, with a methoxyiodobenzene yield of 83% after a reaction time of 2 h, providing further experimental evidence for the hydroxyl radical mechanism.

Combining the experimental and computational study, we propose the mechanism for the direct iodination, which includes five steps: the 'OH generation from H_2O_2 catalyzed by CeO₂ nanocrystals; the I₂ activation promoted by 'OH giving two IOH species; the protonation of IOH leading to more electrophilic I⁺-type species (i.e., IOH₂⁺ complex); the attack of IOH₂⁺ to arenes to form the σ -complex; and the hydrogen abstraction by another IOH, finally resulting in the aromatic iodide.

Conclusions

In summary, we have developed a green strategy for direct mono-iodination of arenes in aqueous medium starting with molecular iodine. The strategy uses rod-like CeO₂ nanocrystals to promote the decomposition of hydrogen peroxide, giving hydroxyl radicals which then activate I_2 to complete the iodination. The new strategy has the advantages of easy product isolation, high regioselectivity, good yields, no hazardous waste, and convenient recycle of the catalyst. The computational study reveals the following mechanism for the hydroxyl radical-promoted iodination. Two hydroxyl radicals first activate I_2 giving two IOH species. The IOH species is not electrophilic enough to promote iodination but can be protonated to more electrophil-

ic IOH_2^+ under the strongly acidic conditions. IOH_2^+ can readily attack arenes to form σ -complexes. Another IOH species then abstracts the hydrogen from the σ -complex, resulting in the aromatic iodide. The predicted mechanism successfully elucidates why the reactions occur, but further study will be needed to fully understand other features such as the regioselectivity.

Experimental Section

Synthesis and Characterization of CeO₂ Nanocrystals

CeO₂ nanocrystals were prepared according to our previously reported method. CeCl₃7H₂O (1.5 g) was dissolved in distilled water, and proper amounts of 10 wt% NaOH solution were rapidly added with stirring vigorously. A purpure precipitate of amorphous Ce(OH)₃ appeared. After about 15 min of stirring, all of the slurry (the volume was about 35 mL) was transferred into a 50 mL autoclave, which was filled with deionized water up to 80% of the total volume (the final NaOH concentration in the autoclave is about 2M), and heated at 120 °C under autogenous pressure for 12 h. Then the system was allowed to cool to room temperature. The final product was collected by filtration, washed with deionized water and alcohol to remove any possible ionic remnants, and then dried at room temperature.

Powder X-ray diffraction (XRD) data were collected on MSAL-XD2 using Cu-K_a radiation (λ =1.5418 Å). The size and morphology of CeO₂ nanocrystals were measured with a Philips CM120 transmission electron microscopy.

EPR Measurements

Electron paramagnetic resonance (EPR) spin trapping techniques were used to study the production of hydroxyl radicals. Since the life time of a hydroxyl radical is only 10^{-9} s, it cannot be detected directly by EPR. Thus, spin trap, 5,5-dimethyl-1-pyrroline 1-oxide (DMPO), was used to capture OH to generate a long-lived free radical (spin adduct, DMPO-OH) which can then be detected by EPR spectroscopy. The EPR experiments were carried out with a JES-FA200 instrument operating in the X-band. For the DMPO (5,5-dimethyl-1-pyrroline N-oxide) spin trapping EPR experiments, the samples were suspended in water (at a concentration of 0.5 $\text{mmol } L^{-1}$) and sonicated for 5 min. An aqueous (0.01 M) of DMPO spin trap (supplied by Sigma) was prepared shortly before the experiment and kept on ice during the whole set of experiments and bidistilled water was employed for these preparations. H₂O₂ used in the experiments was diluted with water (1:5). 100 µL of the solid suspension, 100 μ L diluted H₂O₂ and 20 μ L of the DMPO solution were mixed into an EPR flat quartz capillary under atmospheric air at room temperature. And the capillary was immediately transferred to the spectrometer cavity for EPR analysis. The spectra were recorded at room tempertaure by accumulating two scans.

General Procedure for the Formation ofIodinated Products

All the reactants were used directly without further treatment. In a 25-mL three-neck flask, substrates (1 mmol), I₂ (0.1270 g, 0.5 mmol), 35 wt% H_2O_2 aqueous solution (2 mL) and CeO₂ nanocrystals (0.05 g) were added in 1 mL of deionized water under air. The pH value of the water layer was 3.0 which was maintained automatically by the H_2O_2 aqueous solution. The reaction mixture was stirred at reflux temperature for a period of time (0.5 to 24 h). The resulting reaction mixture was centrifugated to separated the CeO₂ nanocrystals, then the supernatant was treated with Na₂S₂O₄ (10 mol%, 10 mL) and extracted with diethyl ether $(2 \times$ 10 mL). The ethereal solution was dried over anhydrous Na₂SO₄ and filtered. Evaporation of the solvent resulted in the desired crude product which was further purified by column chromatography on silica gel with petroleum ether and ethyl acetate (1:10) as eluent to furnish the pure compound.

Analytical thin layer chromatography was performed using glass plates pre-coated with silica gel (0.25 mm, 60 Å pore size, 230-400 mesh, Yantai Chemical Industry Research Institute) impregnated with a fluorescent indicator (254 mm). TLC plates were visualized by exposure to ultraviolet light (UV). Proton nuclear magnetic resonance (¹H NMR) spectra and carbon nuclear magnetic resonance (¹³C NMR) were recorded with JOEL JNM-ECA600 (600 MHz/150 MHz) NMR spectrometers. Chemical shifts for protons are reported in parts per million (δ scale) and internally referenced to the SiMe₄ signal. Chemical shifts for carbon are reported in parts per million (δ scale) and referenced to the carbon resonances of the solvent (CDCl₃: $\delta =$ 77.36, the middle peak). Data are represented as follows: chemical shift, multiplicity (s=singlet, d=double, t=triple), coupling constant in Hz, and integration. Gas chromatographic (GC) analyses for the determination of conversion were performed on an SP-2100 Series instrument.

Computational Methods

All the structures involved in this work were optimized and then characterized by frequency analysis calculations in the solvent (water) by using M05-2X functional with the basis sets of $6-311 + +G^{**}$ for H, C, O and SDD for I. The solvent effects of water were simulated by the IEFPCM (integral equation formalism polarizable continuum solvent model) solvent model with the UFF atomic radii. The harmonic frequencies were used for thermal and entropic corrections at 297.15 K and 1 atm. When necessary, the intrinsic reaction coordinate (IRC) calculations were used to confirm the correct connection between a transition state and its backward and forward minima. All the calculations were performed by using Gaussian 03.

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