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Communication to the Editor

Photo-Induced Atom-Transfer Radical Reactions Using Charge–Transfer Complex between Iodine and Tertiary Amine

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In the presence of charge–transfer complexes between iodine and tertiary amines, the aqueous-medium atom-transfer radical reactions proceeded under visible light irradiation without the typical photocatalysts.

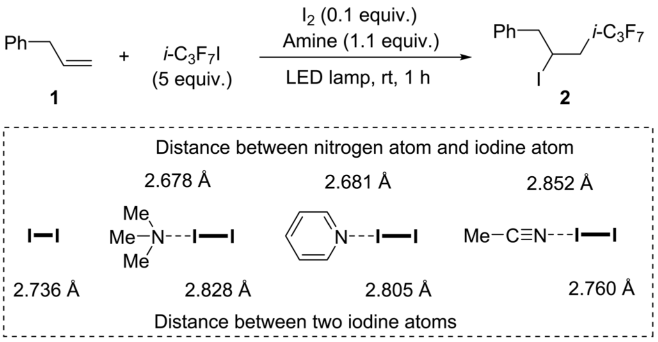
Key words radical; iodine; photochemistry; perfluoroalkyl; charge–transfer complex; aqueous media

The charge–transfer complex (CT complex) is formed by weak association of electron-donor and electron-acceptor. Particularly, the CT complexes between metal atoms and ligands are widely studied in inorganic chemistry.[1,2] In recent years, the metal-to-ligand charge transfer in transition metal photocatalysts has been applied to the synthetic organic chemistry.[3–5] Although the physical properties of organic CT complexes are investigated,[6–10] less is known about the utility of organic CT complexes in synthetic reactions.[11–15] In our studies on the radical reactions using Ru-catalyst or rhodamine B as a photocatalyst,[16–19] we found that the some reactions proceeded in the absence of these photocatalysts. Therefore, our laboratory is interested in developing a new method which doesn't require the external photocatalysts. In this communication, we report the experiments to prove the utility of organic CT complexes between iodine (I_2) and tertiary amines in the aqueous-medium carbon–carbon bond-forming radical reactions.

Iodine is known to interact with amines to form the CT complexes, which have the two broader absorption bands at *ca.* 230–280 and 410–430 nm[20,21] (Chart 1). Therefore, we expected that the visible light irradiation of CT complex **A** in the ground state gives the excited state **B**, which may promote the single electron transfer (SET) from the donor amine to the acceptor iodine giving the iodine radical.[22–24]

At first, we studied the effect of CT complexes derived from I_2 and several amines on the iodine atom-transfer radical reaction of alkene **1** with $i\text{-}C_3F_7I$ (Table 1). In the presence of I_2 (0.1 eq) and trimethylamine (1.1 eq), the biphasic solution of **1** and $i\text{-}C_3F_7I$ (5 eq) in H_2O was stirred for 1 h with white LED light (400–700 nm, 1000 lm) irradiation under Ar atmosphere (entry 1). In this reaction, 1.1 eq of trimethylamine were employed, because 1.0 eq of amine also acts as an electron-donor leading to **C**. As expected, the desired product **2** was obtained in 89% yield. In marked contrast, the reaction did not occur when MeCN was employed as solvent (entry 2). The use of $(i\text{-Pr})_2NEt$ as a tertiary amine led to enhancement in chemical yield (entry 3), although pyridine did not promote the reaction probably due to its low reactivity as an electron-donor (entry 4). The chemical yield of **2** dramatically decreased by using secondary amine such as $(i\text{-Pr})_2NH$, owing to the oxidation of secondary amine by I_2 (entry 5).[25–27] Interestingly, in the absence of iodine, this transformation took place slowly by using $(i\text{-Pr})_2NEt$ (entry 6). Even in the absence of I_2, CT complex between $(i\text{-Pr})_2NEt$ and I_2 would be formed, because $i\text{-}C_3F_7I$ is gradually decomposed to give I_2. However, in the absence of amine, the reaction using only iodine did not occur and the solubility of iodine also decreased without the association with amine (entry 7). Therefore, this CT complex-promoted reaction is differentiated from the reported iodine-mediated radical reactions.[28,29] Theoretical and computational studies

Table 1. Iodine-Atom Transfer Reaction Using Charge–Transfer Complexes[a)]



Entry	Amine	Solvent	Yield (%)[b)]
1	Me_3N	H_2O	89
2	Me_3N	MeCN	ND[d)]
3	$(i\text{-Pr})_2NEt$	H_2O	98
4	Pyridine	H_2O	ND[d)]
5	$(i\text{-Pr})_2NH$	H_2O	3
6[c)]	$(i\text{-Pr})_2NEt$	H_2O	56
7	None	H_2O	ND[d)]

a) Reactions of **1** (1 eq) with $i\text{-}C_3F_7I$ (5 eq) were carried out in the presence of I_2 (0.1 eq) and amine (1.1 eq) under the LED light irradiation. The calculation studies were performed on density functional B3LYP 6–311+G** by using Spartan'10 (WAVEFUNCTION, INC.). *b*) Isolated yields. *c*) Reaction was carried out in the absence of I_2 for 4 h. *d*) The formation of product **2** was not detected.

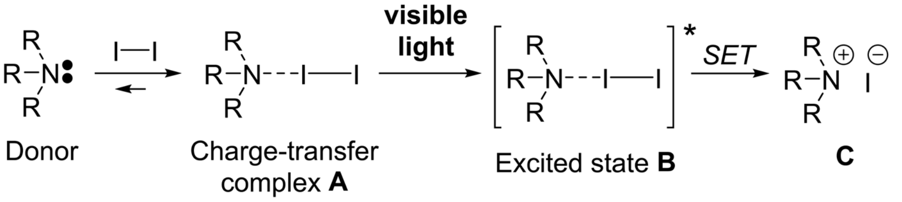


Chart 1. Charge–Transfer Complex between Amine and Iodine

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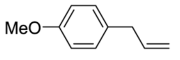
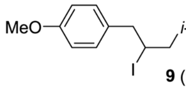
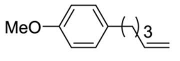
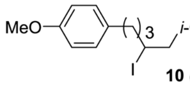
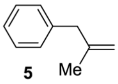
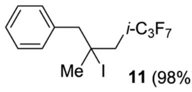
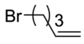
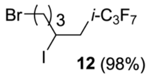
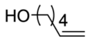
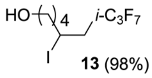
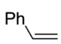
Table 2. Reaction of **3**–**8** with i-C_3F_7I[a)]

Entry	Substrate	Product (% Yield)[b)]
1	 **3**	 **9** (98%)
2	 **4**	 **10** (85%)
3	 **5**	 **11** (98%)
4	 **6**	 **12** (98%)
5	 **7**	 **13** (98%)
6	 **8**	ND[c)]

a) Reactions of **3**–**8** (1 eq) with i-C_3F_7I (5 eq) were carried out in H_2O in the presence of I_2 (0.1 eq) and (i-Pr)$_2$NEt (1.1 eq) for 1 h under the LED light irradiation. *b*) Isolated yields. *c*) The formation of product was not detected.

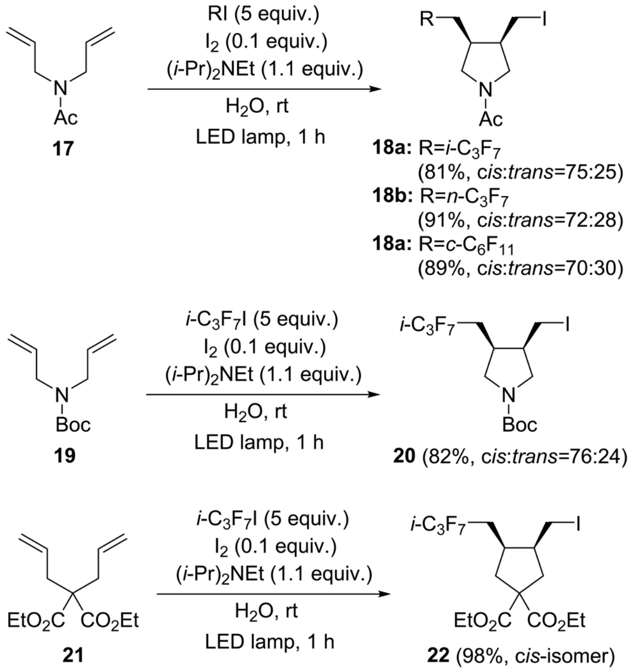


Chart 3. Cascade Radical Addition-Cyclization-Trapping Reaction

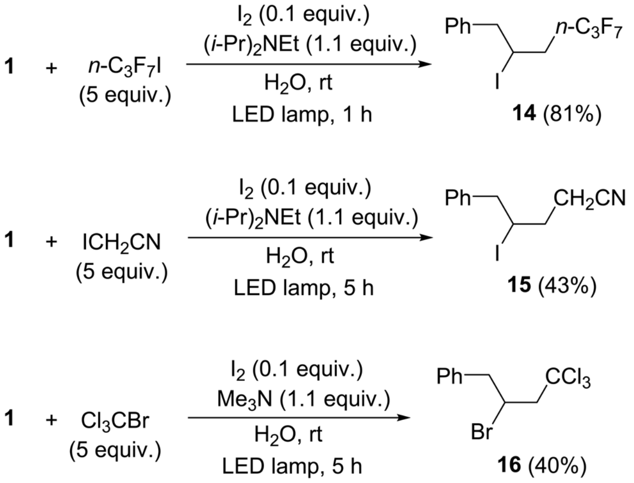


Chart 2. Reaction with Other Carbon Radical Precursors

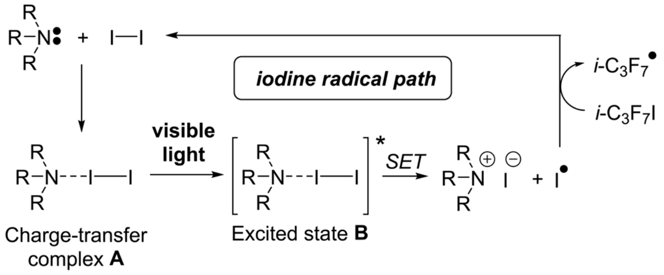


Chart 4. Possible Reaction Pathway

on halogen bonding interactions have been a subject of current interest.[30,31)] To understand the above results, we calculated the optimized structures of iodine complexes. The calculation shows that the noncovalent interaction between trimethylamine and I_2 is strong to form the stable CT complex, while pyridine weakly interacts with I_2. Additionally, we presume that the negligible interaction of MeCN solvent with I_2 may suppress the formation of CT complex.

We next explored the iodine atom-transfer radical reaction of various alkenes **3**–**8** with i-C_3F_7I under the optimized reaction conditions (Table 2). Except for styrene **8**, alkenes **3**–**7** reacted with excellent chemical efficiencies and regioselectivities. It is important to note that the reactions of alkene **6** having bromine atom and alkene **7** having hydroxy group proceeded without any problems.

To study the viability of the present method, n-C_3F_7I, ICH_2CN and CCl_3Br were next employed as carbon radical precursors (Chart 2). The reaction of **1** with n-C_3F_7I proceeded to give the product **14** in 81% yield. Although the reaction in MeCN did not occur (entry 2 in Table 1), ICH_2CN having cyano group worked as a radical precursor to give the adduct **15** in 43% yield. Moreover, the bromine atom-transfer radical reaction using CCl_3Br took place with moderate chemical efficiency.

We finally investigated the radical addition-cyclization-trapping reaction of symmetrical substrates **17**, **19** and **21** in aqueous media (Chart 3). When i-C_3F_7I was employed, the reaction of **17** was completed within 1 h to give the products *cis*-**18a** and *trans*-**18a** in 81% combined yield. Other radical precursors n-C_3F_7I and c-$C_6F_{11}I$ worked well. Similarly, the reaction of **19** with i-C_3F_7I gave the products *cis*-**20** and *trans*-**20** in 82% combined yield. The reaction of **21** also proceeded effectively to give the product **22** in 98% yield with excellent *cis*-diastereoselectivity.

The possible reaction pathway for the generation of i-C_3F_7 radical is shown in Chart 4. The reaction is initiated by the visible light irradiation of CT complex **A** in the ground state to produce the excited state **B**. We presume the generation of an iodine radical *via* the single electron transfer from the donor amine to the acceptor iodine in the excited state **B**, which is evident from observation of the transient species generated in the photoexcitation of quinuclidine–I_2 and triethylenediamine–I_2 complexes by means of transient absorption spectroscopy,[22] although it cannot be excluded that the excited state **B** acts as a reducing agent toward i-C_3F_7I. Finally, an iodine radical reacts with i-C_3F_7I to give i-C_3F_7 radical and the regenerated iodine.

In summary, we have demonstrated that CT complexes between iodine and tertiary amines have the potential to induce the atom-transfer radical reactions in aqueous media. In addition to typical photocatalysts, the CT complexes disclosed a broader utility of photo-induced radical reactions.

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Conflict of Interest The authors declare no conflict of interest.

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