Photo-activation of Pd-catalyzed Sonogashira coupling using a Ru/bipyridine complex as energy transfer agent†

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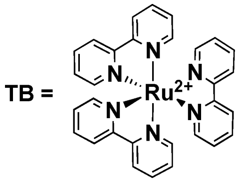
The mixed catalyst system, $Pd(CH_3CN)_2Cl_2/P(t\text{-}Bu)_3/[Ru(2,2'\text{-bipyridine})_3]\cdot 2PF_6$, promotes the copper-free Sonogashira coupling reaction of aryl bromides at room temperature under irradiation of visible light.

The tris(bipyridine)ruthenium(II) complex (**TB** = $[Ru(2,2'\text{-bipyridine})_3]^{2+}$, Scheme 1) has been known as one of the effective groups which trap visible light efficiently because of its outstanding photochemical, photophysical, and electrochemical properties based on metal-to-ligand charge transfer (MLCT).[1] The irradiation of **TB**(II) in solution yields ***TB**(II) (triplet excited state), and if a sacrificial electron donor such as Et_3N exists, **TB**(I) (univalent state) is photochemically generated *via* ***TB**(II) (eqn (1) and (2)).[1]

$$\mathbf{TB}(\text{II}) \xrightarrow{h\nu} {}^*\mathbf{TB}(\text{II}) \quad E_0({}^*\mathbf{TB}(\text{II})/\mathbf{TB}(\text{III})) = -0.84\ \text{V} \qquad (1)$$

$$\mathbf{TB}(\text{II}) \xrightarrow[\text{Et}_3\text{N}]{h\nu} \mathbf{TB}(\text{I}) \quad E_0(\mathbf{TB}(\text{I})/\mathbf{TB}(\text{II})) = -1.28\ \text{V} \qquad (2)$$



Scheme 1 Structure of **TB** ($[Ru(2,2'\text{-bipyridine})_3]^{2+}$).

Therefore, **TB** and its derivatives are often used as co-catalysts in the photocatalytic systems composed of a photsensitizer and a catalyst, *e.g.*, photodissociation of water[2] and photoreduction of CO_2 to CO.[3] Photo-activated ***TB**(II) and **TB**(I) states in themselves are unable to catalyze a reaction, but they may be able to play a crucial role to activate the precursor catalyst *via* electron and/or energy transfer.[4] To the best of our knowledge, there is no precedent of a light-promoted, metal-catalyzed coupling reaction and therefore it is challenging to study this new type of multicomponent catalyst. As the first attempt, the Sonogashira coupling reaction has been used and herein we describe the **TB**-containing catalyst system that can undergo the Pd-catalyzed Sonogashira coupling reaction under irradiation of visible light.

Typical procedures for this Pd-catalyzed reaction involve the use of CuI as a co-catalyst, an amine as a base and a phosphine as the ligand for palladium, the key transition metal component. Since the first report in 1975,[5] a number of modifications and improvements of the original protocol have been reported, such as reaction in ionic liquids with the purpose of recycling the catalyst,[6] the use of TBAF/Ag_2O as effective co-catalysts,[7] under aerobic conditions for the practical convenience[8] and recoverable dendritic catalysts.[9] In the conventional catalytic cycle, (i) formation of the Pd(0) species *via* reductive elimination of the palladium diacetylide intermediate and (ii) oxidative addition of aryl halide to the Pd(0) species are involved as key steps. We envisaged that if **TB**(I) or ***TB**(II) can be generated by irradiation of the mixed Pd–**TB** catalyst system, the activated **TB** species may readily reduce the Pd(II) precursor without forming the palladium diacetylide intermediate to promote the catalytic reaction. In addition, the activated **TB** species may affect the oxidative addition step.

The palladium catalysts with bulky, electron-rich phosphine ligands such as $P(t\text{-}Bu)_3$ have been reported to exhibit unusually high reactivity for the Sonogashira coupling reaction of aryl bromides at ambient temperature,[10] as typically exemplified by the $Pd(PhCN)_2Cl_2/P(t\text{-}Bu)_3/CuI/HN(i\text{-}Pr)_2$ (Buchwald and Fu),[10a] $Pd_2(dba)_3/P(t\text{-}Bu)_3/Et_3N$ (Herrmann),[10b] and $((\eta^3\text{-allyl})PdCl)_2/P(t\text{-}Bu)_3$/piperidine or DABCO systems (Soheili).[10c] We have applied our **TB** strategy to the $P(t\text{-}Bu)_3$ system, and optimized the ratio of the palladium, phosphine, and **TB** components for the standard reaction as shown in Table 1.[11]

The product yield under irradiation (entry 1) is noted to increase dramatically compared with that in the dark or under irradiation without **TB** (entries 7 and 8). The promoting effect of **TB** under irradiation exceeds that of the conventional co-catalyst, CuI (entry 1 and 9).[12] These observations indicate that photo-activated **TB** is essential to the high performance. The Pd/$P(t\text{-}Bu)_3$ is not crucial to the catalytic activities (entries 1–2). On the other hand, the amount of **TB** is critical. The reaction in the presence of 8% of **TB** (entry 1) gave a result better than the results obtained in the presence of a lesser amount (4%; entry 3) or an excess amount of **TB** (16%; entry 4). (The Pd and $P(t\text{-}Bu)_3$ concentrations were fixed to 4%.) Furthermore, for the reactions with 6% of the Pd–$P(t\text{-}Bu)_3$ reagent (entries 5 and 6), too, addition of an excess amount of **TB** caused a decrease of the product yield. These results suggest that addition of an excess amount of **TB** with the huge absorption based on MLCT in the visible light region (ε = 13 000, at 450 nm)[1] causes a significant decrease of the light transmittance through the reaction media. The results obtained so far reveal that the optimum concentration of the **TB** component is 12.8 mM (55 mg in 5 mL solvent) for the reaction carried out in a 13 mm-diameter Schlenk tube. Having optimized the reaction conditions for the coupling of bromobenzene and phenylacetylene we turned our attention

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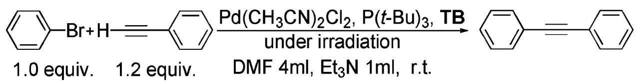
† Electronic supplementary information (ESI) available: Experimental details. See DOI: 10.1039/b618007h

Table 1 Optimization of the ratio of palladium, phosphine and **TB** in the Pd-catalyzed Sonogashira coupling of phenylacetylene and bromobenzene under irradiation of visible light[a]

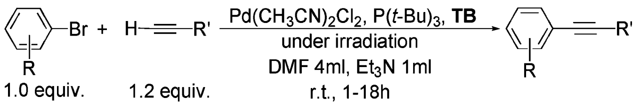


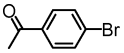
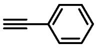
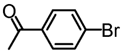
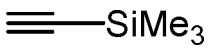
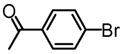
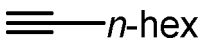
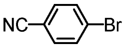
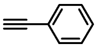
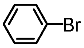
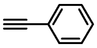
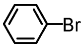
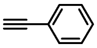
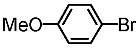
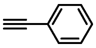
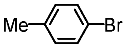
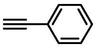
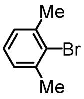
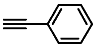
Entry	$Pd(CH_3CN)_2Cl_2$ (%)	P(*t*-Bu)$_3$ (%)	**TB** (%)	Yield[b] (%)	Time/h
1	4	4	8	91	4
2	4	8	8	87	4
3	4	4	4	64	4
4	4	4	16	55	4
5	6	6	8	80	2
6	6	6	16	59	2
7[c]	4	4	8	11	4
8[d]	4	4	—	11	4
9[e]	4	4	—	46	4

[a] Reaction conditions: bromobenzene (0.8mmol), phenylacetylene (0.96 mmol). [b] GC yields. [c] In the dark. [d] Under irradiation without **TB**. [e] CuI (4%) was added instead of **TB**.

to the function of **TB** in the catalytic cycle. The conversion rate curves for the entries 1 and 7 in Table 1 (monitored by GC) are shown as traces (a) and (b) in Fig. 1, respectively. The coupling was completed within 5 h under irradiation to afford the product in 95% yield (Fig. 1a), whereas the reaction in the dark gave the product in 14% yield after 7 h (Fig. 1b). Furthermore, as can be seen from trace (c), the catalytic reaction is promoted only during the irradiated period. The role of **TB** in the catalytic cycle

Table 2 Pd-catalyzed Sonogashira coupling of various aryl bromides with aryl and alkyl acetylenes in the presence of **TB**



Entry	Aryl bromide	Acetylene	Reaction time[a]/h	Yield (%) irrad.[b]	Yield (%) dark[c]
1			2 (4)	99 (91)	30
2			6 (7)	99 (90)	36
3			14 (14)	85 (74)	Trace
4			1 (2)	99 (95)	21
5			5 (8)	95 (94)	14
6			5 (8)	97 (92)	34
7			6 (8)	95 (84)	18
8			10 (10)	99 (90)	34
9			18 (15)	80 (87)	33

[a] The values in parentheses are reaction time for the experiments to determine isolated yields. [b] GC yields and the values in parentheses are isolated yields of the reaction products. [c] GC yields.

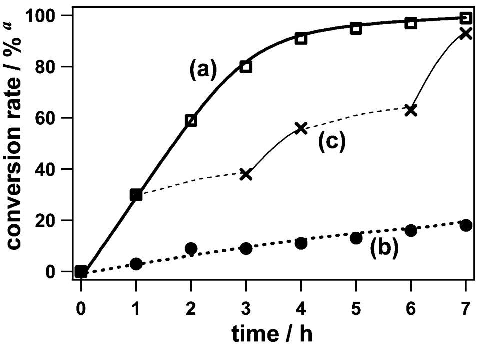
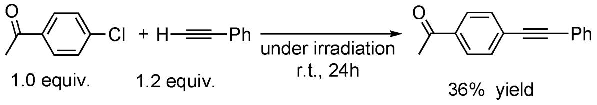


Fig. 1 Conversion rates for the Sonogashira coupling in the presence of **TB**; (a) with irradiation of 150 W-Xe lamp ($420 < \lambda < 800$ nm), (b) in the dark and (c) irradiated on and off. Solid and dotted curves are for the periods with irradiation or in the dark, respectively. [a]GC yield.

is unknown, but we guess that the **TB**(I) state is the key acceleration factor because the degradation products of triethylamine (the sacrificial electron donor; eqn (2)) are detected by GC-MS.[13,14]

We screened the reaction of various aryl bromides; the results are summarized in Table 2.[15] Activated aryl bromides react with aryl-, trimethylsilyl-, and alkyl-acetylenes in excellent yields within a short reaction time (entries 1–4). The less reactive bromobenzene, 4-bromoanisole, and 4-bromotolene also smoothly couple at ambient temperature (entries 5–8). Even sterically hindered 2-bromo-1,3-dimethylbenzene coupled with phenylacetylene high efficiently (entry 9). For every case (entry 1–9), the remarkable promotion effects of irradiation of visible light are evident as compared with the reactions in the dark.

It should be noted that under the same conditions, the reaction of 4-chloroacetophenone[16] and phenylacetylene (eqn (3)) afforded 4-acetylphenyl phenyl acetylene in 36% GC yield.[17] This result suggests that the activated **TB** species affect the oxidative addition step in the catalytic cycle.



(3)

In summary, we have demonstrated the photo-activation of the Pd-catalyzed Sonogashira coupling reaction by using **TB** as a co-catalyst in place of CuI. Attempts to apply this strategy to other transition-metal catalyzed coupling reactions are currently underway in our laboratory.

Acknowledgements

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Notes and references

1 A. Juris, V. Balzani, F. Barigelletti, S. Compagna, P. Belser and A. Von Zelewsky, *Coord. Chem. Rev.*, 1988, **84**, 85–277, and references therein.
2 (*a*) V. Balzani, L. Moggi, M. F. Manfrin, F. Bolletta and M. Gleria, *Science*, 1975, **189**, 852–856; (*b*) C. Crentz and N. Sutin, *Proc. Natl. Acad. USA*, 1975, **72**, 2858–2862; (*c*) J. R. Bolton, *Science*, 1978, **202**, 705–710; (*d*) E. Borgarello, J. Kiwi, E. Pelizzetti, M. Visca and M. Gräetzel, *J. Am. Chem. Soc.*, 1981, **103**, 6324–6329.
3 (*a*) J.-M. Lehn and R. Ziessel, *Proc. Natl. Acad. Sci. USA*, 1982, **79**, 701–704; (*b*) R. Maidan and I. Willner, *J. Am. Chem. Soc.*, 1986, **108**, 8100–8101.
4 For recent reports on visible light sensitization of chemical net reactions, see: (*a*) V. W.-W. Yam, V. W.-M. Lee and K.-K. Cheung, *Organometallics*, 1997, **16**, 2833–2841; (*b*) M. Osawa, M. Hoshino and Y. Wakatsuki, *Angew. Chem., Int. Ed.*, 2001, **40**, 3472–3474; (*c*) A. Inagaki, S. Edure, S. Yatsuda and M. Akita, *Chem. Commun.*, 2005, 5468–5470.
5 K. Sonogashira, Y. Toda and N. Hagiwara, *Tetrahedron Lett.*, 1975, **50**, 4467–4470.
6 (*a*) T. Fukuyama, M. Shinmen, S. Nishitani, M. Sato and I. Ryu, *Org. Lett.*, 2002, **4**, 1691–1694; (*b*) S. B. Park and H. Alper, *Chem. Commun.*, 2004, 1306–1307.
7 A. Mori, J. Kawashima, T. Shimada, M. Sugro, K. Hirabayashi and Y. Nishihara, *Org. Lett.*, 2000, **2**, 2935–2937.
8 (*a*) B. Liang, M. Dai, J. Chen and Z. Yang, *J. Org. Chem.*, 2005, **70**, 391–393; (*b*) J.-H. Li, Y. Liang and Y.-X. Xie, *J. Org. Chem.*, 2005, **70**, 4393–4396.
9 (*a*) K. Heuzé, D. Méry, D. Gauss and D. Astruc, *Chem. Commun.*, 2003, 2274–2275; (*b*) K. Heuzé, D. Méry, D. Gauss, J.-C. Blais and D. Astruc, *Chem.–Eur. J.*, 2004, **10**, 3936–3944.
10 (*a*) T. Hundertmark, A. F. Littke, S. L. Buchwald and G. C. Fu, *Org. Lett.*, 2000, **2**, 1729–1793; (*b*) V. P. W. Böhm and W. A. Herrmann, *Eur. J. Org. Chem.*, 2000, 3679–3681; (*c*) A. Soheili, J. Albaneze-Walker, P. G. Dormer and D. L. Hughes, *Org. Lett.*, 2003, **5**, 4191–4194.
11 **Typical Procedure** (Table 1, entry 2). 4-Bromobenzene (0.126 g, 0.80 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (0.0084 g, 0.032 mmol), and **TB** (0.055 g, 0.064 mmol) were added to a dried Schlenk tube (13 mm in diameter) with a Teflon™ stop cock. The vessel was degassed then backfilled with nitrogen followed by addition of DMF (4.0 mL). Then, P(t-Bu)$_3$ (97.5 μL of a 10 wt% solution in *n*-hexane, 0.032 mmol), phenylacetylene (105 mL, 0.96 mmol), mesitylene (internal standard: 50 μL, 0.362 mmol) and Et$_3$N (1.0 mL, 7.18 mmol) were added *via* a syringe to the stirred reaction mixture under an atmosphere of nitrogen. The irradiation of visible light was carried out by a 150-W Xenon lamp (Ushio SX-UI 150XQ) through a Toshiba Y-42 glass filter and a Sigma-koki CLDF-50S colored filter ($420 < \lambda < 800$ nm). The diameter of the effective irradiation field was 50 mm. For the dark reactions, the Schlenk tube wrapped with an Al-foil was irradiated to make the reaction temperature similar. The yields of products and the consumption of aryl bromides were determinedby GC.
12 **Conditions** (Table 1, entry 9). 4-Bromobenzene (0.126 g, 0.80 mmol), phenylacetylene (105 μL, 0.96 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (0.0084 g, 0.032 mmol), CuI (6.10 mg, 0.032 mmol), Et$_3$N (1.0 mL, 7.18 mmol), DMF (4.0 mL).
13 P. J. DeLaive, B. P. Sullivan, T. J. Meyer and D. G. Whitten, *J. Am. Chem. Soc.*, 1979, **101**, 407–408.
14 HN(Et)$_2$ ($m/z = 73, 58$) and CH$_3$CHO ($m/z = 44, 29$) were detected by GC-MS. These, two compounds were derived from hydrolysis of Et$_2$N$^+$=CHCH$_3$.
15 See ESI† for experimental details.
16 Reports on copper-free Sonogashira coupling of aryl chlorides at room temperature are still few, see: D. Méry, K. Heuzé and D. Astruc, *Chem. Commun.*, 2003, 1934–1935.
17 We observed extensive dimerization of phenylacetylene giving 1,4-diphenylbutadiyne before the consumption of 4-chloroacetophenone.