

Photochemical Formal Alkadiene Insertion into an Aromatic C–CN Bond Using Cyanide Ion as a Catalyst

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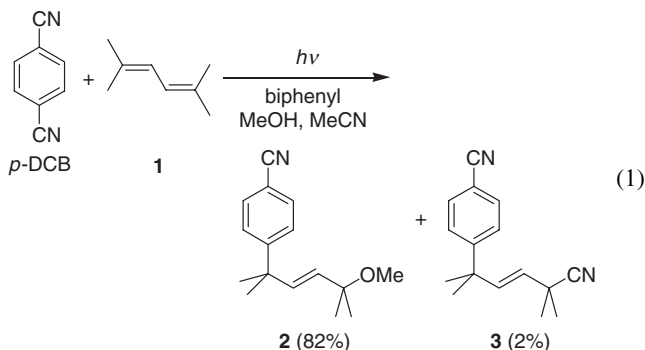
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A reaction involving formal alkadiene insertion into a C–CN bond taking place via a catalytic photo-NOCAS mechanism was developed. The process involves photoirradiation of an acetonitrile solution containing 2,5-dimethyl-2,4-hexadiene (**1**), *p*-dicyanobenzene (*p*-DCB), phenanthrene (Phen), and a catalytic amount (20 mol %) of tetra-*n*-butylammonium cyanide. The reaction proceeds in the absence of noble metals and under mild conditions (ambient temperature without bases). This is the first example of a photo-NOCAS reaction in which a catalytic amount of nucleophilic species is employed to promote the process.

Activation of essentially unreactive chemical bonds such as aromatic C–CN bonds¹ has been actively studied in recent years but it remains a challenging task.^{2–4} Reactions for this purpose often require severe conditions and noble metal catalysts. As a result, the development of C–CN bond cleavage reactions that proceed under mild and noble metal-free conditions is an important goal from the viewpoint of synthetic utility.

Photochemical reactions serve as promising methods to cleave inert bonds. Several years ago, Arnold and his co-workers described photo-NOCAS (nucleophile–olefin combination, aromatic substitution) reactions of *p*-dicyanobenzene (*p*-DCB, terephthalonitrile) and 2,5-dimethyl-2,4-hexadiene (**1**) in a methanolic solution, which proceed via photochemically induced *ipso*-substitution of aromatic cyano groups (eq 1).^{5,6}



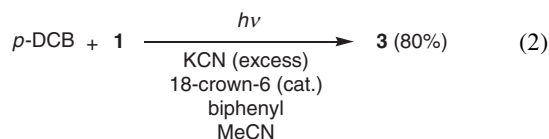
These workers noticed that not only the typical photo-NOCAS product **2** (82%) is produced in this reaction, but also the cyanide containing adduct **3** (2%) is formed. Further investigations demonstrated that when an excess of potassium cyanide is included in the reaction mixture **3** is generated in a high yield (80%) (eq 2). This finding suggests that photo-NOCAS reaction with free cyanide ion as a nucleophile is the true source of **3**. It has been proposed that cyanide ion, involved in the formation of **3** in methanol (eq 1), comes from *ipso*-substitution on the radical anion of *p*-dicyanobenzene (*p*-DCB^{•−}). Based on this suggestion, we expected that incorporation of a catalytic amount

Table 1. Photochemical C–CN insertion reaction^a

Entry	Cyanide	Additive	Solvent	Yields ^b /%			
				3	4	5	6
1	KCN	—	MeCN/ H ₂ O	19	28	3	8
2 ^c	KCN	—	MeCN	0	0	0	0
3	KCN	18-crown-6 ^d	MeCN	36	0	2	0
4	<i>n</i> -Bu ₄ N ⁺ CN [−]	—	MeCN	60	0	0	3
5	<i>n</i> -Bu ₄ N ⁺ CN [−]	MS4A ^e	MeCN	56	0	0	2

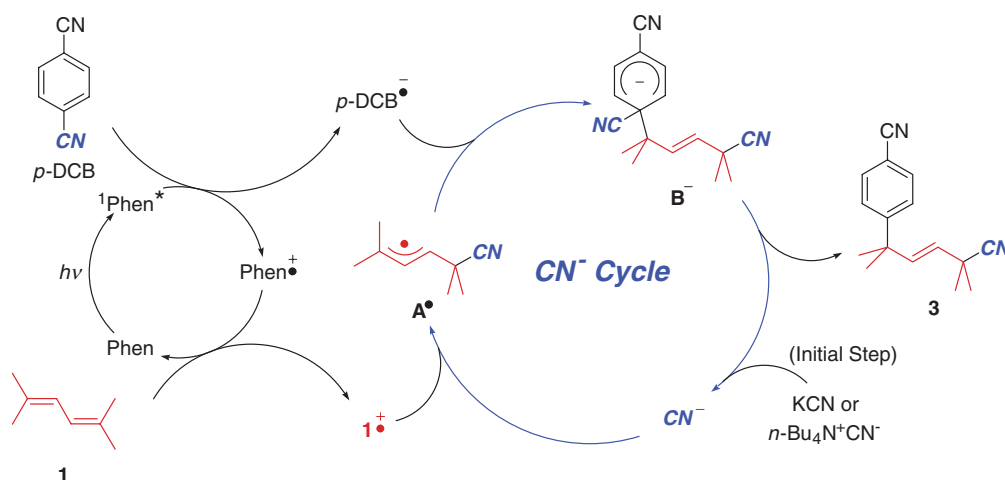
^aConditions: 300-W high-pressure mercury lamp, Pyrex filter, **1** (75 μmol), *p*-DCB (25 μmol), Phen (25 μmol), cyanide (5 μmol), in MeCN (4 mL)–H₂O (1 mL) or in MeCN (5 mL), under Ar, rt, 20 h. ^bDetermined by ¹H NMR analysis based on the amount of *p*-DCB (for **3** and **4**) and **1** (for **5** and **6**) used. ^cPhotoreaction was carried out in a suspension. ^d5 μmol. ^e100 mg.

of cyanide ion in the photo-NOCAS reaction mixture would enable the operation of a chain mechanism for formal alkadiene insertion into aromatic C–CN bonds.⁷



In exploratory studies aimed at testing this proposal, an acetonitrile–water (4:1) solution containing **1**, *p*-DCB, phenanthrene (Phen),^{8,9} and a catalytic amount (20 mol %) of potassium cyanide was photoirradiated for 20 h (Table 1, Entry 1). This process afforded a complex product mixture that contained the desired adduct **3** (19%) along with undesired products **4–6** (28, 3, and 8%, respectively).^{10,11} Recognizing that products **4** and **6** arise by the addition of water (or formally hydroxide ion) to the cation radical of **1**, we assumed that photoreactions in solutions that did not contain water would increase the selectivity for production of **3**. However, potassium cyanide has a very low solubility in anhydrous acetonitrile. As a result, photoirradiation of a suspension of this cyanide salt in anhydrous acetonitrile did not lead to formation of any recognizable products, and only degradation of *p*-DCB was observed (Entry 2).

An optimal procedure for highly selective formation of the formal insertion product **3** was uncovered. At first, 18-crown-6 (equimolar to potassium cyanide) was employed as an additive



Scheme 1. Plausible mechanism for the formation of **3**.

to improve the solubility of potassium cyanide in dry acetonitrile (Entry 3). Despite the high selectivity observed for the photo-reaction in the presence of the crown ether, the process might not be synthetically suitable because of the low yield (36%) of **3** formed and difficulties associated with separation of the crown ether. Use of an acetonitrile-soluble cyanide source, tetra-*n*-butylammonium cyanide, resolved this problem and led to an optimal method for carrying out the photo-NOCAS reaction. Thus, photoirradiation of a mixture of **1** and *p*-DCB in anhydrous acetonitrile, containing tetra-*n*-butylammonium cyanide, led to formation of **3** in a 60% yield (Entry 4).¹³ When a powder form of molecular sieve (MS) 4A was included to remove trace amounts of water, no significant change in the product distribution was observed (Entry 5).

A typical photo-NOCAS mechanistic pathway is responsible for the formation of **3**.^{5,6,10,12} The route is initiated by single electron transfer (SET) from the singlet excited state of Pheno (¹Pheno*) to *p*-DCB ($\Delta G_{\text{et}} = -0.3$ eV), which is then followed by SET from **1** to Pheno^{•+} (Scheme 1) to give **1**^{•+} ($\Delta G_{\text{et}} = -0.4$ eV).⁸ Addition of cyanide ion to **1**^{•+} affords the allylic radical intermediate **A**[•], which couples with *p*-DCB^{•-} to form **B**^{•-}. Regeneration of the aromatic ring affords the three-component adduct **3** and regenerates cyanide ion. The formation of the cyanide containing dimer **5** is a result of dimerization of **A**[•].¹¹ Alcohols **4** and **6** are formed by similar reaction mechanisms to those of **3** and **5**, respectively, with water or hydroxide ion serving as the nucleophile.

The process described above corresponds to a formal alkadiene insertion reaction into an aromatic C–CN bond. Importantly, it takes place under mild (ambient temperature and without base) and noble metal-free conditions. It also represents the first example of the use of a catalytic amount of nucleophilic species to promote photo-NOCAS reactions. We believe that this type of catalytic photoreaction can also be applied to the other photo-NOCAS reactions.⁵

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