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Direct Meta-Selective Alkylation of Perylene Bisimides via Palladium-Catalyzed C−H Functionalization

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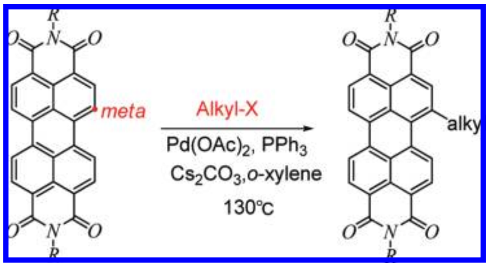
ABSTRACT



A facile palladium-catalyzed procedure for meta-selective alkylation of perylene bisimides with alkyl halides has been achieved by direct C−H functionalization.

Selective direct C−H functionalization/C−C bond formation catalyzed by transition metal has been extensively studied recently.[1] This synthetic strategy provides a viable alternative to a traditional cross-coupling reaction. Approaches for direct functionalization of an unreactive C−H bond represent a powerful and relatively straightforward protocol to avoid the preactivation of the substrates and make the synthetic routine shorter and more efficient in organic synthesis. To date, great elegant progress has been achieved for electron-rich arenes and heterocycles with a directing group which can be ortho-functionalized by aryl or alkyl halides, boronates, and olefins under palladium,[2] ruthenium,[3] or rhodium[4] catalysis. However, direct meta-selective C−H bond transformation of unreactive arenes is still a challenge. Consequently, developing a catalytic procedure for the functionalization of a highly electron-deficient aromatic C−H bond to selectively generate the meta-substituted products is very significant.[5]

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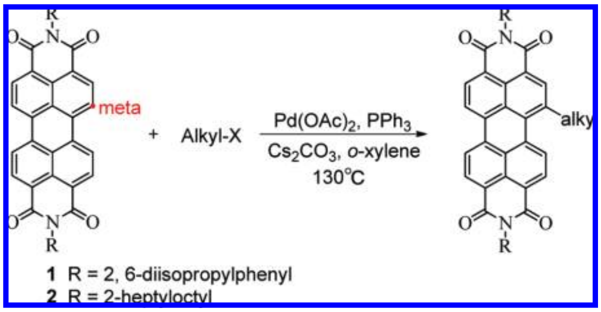
Due to the remarkable electro-optical properties,[6] perylene-3,4:9,10-tetracarboxylic acid bisimides (PBIs) have attracted exclusive attention in a wide range of applications including organic field effect transistors,[7] light-emitting diodes,[8] solar cells,[9] photovoltaic devices,[10] etc. Photophysical and redox properties of PBIs can be conveniently modified through substitution at the bay (meta) position.[11] Substitutions at the bay positions and expansion of the PBI core are usually carried out starting from the halogenated derivatives, such as chlorinated or brominated PBIs.[12] However, the preparation of these halogenated PBIs needs poisonous chlorine, bromine, and iodine with harsh conditions (concentrated H_2SO_4 or oleum upon heating). Thus, an economical and ecological method to construct the C−C bond would be the direct functionalization of C−H bonds of PBIs. Very recently, Shinokubo reported success with Ru-catalyzed ortho-alkylation of PBIs directed by the carbonyl carbons;[3d] however, direct alkylation of unactivated arene with alkyl halide which selectively occurs at the meta position has not been achieved to date.

Herein, we present the first example of a palladium-catalyzed meta-selective alkylation process of highly electron-deficient PBIs with cheap and readily available alkyl halides. These facile reactions offer good functional group compatibility.

Various ligands, the reaction temperature, and the amount of catalyst were examined to optimize the reaction conditions. The best results were obtained under the system of $Pd(OAc)_2$ as the catalyst, PPh_3 as the ligand, and Cs_2CO_3 as the base in *o*-xylene (Table 1). This particular reaction takes place in the presence of an excess of cesium carbonate, whereas stronger base *t*-BuOK leads to unchanged starting materials. PBI derivatives with two alkyl groups were also detected by MALDI-TOF; however, dialkylated PBIs have possible isomers, and the separation is very difficult.

Table 1. Pd-Catalyzed Alkylation of PBIs with Alkyl Halides



entry	halide (Alkyl-X)	yield (%)[a,b]	product
1	n-$C_6H_{13}Br$	41(62)	**1a**
2	n-$C_8H_{17}Br$	45(63)	**1b**
3	n-$C_{12}H_{25}Br$	51(72)	**1c**
4	$CF_3CF_2C_2H_4I$	22(50)	**1d**
5	n-$C_4H_9(OCH_2CH_2)_3Br$	28(48)	**1e**
6	n-$C_6H_{13}I$	55(68)	**1a**
7	n-$C_6H_{13}Br$	40(64)	**2a**

[a] Yields are isolated yields. [b] Yields are based on recovery of starting materials.

Under the optimized catalytic system above, the substrate scope was also explored (Table 1). A variety of alkyl bromides with different lengths of alkyl chains can be direct alkylated regioselectively (Table 1, entries 1−3), while an alkyl iodide also leads to a good yield (Table 1, entry 6), which is slightly higher than those of alkyl bromides. The corresponding alkyl chloride turned out to be a great challenge due to its low reactivity. Notably, our catalytic system was not limited to the use of simple alkyl halides but also enabled the transformation of the alkylhalide bearing fluorocarbon chain and oligo(ethylene glycol) chain (Table 1, entries 4 and 5). Incorporation of the hydrophilic and hydrophobic chains into the PBI skeletons is known to have a strong influence not only on their self-assemble structures but also on their electro-optical properties.[13]

Surprisingly, this condition produces the meta products with exquisite selectivity as evidenced by COSY and HMBC experiments. The assignments of H_a, H_b, H_f, H_g, H_c, H_d, and H_e were determined with the aid of COSY data (see the Supporting Information). The HMBC experiment revealed the correlation between H_a (H_f), H_g, H_f (H_a), and H_b and four corresponding carbonyl carbons C_h, C_i, C_j, and C_k (δ 162, δ 163) (Figure 1), which have proved the alkylation occurs at the meta position.

Recent studies have found that direct arylation of electron-deficient arenes at the meta position could be attributed to higher reactivity of the meta C−H bond.[5b,14]

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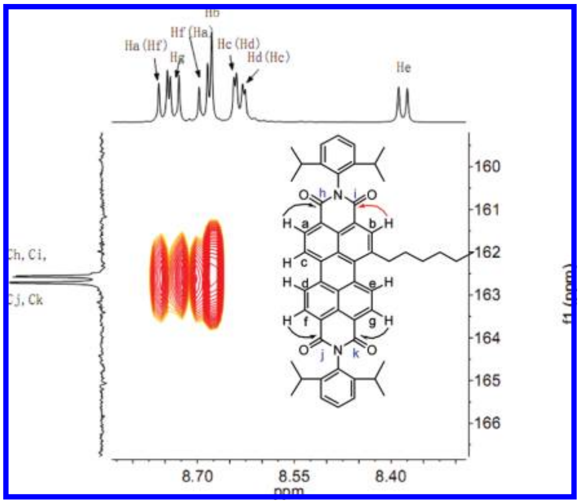
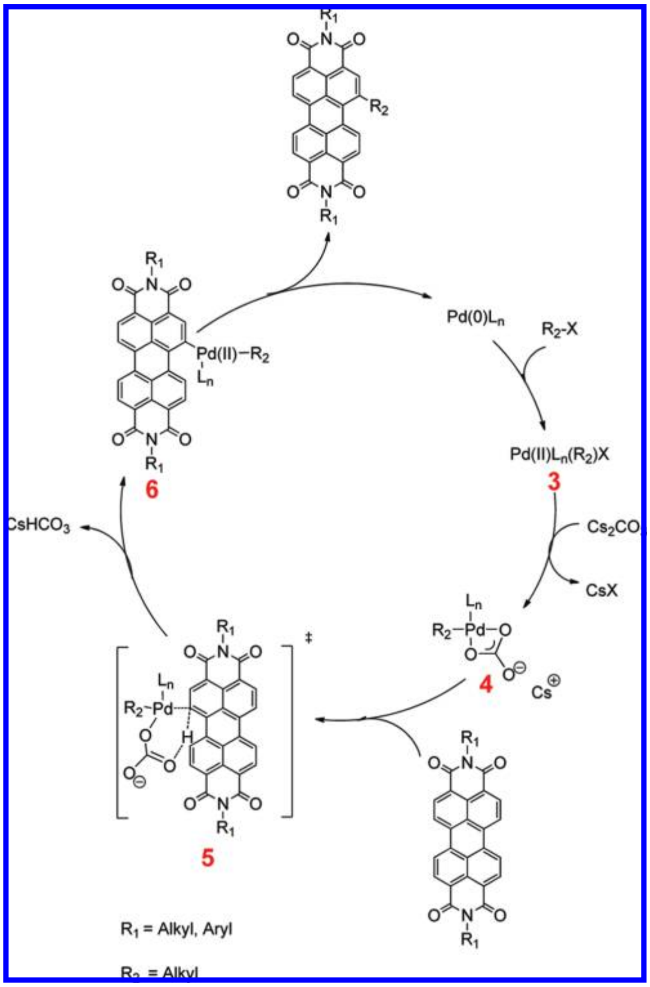


Figure 1. HMBC correlations of **1a**.

Scheme 1



Thus, we propose that the diret meta-selective C−H alkylation of highly electron-deficient PBIs is via a proton abstraction mechanism.

The catalytic cycle was hypothesized as shown in Scheme 1. In this concerted metalation and proton abstraction catalytic cycle,[15] the alkylpalladium(II) intermediate **3** is formed through an oxidative addition of a Pd(0) complex with an alkyl halide. However, intermediate **3** may easily undergo β-hydrogen elimination to form alkene. Therefore, excessive alkyl halides are needed to make this transformation proceed smoothly. As we have mentioned, the excess of carbonate is critical for this transformation. Carbonate ligand exchanges with the X ligand of **3** to form intermediate **4**, which attacks the meta position of the PBIs to give the key transition state **5**. Deprotonation of the latter forms alkyl-palladium(II) intermediate **6**, which upon reductive elimination gives product and regenerates the palladium(0) catalyst.

The UV−vis absorption (Figure 2) and fluorescence spectra (see the Supporting Information) have not been changed significantly compared with compound **1**.[16] The absorption spectra show well-defined vibronic fine structure of the S_0-S_1 transition (Figure 2) and display two major bands near 490 and 524 nm arising from the PBI core. However, the molar extinction coefficients of the lowest-energy absorption band are somewhat reduced with the introduction of the alkyl chains, especially electron-withdrawing fluorocarbon chains (Table 2).

Cyclic voltammograms (see the Supporting Information) of these compounds exhibit one reversible reduction wave and one quasireversible reduction wave, and the reduction potential of **1d** is less negative than the other PBIs, which can also be attributed to the electron affinity of fluorine atoms (Table 2).

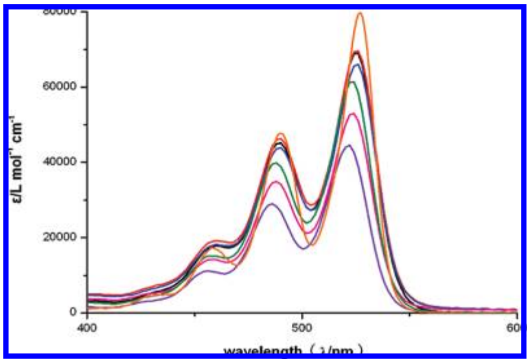


Figure 2. UV−vis absorption spectra of PBI **1** (orange line), **1a** (black line), **1b** (red line), **1c** (blue line), **1d** (violet line), **1e** (pink line), and **2a** (olive line) in CH_2Cl_2 (1×10^{-5} M) at room temperature.

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Table 2. Electro-Optical Properties of Alkylated PBIs

PBI	ε [m^{-1}, cm^{-1}]	λ_{max} [nm]	λ_{em} [nm]	E^a_{1r}	E^a_{2r}
1a	6.91×10^4	526	542	−0.65	−0.89
1b	7.06×10^4	526	542	−0.65	−0.85
1c	6.60×10^4	526	542	−0.65	−0.87
1d	4.05×10^4	522	539	−0.60	−0.85
1e	5.30×10^4	524	539	−0.64	−0.86
2a	6.35×10^4	524	540	−0.73	−0.94

[a] Half wave redox potential (in V vs Ag/AgCl) measured in CH_2Cl_2 with a scan rate of 100 mV/s.

In conclusion, a palladium-catalyzed meta-selective alkylation process of highly electron-deficient PBIs with cheap and readily available alkyl halides has been achieved. This synthetic route can be applied to a wide range of substrates, especially alkanes with fluorocarbon chains and hydrophilic oligo(ethylene glycol) chains. The generality and unique properties of perylene bisimides may expand the scope of this reaction to more academic and industrial applications.

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Supporting Information Available: Experimental procedure and characterization of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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