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PAPER

Palladium/silver reagent-promoted aryl phosphorylation: flexible synthesis of substituted-3-benzylidene-2-(2-(diphenylphosphoryl)-aryl)-isoindolin-1-one†

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A novel Pd(OAc)$_2$/Ag$_2$CO$_3$-catalyzed coupling reaction was investigated. Substituted 3-benzylidene-2-arylisoindolin-1-ones were reacted with diphenylphosphine oxide to afford 3-arylidene-2-(2-(diphenylphosphoryl)aryl)isoindolin-1-ones. The reaction proceeded at 25 °C in an air atmosphere in the absence of base and ligands. Our results indicate that the diphenylphosphine oxide free radical tends to attack the aryl rather than the double bond in this reaction.

Introduction

Nitrogen-containing heterocycles are a series of notable compounds known for their bioactivity in nature.[1] In particular, isoindolin-1-ones such as I and II are the core structural motifs of several compounds of medicinal value (Fig. 1). 3-Methyleneisoindolin-1-ones are known for their use as anaesthetic and sedative drugs.[2] As these compounds have a double bond and phenyl cycle we have tried to find a catalytic system for direct phosphorylation of substituted 3-benzylidene-2-arylisoindolin-1-one.

Diphenylphosphine oxide has become a research focus in the field of organic synthesis due to its unique biological

activities.[3] In 1982, Hirao and co-workers reported the first palladium-catalyzed phosphorylation of aryl iodides.[4] Since then, a series of formations of Csp^2–P bonds by cross-coupling has been published in the last thirty years. The coupling partners, included aryl triflates, tosylate, diaryliodonium salts, diazonium salts, boronic acids, triarylbismuths, phenylhydrazine and so on.[5] Moreover, direct radical phosphorylation of benzene derivatives[6] and heterocycle[7] with diethyl phosphate has been successfully developed by using Mn(OAc)$_3$ as an oxidant (Scheme 1a). There were also studies of the manganese-catalyzed reactions of H-phosphinates.[8] Recently, palladium-catalyzed direct phosphorylation reaction of arene and heteroarenes has been established (Scheme 1b).[9,10] On the other hand, Ag system has been used for the synthesis of direct phosphorylation reaction (Scheme 1c).[11] Visible light promoted C–P
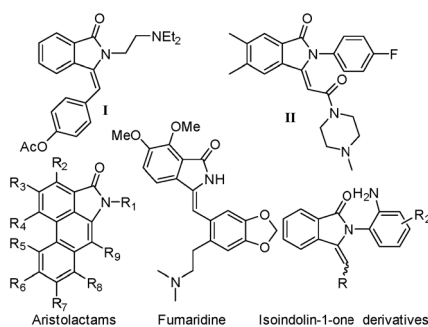

Fig. 1 Bioactive and drug compounds containing isoindolin-1-one motifs.

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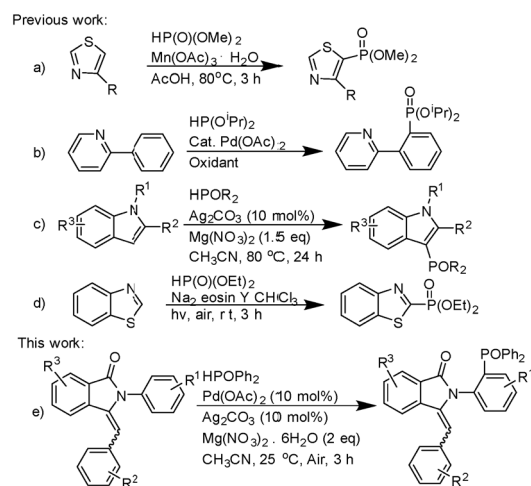
Scheme 1

functionalization has been rapidly developed (Scheme 1d).[12] As part of our research on the transition metal-catalyzed C–P bond formation, this communication reports the first example of a coupling reaction of 3-benzylidene-2-arylisoindolin-1-one with diphenylphosphine oxide catalyzed by Pd(OAc)$_2$/Ag$_2$CO$_3$ (Scheme 1e).

Results and discussion

When the model reaction of 3-benzylidene-2-phenylisoindolin-1-one (**1a**) with diphenylphosphine oxide (**2**) was performed in CH$_3$CN in the presence of oxidants such as TBHP, DTBP, Mn(OAc)$_3$ and AgNO$_3$, no desired products were obtained (Table 1, entries 1, 2, 3 and 5). After the addition of 10 mol% Ag$_2$CO$_3$ and Mg(NO$_3$)$_2$·6H$_2$O, the reaction proceeded smoothly to afford the desired product, 3-benzylidene-2-(2-(diphenylphosphoryl)phenyl)isoindolin-1-one (**3a**) in 60% yield (Table 1, entry 4).

Further investigations of palladium catalysts, the yield of **3a** was improved to 78% when we used Pd(OAc)$_2$ as the catalyst

(Table 1, entries 7). On the other hand, when we use Ag(OAc) in place of Ag$_2$CO$_3$, the reaction afforded the desired product in a lower yield (Table 1, entry 9). By screening polar solvents such as DMF, THF, i-PrOH, and a representative nonpolar solvent, toluene (Table 1, entries 10–13), we found that CH$_3$CN works best for the reaction. Apart from the above-mentioned factors, the effects of catalyst loading, reaction temperature, time and molecular sieves were also investigated, and the optimal reaction conditions were determined to be room temperature reaction for 3 h in air atmosphere, with the addition of 10 mol% Pd(OAc)$_2$ and 10 mol% Ag$_2$CO$_3$ as catalyst, Mg(NO$_3$)$_2$·6H$_2$O as promoter and CH$_3$CN as solvent (Table 1, entries 14–23).
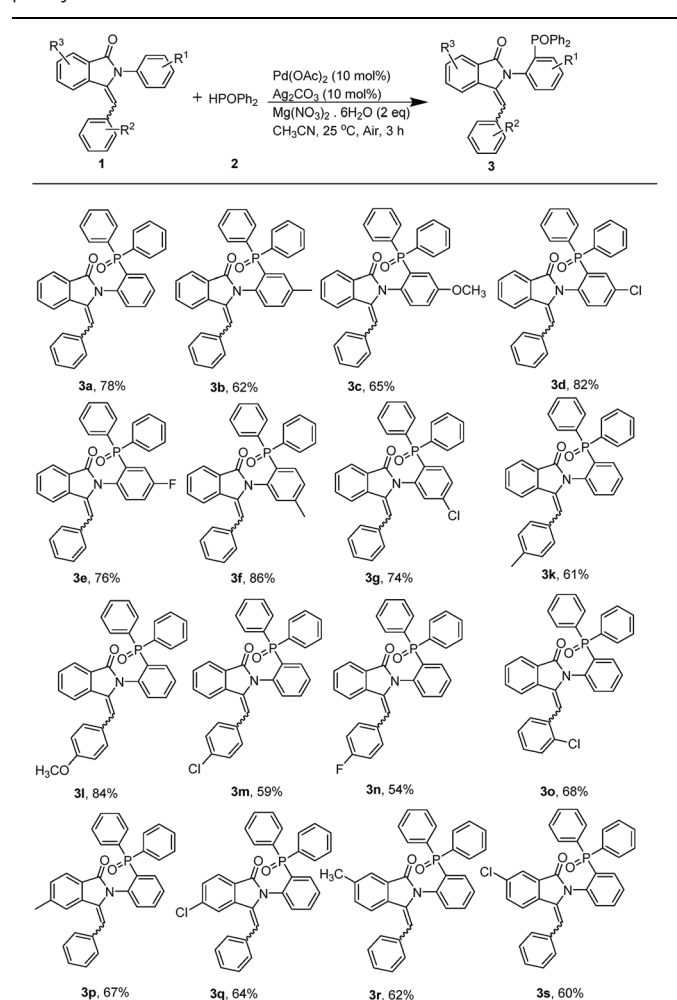
With the promising results obtained in the model reaction, we subsequently examined the substrate scope of 3-benzylidene-2-arylisoindolin-1-one under the optimized reaction conditions (10 mol% Pd(OAc)$_2$ and 10 mol% Ag$_2$CO$_3$ as catalyst, and Mg(NO$_3$)$_2$·6H$_2$O as promoter in CH$_3$CN at 25 °C, for 3 h in air atmosphere). As shown in Table 2, electron-

Table 1 Optimization of the reaction conditions[a]

Entry	Catalyst (%)	Oxidant (%)	Temperature	Solvent	Yeild[b]
1		TBHP(10)	25 °C	CH$_3$CN	N.D
2		DTBP(10)	25 °C	CH$_3$CN	N.D
3		Mn(OAc)$_3$	25 °C	CH$_3$CN	N.D
4		Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	60%
5		AgNO$_3$(10)	25 °C	CH$_3$CN	N.D
6	Pd(PPh$_3$)$_4$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	38%
7	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	**78%**
8	PdCl$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	72%
9	Pd(OAc)$_2$(10)	Ag(OAc)10	25 °C	CH$_3$CN	48%
10	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	THF	32%
11	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	DMF	36%
12	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	i-PrOH	40%
13	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	Toluene	30%
14	Pd(OAc)$_2$(5)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	48%
15	Pd(OAc)$_2$(20)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	65%
16[c]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	20%
17	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	0 °C	CH$_3$CN	10%
18	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	40 °C	CH$_3$CN	72%
19	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	60 °C	CH$_3$CN	20%
20[d]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	30%
21[e]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	58%
22[f]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	76%
23[g]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	35%
23[h]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	66%
23[i]	Pd(OAc)$_2$(10)	Ag$_2$CO$_3$(10)	25 °C	CH$_3$CN	75%

[a] Reaction condition: **1a** (0.2 mmol), HPOPh$_2$ (0.4 mmol), Pd(OAc)$_2$, (0.02 mmol), Ag$_2$CO$_3$ (0.02 mmol), Mg(NO$_3$)$_2$·6H$_2$O (0.4 mmol), solvent (2 ml), at 25 °C in air atmosphere, 3 h. [b] Yields are given for isolated products. [c] Without Mg(NO$_3$)$_2$·6H$_2$O. [d] HPOPh$_2$ (0.2 mmol) was added. [e] HPOPh$_2$ (0.6 mmol) was added. [f] Molecular sieves (0.1 g) was added. [g] 1 h. [h] 2 h. [i] 4 h.

**Table 2** Scope studies of 3-benzylidene-2-(2-(diphenyl-phosphoryl) phenyl)isoindolin-1-one[a]

3a, 78%   3b, 62%   3c, 65%   3d, 82%

3e, 76%   3f, 86%   3g, 74%   3k, 61%

3l, 84%   3m, 59%   3n, 54%   3o, 68%

3p, 67%   3q, 64%   3r, 62%   3s, 60%

[a] Reaction condition: **1** (0.2 mmol), HPOPh$_2$ (0.4 mmol), Pd(OAc)$_2$, (0.02 mmol), Ag$_2$CO$_3$ (0.02 mmol), Mg(NO$_3$)$_2$·6H$_2$O (0.4 mmol), CH$_3$CN (2 ml), at 25 °C in air atmosphere, 3 h. Yield of isolated products are given.

withdrawing substituent such as F and Cl groups on the *para*-position of arylamine ring of substituted 3-benzylidene-2-arylisoindolin-1-one (**1**) facilitated the reaction to afford the arylphosphonates (**3**) in good yields (Table 2, **3d** and **3e**). On the contrary, election-donating groups such as alkyl and methoxy were unfavorable for the reaction and led to lower yields (Table 2, **3b** and **3c**). Substituted groups such as CH_3 and Cl on the *meta*-position of arylamine ring are both given good yields (Table 2, **3f** and **3g**). We also investigated the substituent R^2 on the benzylidene and the substituent R^3 on the isoindolin-1-one, the results indicate that the reaction affords the arylphospho-nates (**3**) in moderate to good yields (Table 2, **3k**, **3l**, **3m**, **3n**, **3o**, **3p**, **3q**, **3r** and **3s**). In order to understand the reaction mecha-nism, following control experiments were carried out. We repeated the reaction in the presence of radical quencher 2,2,6,6-tetramethylpiperidin-1-oxyl (TEMPO) and none of **3a** was obtained (Scheme 2a). The result suggested that the diphenyl-phosphine oxide free radical was probably generated during the reaction. Furthermore, neither aliphatic amine nor benzyl-amine substrate produced the corresponding products (Scheme 2b and c). These results indicated that the reaction is only suitable for arylamine substrates which have enough electron cloud density.

As the phosphorylation always took place on the *ortho*-position of aniline in the above experiments, we wondered
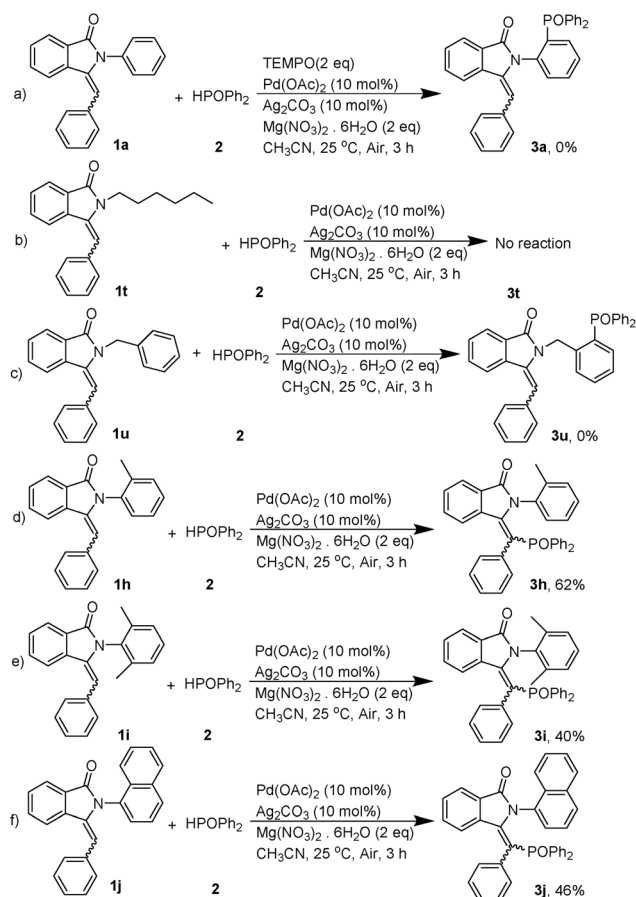
Scheme 2 Control experiments.
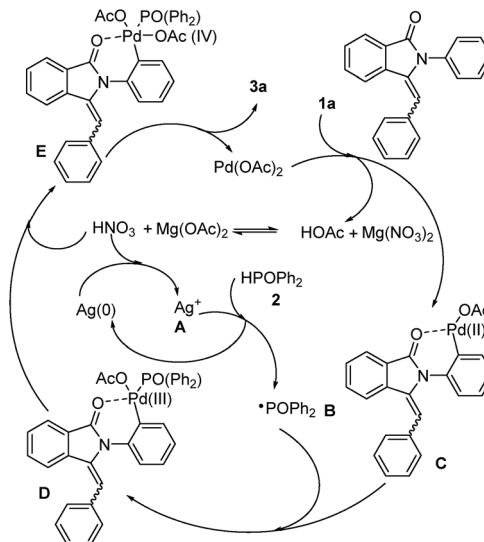
Scheme 3 Proposed reaction mechanism.

whether the reaction would proceed if the aniline had substit-uent groups at the *ortho*-position. Hence, we did further reac-tions (Scheme 2d–f). Surprisingly, the diphenylphosphine oxide free radical will attack the double bond instead of aniline with a moderate yield. These results further indicated that this reaction has a high regioselectivity that the diphenylphosphine oxide free radical would prioritize its attack on the *ortho*-posi-tion of aniline rather than the *para*-position of aniline or the double bond. On the basis of the mechanistic studies and experimental results, a plausible mechanism is proposed in Scheme 3.

Initially, $Pd(OAc)_2$ reacted with the substrate (**1a**) to form a six-membered palladacycle (**C**) in presence of $Mg(NO_3)_2$, and generated HNO_3 through C–H activation. The diphenylphos-phine oxide (**2**) was excited by Ag(I) (**A**) to generate the key intermediate P-centered radical (**B**), which then underwent addition with palladacycle (**C**) to form Pd^{III} intermediate **D**.[13] Thereafter, the radical intermediate **D** was oxidized by HNO_3 to produce the Pd^{IV} intermediate **E**. **E** underwent reductive elimi-nation to afford the product (**3a**) together with the regeneration of $Pd(OAc)_2$ which could complete the palladium catalytic cycle. Finally, Ag (0) was also oxidized to Ag(I) by HNO_3 to complete the silver catalytic cycle.

Conclusions

In summary, we have developed a novel catalytic system for direct phosphorylation of substituted 3-benzylidene-2-arylisoindolin-1-one *via* a radical pathway. The reaction has a high regioselectivity that diphenylphosphine oxide free radical is prone to attacking aryl rather than a double bond. The method has a broad scope and offers a good yield. The corre-sponding products are potentially useful in drug discovery.

Conflicts of interest

There are no conflicts to declare.

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