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Synthesis of 2-substituted benzo[*b*]thiophene via a Pd-catalyzed coupling of 2-iodothiophenol with phenylacetylene†

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A Pd(II)-catalyzed Sonogashira type cross-coupling reaction between 2-iodothiophenol and phenylacetylene has been developed. A series of 2-substituted benzo[*b*]thiophenes were obtained in moderate to good yield (up to 87%). The application of this method was demonstrated by the synthesis of 2-(4-(*tert*-butyl)phenyl)benzo[*b*]thiophene 1,1-dioxide and (4-methoxyphenyl)(2-(4-methoxyphenyl)benzo[*b*]thiophen-3-yl)methanone, which exhibit a fluorescence quantum yield of up to 1 and can be used as a cannabinoid receptor ligand, respectively.

Introduction

As a crucial class of heterocyclic compounds, 2-substituted benzo[*b*]thiophenes have broad biological properties¹ and diversified applications in the field of materials science.² They are usually considered as important structural motifs in pharmaceuticals and biologically active molecules. For example, as shown in Fig. 1, Bi-BTBT, raloxifene, and iPr-BTBT are examples of commercial drugs and organic semiconductors containing benzothiophene cores.³

The normal approaches to synthesize 2-substituted benzo[*b*]thiophenes are normally focused on a coupling cyclization

reaction of *o*-bromoalkynylbenzenes with various thiol surrogates upon lithium halogen exchange at -78°C (Scheme 1a)⁴ or the annulation of alkynylbenzenes (Scheme 1b).⁵ While in the process of reporting this study, a similar study was reported by Fu and co-workers using the electrophilic cyclization of *o*-alkynyl thioanisole (Scheme 1c).⁶ However, the major obstacles of these methods are a result of the harsh reaction conditions or the limitation of the starting materials used.

On the other hand, the Sonogashira cross-coupling reaction⁷ between aryl or alkenyl halides with terminal alkynes in the presence of a transition-metal catalyst has become one of the most powerful methods to prepare alkyl-aryl and diaryl-substituted acetylenes.⁸ In a continuation of our study on catalytic Sonogashira cross-coupling reaction and synthesis of sulfur-containing heterocyclic compounds,⁹ herein we report

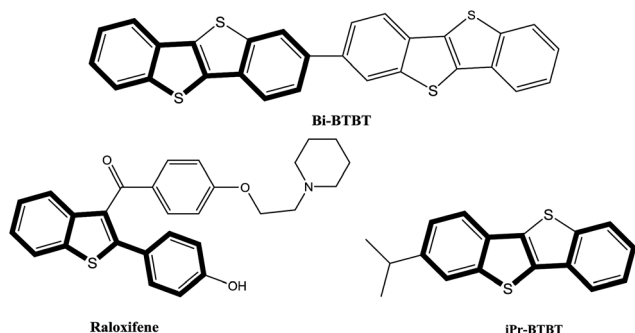
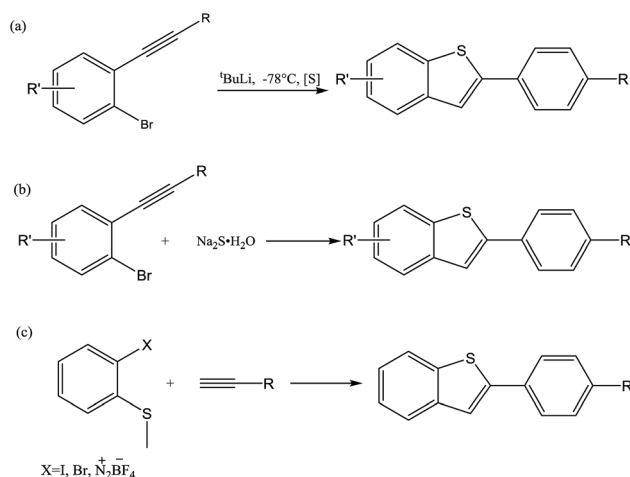


Fig. 1 Selected pharmaceutical and biologically active 2-substituted benzo[*b*]thiophenes.



Scheme 1 Selected examples of the commonly used synthetic methods to prepare 2-substituted benzo[*b*]thiophenes.

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the palladium-catalyzed synthesis of 2-substituted benzo[*b*]thiophenes using 2-halothiophenols and phenylacetylenes as starting materials.

Results and discussion

Our investigation started with the model substrates 2-iodothiophenol **1a** and phenylacetylene **2a**. As shown in Table 1, a variety of transition metal salts were tested and palladium acetate exhibited the best catalytic ability with a yield of 34% (Entries 1–8). Moreover, other metals including nickel, cobalt, and iron salts gave much less yields of 4%, 8%, and 5%, respectively (Entries 3, 4, and 5). In the case of copper salt, the coupling product between the alkyne was found to be the major product (Entries 1 and 2).¹⁰ The blank experiment further confirmed that no reaction occurred in the absence of a catalyst

and ligand (Entry 9). Furthermore, silver salts were found to be beneficial to the reaction. In addition, AgTFA was shown to be the best one with a yield of 71% (Entries 10–12). Moreover, the ligand was also proved to promote the catalysis by up to 81% yield in the case of TMEDA (Entries 13–16). Lastly, screening the reaction temperature and catalyst loading indicated that 110 °C and 15 mol% catalyst were optimal for the reaction with yields up to 87% (Entries 17–23). Hence, it was concluded that the best conditions were 15 mol% Pd(OAc)₂, 20 mol% TMEDA, and 1.1 equiv. AgTFA in DMF at 110 °C for 24 h.

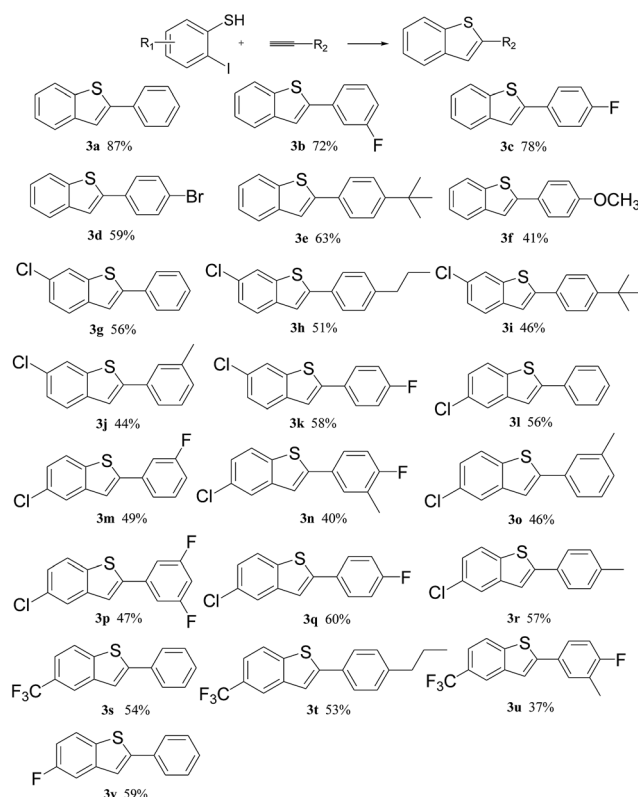
With the optimal reaction conditions in hand, we then explored the scope of 2-iodothiophenols and alkynes. As shown in Scheme 2, different alkynes with either electron-withdrawing groups (–F, –Br) or electron-donating groups (–*t*Bu, –OCH₃) can generate the desired products in yields from 41 to 78% under the standard conditions (**3b–3e**). Moreover, 2-iodothiophenols with various functional groups (such as –F, –Cl, and –CF₃) can also be successfully applied in this method and novel compounds such as **3g**, **3h**, and **3i** were also obtained in around 50% yield, which have great potential, especially in pharmaceutical compounds and materials synthesis.

To further explore the potential application of this method, the reaction of **1a** and **2a** was scaled up to 10.0 mmol in a 50 mL one-necked flask and the same efficiency was maintained (Scheme 3). The desired product can be obtained in 75% yield, which confirms its suitability for large-scale reaction.

Table 1 Optimization of the reaction conditions^a

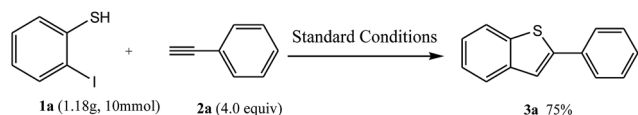
Entry	Catalyst	Ligand	Additive	<i>T</i> /°C	Yield ^b (%)
1	CuI	—	—	100	14
2	CuCl	—	—	100	Trace
3	NiCl ₂	—	—	100	4
4	CoCl ₂ ·6H ₂ O	—	—	100	8
5	FeSO ₄	—	—	100	5
6	Pd(PPh ₃)Cl ₂	—	—	100	28
7	Pd(PPh ₃) ₄	—	—	100	21
8	Pd(OAc) ₂	—	—	100	34
9	—	—	—	100	Trace
10	Pd(OAc) ₂	—	AgOAc	100	68
11	Pd(OAc) ₂	—	Ag ₂ CO ₃	100	66
12	Pd(OAc) ₂	—	AgTFA	100	71
13	Pd(OAc) ₂	PPh ₃	AgTFA	100	75
14	Pd(OAc) ₂	TMEDA	AgTFA	100	81
15	Pd(OAc) ₂	L-Proline	AgTFA	100	69
16	Pd(OAc) ₂	Pyridine	AgTFA	100	72
17	Pd(OAc) ₂	TMEDA	AgTFA	105	82
18	Pd(OAc) ₂	TMEDA	AgTFA	110	85
19	Pd(OAc) ₂	TMEDA	AgTFA	115	84
20	Pd(OAc) ₂	TMEDA	AgTFA	120	84
21 ^c	Pd(OAc) ₂	TMEDA	AgTFA	110	87
22 ^d	Pd(OAc) ₂	TMEDA	AgTFA	110	87
23 ^e	Pd(OAc) ₂	TMEDA	AgTFA	110	86

^a Reaction conditions: 2-iodothiophenol **1a** (0.5 mmol), phenylacetylene **2a** (4 equiv.), catalyst (10 mol%), ligand (20 mol%), and additive (1.1 equiv.) in DMF (2 mL) under N₂ for 24 h. ^b Isolated yields. ^c Pd(OAc)₂ (15 mol%). ^d Pd(OAc)₂ (20 mol%). ^e Pd(OAc)₂ (25 mol%).

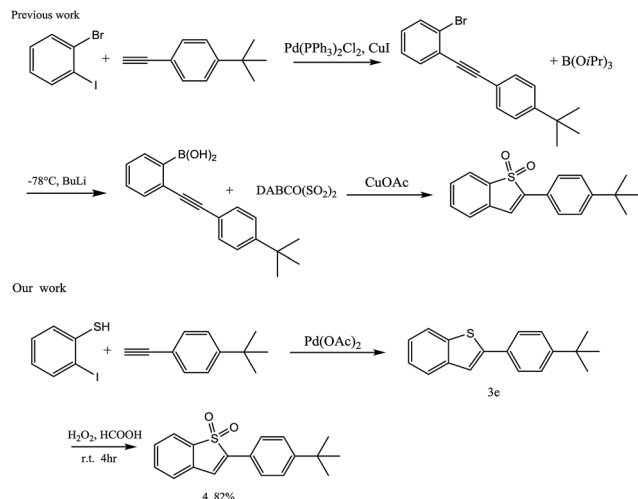


Scheme 2 The synthesis of different benzo[*b*]thiophenes.^{a,b} ^a Reaction conditions: 2-iodothiophenol (0.5 mmol), alkyne (4 equiv.), Pd(OAc)₂ (15 mol%), TMEDA (20 mol%), and AgTFA (1.1 equiv.) in DMF (2 mL) under N₂ at 110 °C for 24 h. ^b Isolated yield.





Scheme 3 The gram scale reaction performed under the standard conditions.



Scheme 4 A comparison of the synthesized compounds 4 and 5.

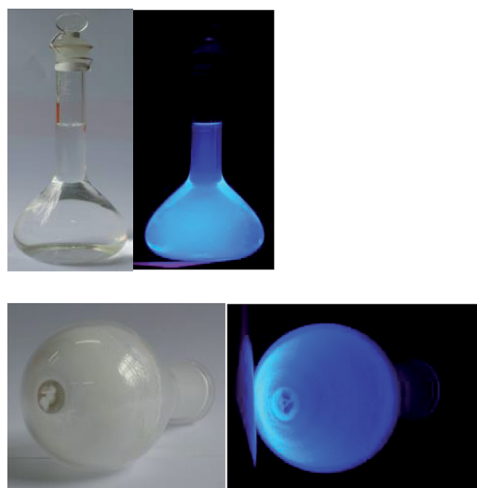


Fig. 2 Images of compound 4 in MeCN ($1.0 \times 10^{-5} \text{ mol L}^{-1}$) and the solid state under sunlight (left) and under 360 nm UV light (right).

Furthermore, 2-(4-(*tert*-butyl)phenyl)benzo[*b*]thiophene 1,1-dioxide 4 can be easily obtained after adding H_2O_2 into 3e at room temperature, which could shorten one step and uses milder reaction conditions when compared with those reported in the literature (Scheme 4).¹¹ Furthermore, Fig. 2 shows images of the compound 4 in MeCN and the solid state under sunlight (left) and under 360 nm UV light (right). Fig. 3 displays the absorption and emission spectra of compound 4 in MeCN ($1.0 \times 10^{-5} \text{ mol L}^{-1}$). Note that compound 4 in MeCN exhibited an

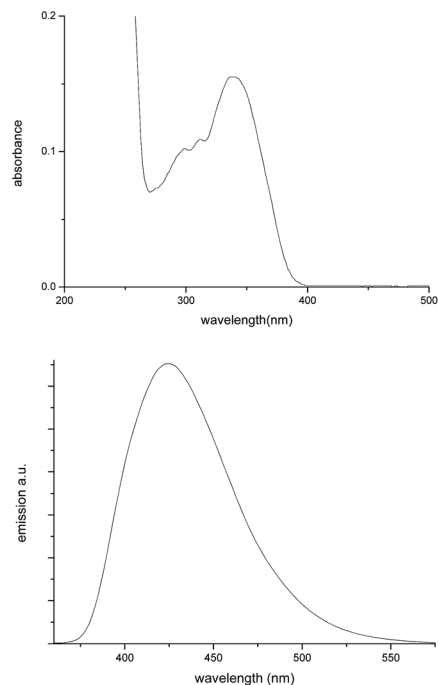
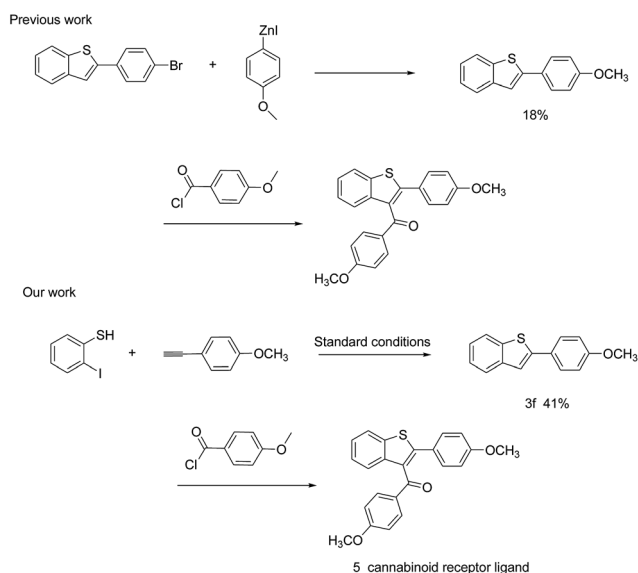
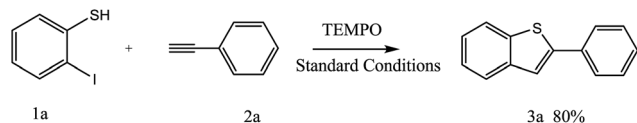


Fig. 3 The absorption and emission spectra of compound 4 in MeCN ($1.0 \times 10^{-5} \text{ mol L}^{-1}$).

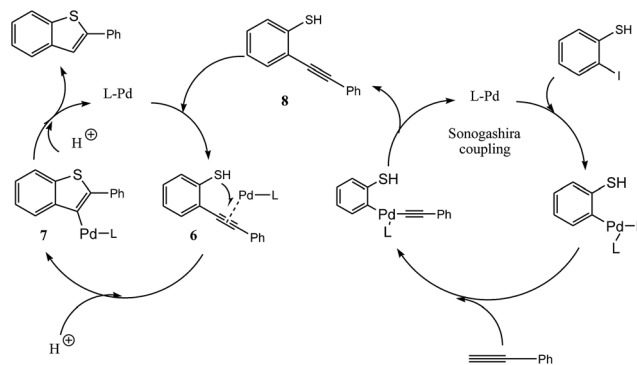
unexpectedly high fluorescence quantum yield of up to 1 that was measured using quinine sulfate as a standard (quinine in $5.0 \times 10^{-5} \text{ mol L}^{-1}$ sulfuric acid), which would shows broad prospects for use in organic light-emitting diodes (OLEDs).

Besides this, we also tried to synthesize the benzothiophene derivative (4-methoxyphenyl)(2-(4-methoxyphenyl)benzo[*b*]thiophen-3-yl)methanone 5 using product 3f as the starting material in a higher yield than that reported in the literature. Compound 5 has been reported as a new cannabinoid receptor ligand and an intermediate of thrombin inhibitor.¹²





Scheme 5 The radical/electron trapping experiment.



Scheme 6 The proposed reaction pathway.

To explore the reaction pathway, a radical trapping experiment was carried out by the addition of a typical radical scavenger TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl). Almost the same yield (80%) indicated that the reaction did not involve a radical intermediate (Scheme 5). Furthermore, the intermediate 2-(phenylethynyl)benzenethiol **8** was observed by GC/MS in the reaction between 2-iodothiophenol and phenylacetylene after 3 hours.

Based on the experimental and literature data, we proposed a reaction pathway for the palladium-catalyzed synthesis of 2-substituted benzo[*b*]thiophenes from 2-halophenols and alkynes, which consists of two steps: the Sonogashira coupling of 2-halothiophenol with the alkyne and the subsequent cyclization of 2-alkynylthiophenol (Scheme 6). First, the Pd-catalyzed Sonogashira coupling of 2-halothiophenol with the alkyne affords intermediate **8**. Then, coordination of Pd with intermediate **8** may provide complex **6**, whose subsequent addition to the C–C triple bond gave intermediate **7**. Protonation of intermediate **7** results in the formation of benzo[*b*]thiophene and the regenerated Pd-catalyst.

Conclusions

In summary, we developed an efficient catalytic system using 2-iodothiophenols as the starting material for the synthesis of a variety of 2-substituted benzo[*b*]thiophenes. This protocol involves the following advantages: easily available starting materials and simple operations with moderate to good yields, and will contribute a new optional route for the construction the benzo[*b*]thiophene ring. Moreover, the application of this method was considered as an example by the synthesis of 2-(4-(*tert*-butyl)phenyl)benzo[*b*]thiophene 1,1-dioxide and (4-methoxyphenyl)(2-(4-methoxyphenyl)benzo[*b*]thiophen-3-yl) methanone, which exhibit a fluorescence quantum yield up to 1 and use as a cannabinoid receptor ligand, respectively.

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