Short communication

A novel MCM-41-supported sulfur palladium(0) complex catalyst for Sonogashira coupling reaction

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Abstract

A novel MCM-41-supported sulfur palladium(0) complex was conveniently prepared from commercially available and cheap γ-mercaptopropyltriethoxysilane via immobilization on MCM-41, followed by reacting with palladium chloride and then the reduction with hydrazine hydrate. This complex exhibited excellent performance in Sonogashira coupling reaction.
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The palladium-catalyzed coupling reaction of aryl and vinyl halides with terminal alkynes (the Sonogashira reaction) represents one of the most versatile tools in modern synthetic chemistry and has great potential for industrial applications [1–4]. It is a homogeneous reaction, generally using soluble palladium complexes such as Pd(PPh$_3$)$_4$, Pd(PPh$_3$)$_2$Cl$_2$ and Pd(PhCN)$_2$Cl$_2$ as catalysts. The amount of palladium catalyst used is about 2 mol% of reactant; however, use of homogeneous palladium catalysts is still uneconomic for large-scale preparations in the laboratory and for industrial production. Polymer-supported transition metal complexes having high activity are currently attracting great interest because they can be easily recovered and reused [5–7]. Furthermore the intrinsic toxicity of most transition metals makes the complete removal of even traces thereof an imperative for providing substances qualified for biological testing. Despite the general use of the Sonogashira reaction in organic synthesis, polymer-supported palladium catalysts have not been widely used for this reaction yet [8–11]. Study of new types of polymer-supported palladium catalysts which might be suitable for the Sonogashira reaction has theoretical and practical significance. In the past, most of these studies have been related to polystyrene or silica-supported phosphine palladium catalysts. It is known that catalysts containing phosphine ligands are unstable [12–14]. Furthermore, the procedure for preparing the polymer-supported phosphine palladium complex is rather complicated since the synthesis of the phosphine ligands requires multi-step sequences. Therefore, the development of phosphine-free heterogeneous palladium catalysts having a high activity and good stability is a topic of enormous importance.

Recent developments on the mesoporous material MCM-41 provided a new possible candidate for a solid support for immobilization of homogeneous catalysts [15]. MCM-41 has a regular pore diameter of ca. 50 Å and a specific surface area >700 m^2 g^{-1} [16]. Its large pore size allows passage of large molecules such as organic reactants and metal complexes through the pores to reach to the surface of the channel [17–19]. To date, a few palladium complexes on functionalized MCM-41 support have been prepared and used in organic reactions [20–24]. However, to the best of our knowledge, there has been no general study of Sonogashira reaction catalyzed by a MCM-41-supported palladium complex catalyst described to date. In this study, we report the synthesis of a novel MCM-41-supported sulfur palladium(0) complex catalyst and its catalytic behavior in the Sonogashira coupling reaction of aryl iodides with terminal alkynes.

Our approach was guided by three imperatives: the polymeric ligand should be easily accessible (1), starting from readily available and cheap reagents (2). The polymeric pal-
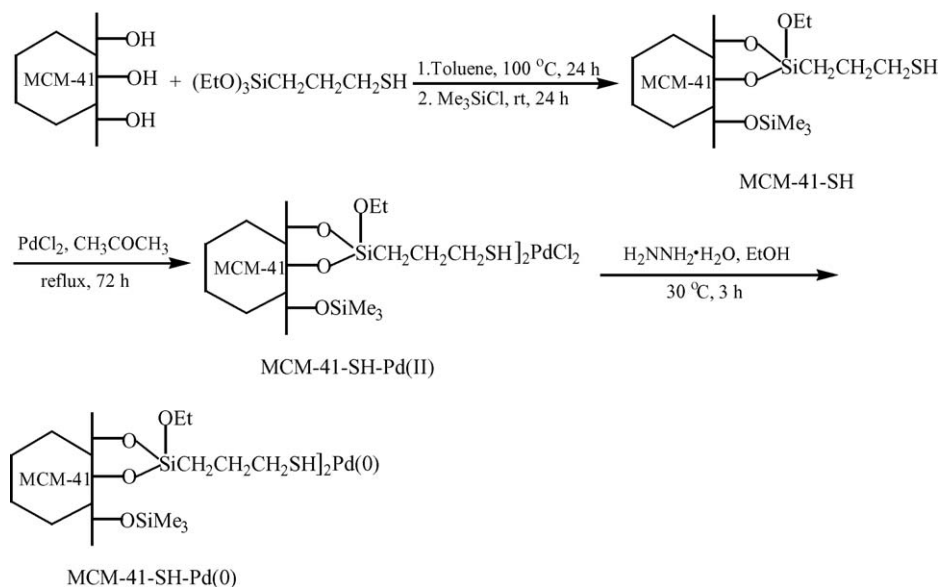
Scheme 1.

ladium catalyst should be air stable at room temperature, which should allow its storage in normal bottles with unlimited shelf life (3). The mesoporous material MCM-41 was easily prepared from tetramethoxysilane (TMOS) and cetyltrimethylammonium bromide (CTAB) according to literature procedure [25]. As shown in Scheme 1, The first MCM-41-supported sulfur palladium(0) complex [MCM-41-SH-Pd(0)] was conveniently synthesized from commercially available and cheap γ-mercaptopropyltriethoxysilane via immobilization on MCM-41, followed by reacting with palladium chloride in acetone, and then the reduction with hydrazine hydrate in ethanol. The XRD analysis of the MCM-41-SH-Pd(0) indicated that, in addition to an intense diffraction peak (1 0 0), two higher order peaks with lower intensities were also detected, and therefore the chemical bonding procedure did not diminish the structural ordering of the MCM-41. The nitrogen adsorption studies demonstrated that a significant decrease in pore size by virtue of silylation of the MCM-41 channels was observed. Additionally, upon modification the surface area and pore volume decreased obviously. These results are in good agreement with the fact that the surface modification indeed occurred inside the primary mesopores of the MCM-41.

Elemental analyses and X-ray photoelectron spectroscopy (XPS) were used to characterize the MCM-41-supported sulfur palladium(0) complex. The sulfur and palladium content of the MCM-41-SH-Pd(0) was determined to be 0.81 and 0.38 mmol/g, respectively, and the S:Pd mole ratio of this complex was 2.13. The XPS data for MCM-41-SH, MCM-41-SH-Pd(II), MCM-41-SH-Pd(0) and PdCl$_2$ are listed in Table 1. It can be seen that the binding energies of Si$_{2p}$ and O$_{1s}$ of MCM-41-SH-Pd(II) are similar to those of MCM-41-SH, and the binding energy of Cl$_{2p}$ of MCM-41-SH-Pd(II) is similar to that of PdCl$_2$. However, the difference of Pd$_{3d5/2}$ binding energies between MCM-41-SH-Pd(II) and PdCl$_2$ is 0.9 eV. The difference of S$_{2p}$ binding energies between MCM-41-SH-Pd(II) and MCM-41-SH is 0.5 eV. These results suggest that a coordination bond between S and

Pd is formed in the MCM-41-SH-Pd(II). The binding energy (336.8 eV) of Pd$_{3d5/2}$ of MCM-41-SH-Pd(0) was lower than the binding energy (337.4 eV) of Pd$_{3d5/2}$ of MCM-41-SH-Pd(II). The Pd$_{3d5/2}$ binding energy depends strongly on the nature of the ligands. Consequently, it is impossible to identify the reduced complex as a zerovalent one on the basis of its Pd$_{3d5/2}$ binding energy only. However, the binding energy of Cl$_{2p}$ in the MCM-41-SH-Pd(0) cannot be detected, the shift (lower) of Pd$_{3d5/2}$ binding energy together with the change in color (from yellow to dark gray) suggests that the reduction of the starting palladium(II) complex to the lower valent state has taken place. The MCM-41-SH-Pd(0) complex catalyst formed is stable in air but for prolonged storage is better stored under an atmosphere of argon in which case no decomposition and deactivation are noted over the period of 6 months at room temperature.

The novel MCM-41-supported sulfur palladium(0) complex [MCM-41-SH-Pd(0)] was employed as catalyst in the Sonogashira coupling reaction of aryl iodides with terminal alkynes under the conditions similar to those used in the corresponding homogeneous reactions. The influences of bases, solvents and amount of the catalyst on catalytic property of the MCM-41-SH-Pd(0) complex were investigated by using coupling reaction of iodobenzene with 1-hexyne. The results are showed in Table 2. It was found that among the bases tested, piperidine proved to

Table 1
XPS data for MCM-41-SH, MCM-41-SH-Pd(II), MCM-41-SH-Pd(0) and PdCl$_2$[a]

Sample	Pd$_{3d5/2}$	S$_{2p}$	Si$_{2p}$	O$_{1s}$	Cl$_{2p}$
MCM-41-SH-Pd(0)	336.8	164.2	103.2	533.0	
MCM-41-SH-Pd(II)	337.4	164.3	103.3	533.1	199.3
MCM-41-SH		163.8	103.2	533.0	
PdCl$_2$	338.3				199.2

[a] The binding energies are referenced to C$_{1s}$ (284.6 eV) and the energy differences were determined with an accuracy of ±0.2 eV.

Table 2

Coupling reaction of iodobenzene with 1-hexyne in the presence of several bases and solvents[a]

Entry	Base	Solvent	MCM-41-SH-Pd(0) (mol%)	Time (h)	Yield[b] (%)
1	Et$_3$N	Toluene	0.5	7	83
2	Et$_3$N	DMF	0.5	4	85
3	Et$_3$N	Dioxane	0.5	5	82
4	Et$_3$N	Et$_3$N	0.5	2.5	88
5	BuNH$_2$	DMF	0.5	5	84
6	BuNH$_2$	Dioxane	0.5	6	81
7	BuNH$_2$	BuNH$_2$	0.5	3	87
8	Piperidine	DMF	0.5	4	89
9	Piperidine	Piperidine	0.5	2	96
10	Pyrrolidine	DMF	0.5	4	84
11	Pyrrolidine	Pyrrolidine	0.5	2.5	92
12	Piperidine	Piperidine	1.0	1	95

[a] All reactions were performed using 1.0 mmol of iodobenzene, 1.5 mmol of 1-hexyne, 0.05 mmol of CuI and 3.0 mmol of base in 3 ml of solvent at room temperature under Ar.

[b] Isolated yield based on the iodobenzene used.

Table 3

Sonogashira coupling reactions of aryl iodides with terminal alkynes[a]

Entry	R^1	R^2	Time (h)	Product	Yield[b] (%)
1	H	Ph	2.0	**3a**	95
2	H	CH$_3$OCH$_2$	2.0	**3b**	92
3	H	Me$_3$Si	2.0	**3c**	93
4	4-Cl	n-C$_4$H$_9$	1.0	**3d**	97
5	4-Cl	Ph	1.0	**3e**	94
6	4-CH$_3$	CH$_3$OCH$_2$	2.0	**3f**	93
7	4-CH$_3$	n-C$_4$H$_9$	2.0	**3g**	95
8	3-O$_2$N	Ph	1.0	**3h**	96
9	3-O$_2$N	HOCH$_2$	1.0	**3i**	91
10	4-CH$_3$OCO	n-C$_4$H$_9$	1.0	**3j**	94
11	4-CH$_3$OCO	Me$_3$Si	1.0	**3k**	92
12	3-NC	Ph	1.0	**3l**	93
13	3-NC	n-C$_4$H$_9$	1.0	**3m**	94
14	4-CH$_3$O	n-C$_4$H$_9$	2.5	**3n**	97
15	4-CH$_3$O	Me$_3$Si	2.5	**3o**	93
16	4-CH$_3$CO	n-C$_4$H$_9$	1.0	**3p**	96
17	4-CH$_3$CO	CH$_3$OCH$_2$	1.0	**3q**	92

[a] All reactions were performed using 1.0 mmol of aryl iodide, 1.5 mmol of terminal alkyne, 0.005 mmol of MCM-41-SH-Pd(0) and 0.05 mmol of CuI in 3 ml of piperidine at room temperature under Ar.

[b] Isolated yield based on the aryl iodide used.

be the most efficient. Among the solvents used, piperidine was also the best choice. Increasing the amount of palladium catalyst could shorten the reaction time, but did not increase the yield of 1-phenyl-1-hexyne (entry 12). Taken together, excellent result was obtained when the coupling reaction was carried out with 0.5 mol% of MCM-41-SH-Pd(0) and 5 mol% of CuI in piperidine at room temperature (entry 9).

To examine the scope for this coupling reaction, a variety of terminal alkynes were coupled with different phenyl iodides in piperidine in the presence of a catalytic amounts of MCM-41-SH-Pd(0) and CuI at room temperature (Scheme 2). The experimental results are summarized in Table 3. As shown in Table 3, the Sonogashira coupling reactions of aryl iodides with a variety of terminal alkynes proceeded smoothly under very mild conditions giving the corresponding coupling products in excellent yields. The coupling reaction of aryl iodides with terminal alkynes catalyzed by polystyrene-supported phosphine palladium complex was also very high yielding, but it is necessary to pre-soak the catalyst with a large amount of solvent and a higher temperature (60 °C) was required [10]. The optimized catalyst system is quite general and tolerant of a range of functional groups. For the electron-deficient aryl iodides, the coupling reactions were rapidly completed within 1 h, and the others required slightly longer reaction times. In all reactions only 0.5 mol% of MCM-41-SH-Pd(0) based on the aryl iodides was used, the molar turnover numbers are larger than those in the corresponding coupling reaction catalyzed by other heterogeneous catalysts reported [8–11].

This MCM-41-supported sulfur palladium catalyst can be easily recovered by simple filtration. In an attempt to show that the MCM-41-SH-Pd(0) can be recycled, the coupling reaction of iodobenzene with 1-hexyne was repeated five times using the same batch of supported catalyst. The yields of 1-phenyl-1-hexyne remain around 95% clearly illustrating the high stability and excellent reusability of the catalyst. The result is important from a practical point of view. In the past, we reported the preparation of silica-supported sulfur palladium(0) complex catalyst ['Si'-SH-Pd(0)] and its catalytic behavior in the Sonogashira coupling reaction [26]. It was found that the 'Si'-SH-Pd(0) was also an efficient catalyst for the Sonogashira coupling reaction, but the activity of the catalyst was slightly lower than the MCM-41-SH-Pd(0) and decreased gradually with repeated use. The high catalytic activity, excellent reusability and the easy accessibility of the MCM-41-SH-Pd(0) make them a highly attractive supported palladium catalyst for the parallel solution phase synthesis of diverse libraries of compounds.

In summary, we have established that the phosphine-free heterogeneous palladium catalyst [MCM-41-SH-Pd(0)] is a highly efficient, stable and recyclable catalyst for the Sonogashira coupling reactions of aryl iodides with terminal alkynes. The advantages of our heterogeneous catalytic system over others are: (1) the preparation of the heterogeneous MCM-41-SH-Pd(0) catalyst is rather simple and convenient from commercially available and cheap reagents, (2) the reaction conditions are mild, i.e., only
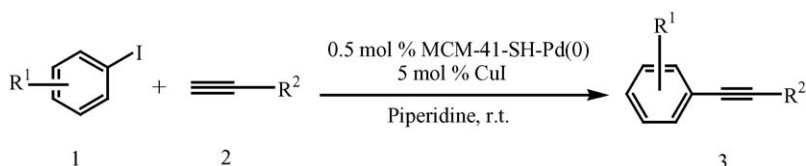
Scheme 2.

0.5 mol% palladium catalyst and room temperature, (3) excellent performance and reusability of the catalyst.

Acknowledgement

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