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Functionalization of silica surface using Chan–Lam coupling

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ABSTRACT

The reaction of base-free Chan–Lam coupling was successfully used for functionalization of surface of mesoporous silica gel. Various aromatic, aliphatic, and heterocyclic compounds were immobilized by a copper-catalyzed reaction of corresponding boronic acids with surface amino groups at mild conditions. Obtained functionalized materials were mesoporous although their surface area decreased after immobilization. The reactivity of some surface functional groups was tested in their characteristic reactions.

Catalytic cross-coupling reactions are well known as a simple and efficient strategy for the synthesis of organic compounds containing C–C, C–N, C–O, and C–S bonds.[1] One of the most interesting reactions of this type is Chan–Lam coupling.

The reaction of N-arylation of amines by phenylboronic acids was discovered by research groups of Chan and Lam in 1998. Chan et al.[2] studied the formation of C–N bond in the reaction of various substituted phenylboronic acids with aliphatic and aromatic amines and amides in the presence of a base and $Cu(OAc)_2$. The reaction continued for 18–65 h at room temperature yielding corresponding arylation products. Lam et al.[3] extended this procedure to N-arylation of heterocyclic compounds. Vinylboronic and alkylboronic acids are also reactive to amines, amides, and N-heterocyclic compounds.[4–6] Copper compounds are not the only catalysts that can catalyze this reaction. Raghuvanshi et al.[7] demonstrated a possibility to use Ni-complex with 2,2′-bipyrydil ligand though this catalyst was highly active only in strongly basic media.

Numerous attempts were made to arylate N-containing compounds in heterogeneous conditions. The reaction was tested in the presence of heterogeneous copper catalysts immobilized on silica gel.[8] However, the catalysts were sufficiently active in arylation of benzylamines and N-heterocyclic compounds only at elevated temperature. Copper-catalyzed N-arylation was successfully used in solid-phase synthesis of *N*-aryl compounds. Imidazole and benzimidazole were bonded to a polymer support, arylated with 4-methylphenylboronic acid, and the products were separated from the support. The reaction rate increased under microwave irradiation.[9] Solid-phase methodology demonstrated effectiveness in N-arylation of sulfonamides and aliphatic amines.[10,11]

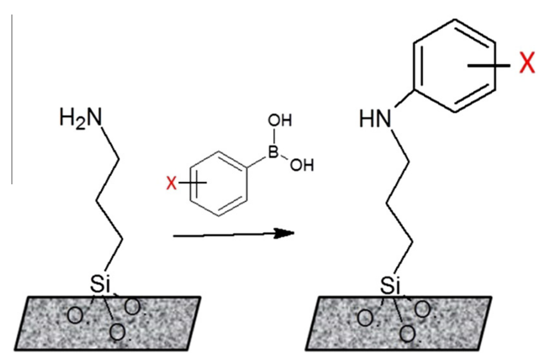

Figure 1. General scheme of surface N-arylation with arylboronic acids.

Most of earlier publications report Chan–Lam coupling in the presence of a base. As it was shown by Quach and Batey,[12] it is possible to achieve high yields of the products even in base-free media. The reaction with $PhBF_3^-K^+$ as an arylating agent proceeds at room temperature while the reaction with $PhB(OH)_2$ requires mild heating. Sreedhar et al. arylated amines and azoles on immobilized Cu(I) catalyst with excellent yields in the absence of a base.[13] The yields exceeded 90% for almost all amines and substituted phenylboronic acids.

A possibility to use a large variety of boronic acids containing various functional groups can be a novel approach to the synthesis of functionalized materials. In the last decades, organic–inorganic

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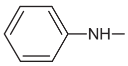
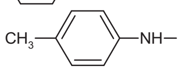
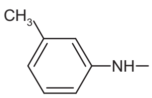
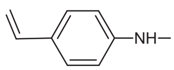
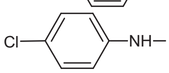
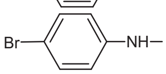
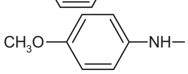
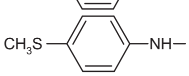
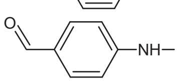
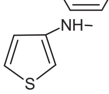
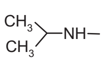
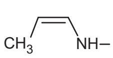
Table 1
Characteristics of the functionalized silica gels

#	Functional group	C/N ratio	Fraction of NH_2 groups reacted	Surface density (molecules/nm^2)	S_{BET} (m^2/g)	Pore volume (cm^3/g)	Average pore radius (Å)
1	None	–	–	–	457	0.748	33.1
2	NH_2–	3.1	–	1.57	371	0.653	33.1
3		4.8	0.30	0.48	362	0.619	22.8
4		3.7	0.10	0.16	365	0.563	22.9
5		3.9	0.13	0.22	355	0.464	22.9
6		3.9	0.11	0.16	365	0.643	22.8
7		4.1	0.18	0.30	352	0.616	22.9
8		4.3	0.23	0.38	358	0.613	22.9
9		3.8	0.11	0.18	365	0.554	22.9
10		3.7	0.10	0.16	357	0.632	22.9
11		3.8	0.11	0.18	353	0.562	22.9
12		3.6	0.15	0.24	372	0.550	22.9
13		3.6	0.20	0.33	358	0.639	22.7
14		3.6	0.29	0.49	360	0.651	22.8

hybrid materials containing surface functional groups have found many applications in various fields of science. They can serve as heterogeneous catalysts, heavy metal scavengers, and immobile phases in HPLC. Silica-based biosensors containing immobilized enzymes and antibodies are widely used in medicine. Hybrid materials with immobilized molecules of organic dyes have extraordinary optical properties.

In this work Chan–Lam coupling in base-free media was suggested for functionalization of the surface of silica gel (Fig. 1).

Functionalization of the surface was carried out by a reaction of substituted boronic acids with amino-modified silica gel (**2**).[14] Sample **2** was prepared by grafting of (3-aminopropyl)trimethoxysilane on mesoporous silica gel **1** using a well-known procedure.[15] Elemental analysis of the product showed 0.97 mmol/g of chemosorbed (3-aminopropyl)silane molecules on the surface. The surface density of NH_2 groups was calculated considering BET surface area, and found 1.57 molecules/nm^2 (Table 1).

In the syntheses, surface amino groups in **2** reacted with nine arylboronic acids containing various substituents. Also, one heterocyclic and two aliphatic boronic acids were used. During the synthesis, initially blue solution gradually changed to yellow.

The extent of the reaction was calculated from the atomic ratio C/N in the obtained samples **3**–**14** (Table 1).[16] As it was shown by elemental analysis, all boronic acids reacted with the surface amine groups. The degree of immobilization varied depending on the nature and size of the substituent. The highest yield was achieved at the reaction with non-substituted phenylboronic acid (sample **3**). Aliphatic boronic acids were also highly reactive to the amine (samples **13** and **14**). Among substituted aryl

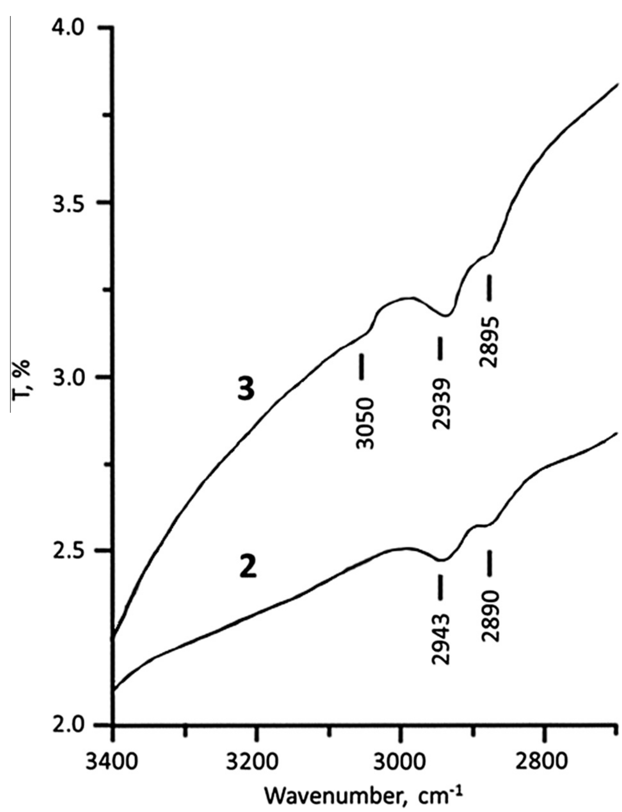


Figure 2. FT-IR spectra of samples **2** and **3**.