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Pd–*N*-heterocyclic carbene (NHC) organic silica: synthesis and application in carbon–carbon coupling reactions

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Abstract

The first Pd–*N*-heterocyclic carbene (NHC) complex in the form of organic silica was prepared using sol–gel method and its application in Heck and Suzuki reactions was demonstrated. These C–C coupling reactions proceeded efficiently under the influence of microwave irradiation, with excellent yield, without any change in catalytic activity for at least five reaction cycles, with negligible Pd concentration in the end product.
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Keywords: Organic silica; Heterogeneous catalysis; Pd–NHC; Suzuki reaction; Heck reaction; Microwave irradiation

1. Introduction

Palladium catalyzed carbon–carbon cross-coupling reactions exemplify one of the important processes in organic chemistry.[1] The Heck[2] and Suzuki[3] reactions are among the most widely used reactions for the formation of carbon–carbon bonds. These reactions are generally catalyzed by soluble Pd complexes with various ligands.[4] However, the efficient separation and subsequent recycling of homogeneous transition-metal catalysts remains a scientific challenge and an aspect of economical and ecological relevance. Heterogeneous Pd-catalyst systems were found to be highly effective to overcome some of these issues.[5] The majority of the novel heterogenised catalysts are based on silica supports, primarily because silica displays some advantageous properties, such as excellent stability (chemical and thermal), good accessibility, porosity and the fact that organic groups can be robustly anchored to the surface to provide catalytic centers.[6,7]

The common structural feature of these materials is the entrapment of the dopant (catalytic) molecule in the pores of silica, a phenomenon, which imparts unique chemical and physical properties to resulting hybrid silica. In general, the process to obtain sol–gel catalyst consists of the synthesis of an inorganic network by hydrolysis and polycondensation of tetraethyl orthosilicate (TEOS) in the presence of the catalytic species. Most of encapsulated-silica catalyst contains 90% inorganic part from TEOS and only 10% the catalytic part. Also, not all catalytic sites are available for reaction, since most of them are in the walls of silica and only those, which are in the pores are available for catalysis. Consequently there is need to design and synthesize pure organic silica, which does not use any inorganic sol–gel precursor, so that most of its sites are catalytically active. In continuation of our work on supported catalysis,[6,8] pursued under the green chemistry program,[9] we propose a new concept of catalyst heterogenisation, by synthesizing the first example of Pd–*N*-heterocyclic carbene (Pd–NHC) complex in the form of organic silica and its application in C–C coupling reactions, which could shed new light on transition-metal catalysis.

2. Results and discussion

The first step in the accomplishment of this goal is the synthesis of an organometallic precursor that has multiple polycondensable organosiloxane functionalized donor ligands. The Pd–*N*-heterocyclic carbene complex **IV** was chosen as it has

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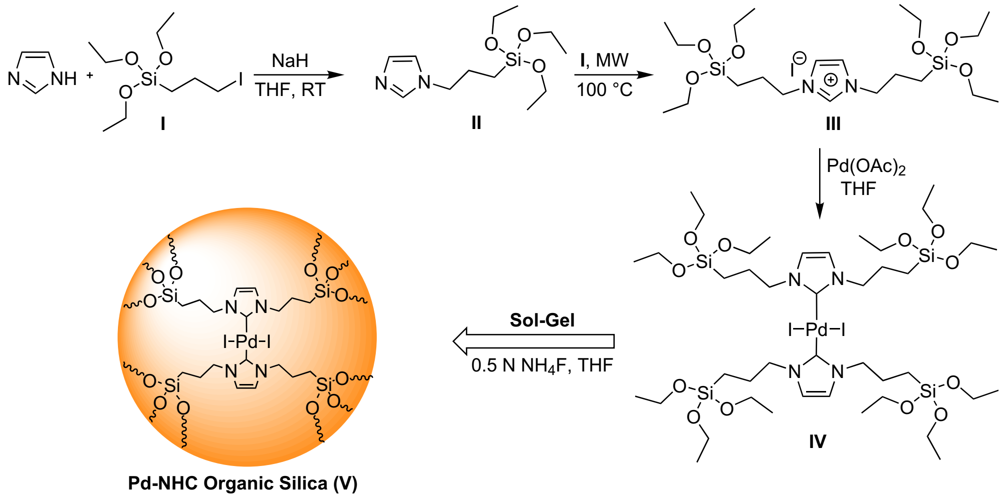


Scheme 1. Preparation of Pd–*N*-heterocyclic carbene (NHC) organic silica.

been demonstrated to be an excellent catalyst for C–C coupling reactions.[10]

The Pd–NHC organic silica **V** was prepared in THF as shown in Scheme 1. The reaction of imidazole with 3-iodopropyl triethoxysilane (**I**) generated silylated imidazole **II**, that on reaction with 3-iodopropyl triethoxysilane (**I**) provided ionic imidazole species **III**, which on treatment with $Pd(OAc)_2$ in THF under reflux condition afforded the complex **IV**. Microwave (MW) irradiation was ideally suited for the conversion of **II** to ionic liquid **III**, which normally requires an extended period of 12 h for the completion of the reaction. This may be due to selective absorption of microwaves by reactants and polar intermediates, which accelerate the reaction rate.[11] The in situ ^{13}C NMR analysis of the complex **IV** showed two peaks at 162.9 and 173.1 ppm concerning two regioisomers of **IV**, which clearly proved the formation of NHC–Pd carbene complex.[10f]

We wanted to use this precursor **IV** directly, without using any inorganic sol–gel precursor TEOS, in the synthesis of organic silica under the classical aqueous basic sol–gel conditions; however, this complex is not stable under these conditions. Alternatively, we adapted the condensation reaction under the mild conditions in THF using ammonium fluoride as a catalyst.[12] Various combinations of THF, NH_4F, and H_2O were explored and the optimum results were obtained with 5 mL THF, 0.6 mL 1 N NH_4F, 0.6 mL H_2O for 0.003 mol of **IV**, which led to the formation of shining orange colored Pd–NHC organic silica material **V**. Thus, we achieved our goal of organic silica synthesis without using any inorganic sol–gel precursor.

In order to determine the properties of this organic silica material, it was characterized by various techniques. TGA analysis of organic silica **V** showed a weight reduction at 180 °C, followed by loss of 30% weight at 350 °C, which corresponds to organic part of the complex. The catalyst **V** exhibited 5 m^2/g of surface area by Brunauer–Emmett–Teller (BET) measurement. The Pd content in the organic silica was 4% based on inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis.

The organic silica **V** was also characterized by solid state MAS NMR spectroscopy. The ^{29}Si CP-MAS spectra displayed two characteristic signals, of these, the signal at −59 ppm corresponded to T^2 and −66 ppm to T^3 sites for $RSiO_3$ substructures of different condensation degree. In order to identify organic functionalities attached to the silica support, ^{13}C CP-MAS experiments were performed. The spectrum showed signals at 166.1, 128.9, 57.8, 53.3, 24.6, 18.4, and 11.1 ppm, similar to the chemical shifts found in the liquid ^{13}C NMR spectrum of the silylated organic precursor molecule **IV**.

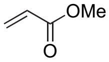
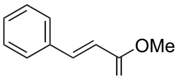
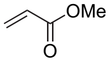
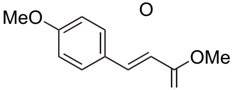
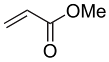
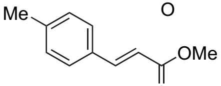
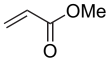
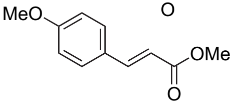
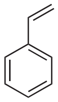
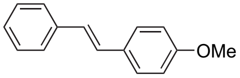
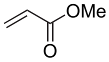
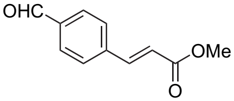
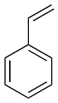
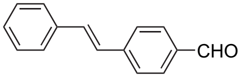
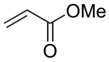
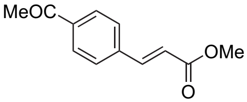
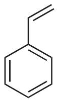
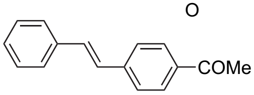
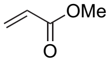
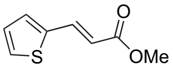
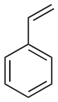
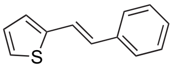
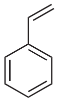
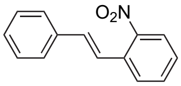
We explored this Pd–NHC organic silica **V** as catalyst in Heck reactions (Scheme 2). In view of the emerging MW chemistry interest in heterogeneous cross-coupling reactions,[13] we used MW irradiation as a heating source for this reaction. Initial trials were performed to optimize reaction conditions using iodobenzene and methyl acrylate as a substrate. After screening a range of usual inorganic and organic bases and exploring the scope of various solvents, we found that this catalyst is most efficient for Heck reaction in presence of triethylamine as a base and DMF as a solvent at 120 °C. Using these optimized reaction conditions, the scope of this catalyst was studied for Heck reaction of various aryl halides and alkenes and results are summarized in Table 1.

X - I, Br
Y - CO_2CH_3, C_6H_5
R - H, Me, OMe, COMe,
CHO.

Scheme 2. Heck reaction using Pd–*N*-heterocyclic carbene organic silica.

Aromatic iodo and bromo compounds reacted efficiently with alkenes to give coupling products in good to excellent yield. The reactions with 2-iodothiophene were successfully

Table 1
Heck reaction of various aryl halides using Pd–NHC organic silica[a]

Entry	Aryl halide	Alkene	Product	Yield[b] (%)	TOF
1	C_6H_5I			95	10,270
2	4-OMeC_6H_4I			96	10,378
3	4-MeC_6H_4I			90	9729
4	4-OMeC_6H_4Br			87	9405
5	4-OMeC_6H_4Br			88	9513
6	4-CHOC_6H_4Br			88	9513
7	4-CHOC_6H_4Br			89	9621
8	4-COMeC_6H_4Br			85	9189
9	4-COMeC_6H_4Br			84	9081
10	2-Iodothiophene			90	9729
11	2-Iodothiophene			88	9513
12	2-$NO_2C_6H_4Br$			78	8432

[a] Reaction was carried out by irradiating 1 mmol of aryl halide, 1.2 mmol of alkene, 1.5 mmol of triethylamine, and 0.1 g of organic silica (0.037 mol % Pd) catalyst in 1 mL of DMF by microwaves for 0.25 h at 120 °C.

[b] GC yields.

achieved (entries 10 and 11), which provide a useful strategy to introduce unsaturated group on the thiophene ring.

The utility of this Pd–NHC organic silica **V** was then explored for Suzuki reaction using a variety of substrates (Scheme 3). Firstly, the reaction conditions were optimized using iodobenzene as a substrate. We found that this catalyst is most efficient for Suzuki reaction in presence of K_2CO_3 as a base and DMF/water (1:2) as a solvent. Using these optimized reaction conditions, the efficiency of this catalyst was studied for Suzuki reaction of various aryl halides and the results are summarized in Table 2.

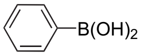
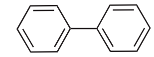
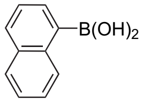
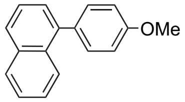
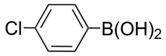
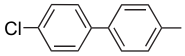
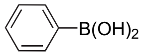
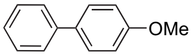
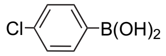
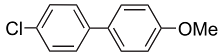
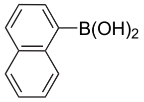
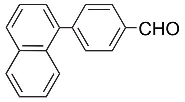
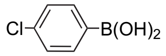
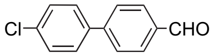
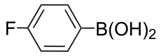
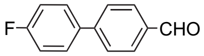
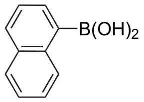
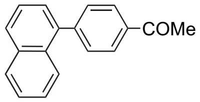
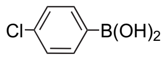
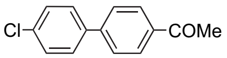
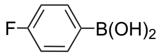
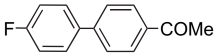
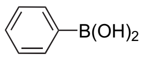
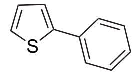
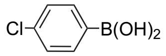
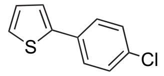
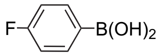
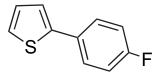
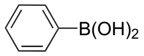
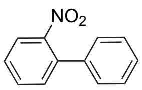
Where, X- I, Br
R^1-H, Me, OMe, COMe, CHO
R^2-H, Cl, F, napthyl

Scheme 3. Suzuki reaction using Pd–*N*-heterocyclic carbene organic silica.

Aryl iodide (entries 1–3) and aryl bromide (entries 4–11) with various functional groups efficiently reacted with boronic acid to yield Suzuki products in good to excellent yields. 2-Iodothiophene underwent smooth reaction with various boronic acids (entries 12–14), providing a useful way for the synthesis of aryl substituted thiophene heterocycles. High turnover frequencies (TOF) are achieved for iodo- and bromoarenes, which are comparable with reported catalyst systems.[14–21]

For practical applications of heterogeneous systems, the lifetime of the catalyst and its level of reusability are very

Table 2
Suzuki reaction of various aryl halides using Pd–NHC organic silica[a]

Entry	Aryl halide	Boronic acid	Product	Yield[b] (%)	TOF
1	C_6H_5I			97	16,385
2	4-$OMeC_6H_4I$			96	16,216
3	4-MeC_6H_4I			94	15,878
4	4-$OMeC_6H_4Br$			90	15,202
5	4-$OMeC_6H_4Br$			90	15,202
6	4-$CHOC_6H_4Br$			91	15,371
7	4-$CHOC_6H_4Br$			90	15,202
8	4-$CHOC_6H_4Br$			90	15,202
9	4-$COMeC_6H_4Br$			88	14,864
10	4-$COMeC_6H_4Br$			87	14,695
11	4-$COMeC_6H_4Br$			88	14,864
12	2-Iodothiophene			90	15,202
13	2-Iodothiophene			91	15,202
14	2-Iodothiophene			91	15,202
15	2-$NO_2C_6H_4Br$			84	14,189

[a] Reaction was carried out by irradiating 1 mmol of aryl halide, 1.2 mmol of boronic acid, 1.5 mmol of K_2CO_3, and 0.1 g of organic silica (0.037 mol % Pd) catalyst in 1 mL of DMF/H_2O (1:2) by microwaves for 0.16 h at 100 °C.

[b] GC yields.

important factors. To clarify this aspect, we established a set of experiments using the recycled catalyst for Heck reaction of iodotoluene and methyl acrylate. The reactions were conducted under similar conditions (120 °C/30 min) in DMF. After the completion of the first reaction to afford the corresponding methyl cinnamate in 90% yield, the catalyst was recovered by filtration, washed with dichloromethane and acetone, and finally dried at 100 °C for 1 h. A fresh reaction was then performed under same conditions. Although the color of silica changed from orange to blackish brown, the Pd–*N*-heterocyclic carbene complex in the form of organic silica could be used for at least five times without any change in activity. Similar study for Suzuki reaction also showed excellent recyclability of catalyst.

Heterogeneity and Pd-leaching of this catalyst for the Heck reaction of iodotoluene and methyl acrylate were also examined by the 'hot filtration' test.[14] Filtration using Whatman filter paper after 10 min (35% conversion) followed by an additional 20 min of reaction time gave a final conversion of 90% for the catalyst-containing portion, and 59% conversion for the filtered portion. Though these results do not rule out the possibility that the organic silica might have been involved in the reaction in a heterogeneous way, it is evident that the catalyst released some Pd species into the solution. Pd-leaching was also studied by Atomic Absorption Spectroscopy (AAS) analysis of the organic part after completion of reaction (before column chromatography), which showed negligible 6 ppm Pd-leaching. These two divergent results indicate that after the completion of reaction (iodotoluene completely disappears), the leached palladium goes back to the surface of the support and gets redeposited[6,15] thereby resulting in negligible Pd content in the final product.

Our results are consistent with previously reported studies using supported Pd-catalysts,[16] some pincer complexes,[17] palladacycles,[18] and simple Pd compounds,[19] which were also demonstrated as Pd reservoirs. The other two similar reports on Pd–*N*-heterocyclic carbene complex functionalized silica by Aksin et al. [20] showed considerable Pd-leaching whereas Karimi and Enders [21] indicate no Pd-leaching. In fact, to date there is no 100% leach proof Pd-catalyst and hence the most important criteria in choosing the catalyst is the Pd-metal recovery. It would be preferable to use a more accessible, low cost silica catalyst provided that the process works efficiently and that the catalyst leaves no remnants of metal within the end product since metal contamination is highly regulated by pharmaceutical industry. All above conditions are well satisfied by the Pd–NHC organic silica catalyst (**V**) used in present studies, with negligible Pd concentration within end product after completion of reaction.

3. Conclusions

In conclusion, we have developed a new concept for the design and synthesis of highly active and recyclable heterogenised Pd–NHC catalysts in the form of organic silica, which does not use any inorganic sol–gel precursor and most of its sites are catalytically active. This work could shed new light on transition-metal catalysis.

4. Experimental

4.1. General

All the solvents and reagents were purchased at the highest commercial quality and used without further purification, unless otherwise stated. Thin layer chromatography (TLC) (silica gel; 20% ethyl acetate/hexane) and gas chromatography (GC) were used to monitor the reactions. The crude products were identified by GC–MS qualitative analysis using a GC system with a Mass selective detector. The identities were further confirmed for representative compounds by ^{1}H and ^{13}C NMR spectra that were recorded in deuterated chloroform-*d* ($CDCl_3$) with tetramethylsilane (TMS) as internal reference using a 300 MHz NMR spectrometer. CEM Discover focused microwave synthesis system was used to carry out Heck and Suzuki reactions.

*4.2. Synthesis of N-3-propyl imidazole triethoxysilane (**II**)*

Sodium hydride 2.4 g (0.1 mol) was suspended in 100 mL of dry THF under inert atmosphere. To this suspension, 4.8 g of imidazole (0.07 mol) in 50 mL THF was added dropwise over 30 min and stirred for 30 more minutes at room temperature. Freshly distilled triethoxysilane propyl iodide (**I**) (23.3 g, 0.07 moles) was then added dropwise over 30 min and the reaction mixture was stirred for 2 days at room temperature. After completion of reaction, THF was evaporated and ether was added to residual and then filtered. After removal of ether from the filtrate, the crude *N*-3-propyl imidazole triethoxysilane was purified under vacuum distillation (10 mm/190 °C) to yield 12.5 g of pure product (65%).

FTIR (KBr): 3110, 2974, 2929, 2888, 1506, 1391, 1228, 1104, 1978, 957, 783, 664 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 0.42 (2H, t, J=8.0 Hz), 1.08 (9H, t, J=6.8 Hz), 1.74 (2H, m), 3.66 (6H, q, J=6.8 Hz), 3.80 (2H, t, J=7.0 Hz), 6.78 (1H, s), 6.90 (1H, s), 7.34 (1H, s) ppm.

^{13}C NMR ($CDCl_3$): δ 7.2, 18.1, 24.8, 49.1, 58.4, 118.7, 129.1, 137.1 ppm.

MS: (M^+) 272. Anal. Calcd for $C_{12}H_{24}N_2O_3Si$: C, 52.91; H, 8.88; N, 10.28. Found: C, 52.85; H, 8.90; N, 10.26%.

*4.3. Synthesis of 1,3-N,N-bis(3-(triethoxysilyl)propyl)-imidazolium iodide (**III**)*

N-3-Propyl imidazole triethoxysilane (**II**) (2.72 g, 0.01 mol) and 3-iodopropyl triethoxysilane (4.3 g, 0.011 mol) were added to 1 mL of acetonitrile in a 10 mL crimp-sealed thick-walled glass tube equipped with a pressure sensor and a magnetic stirrer and the reaction tube was placed inside the cavity of a CEM Discover focused microwave synthesis system at 80 °C for 30 min. After completion of reaction, solvent was evaporated and product was washed with ether to remove excess of 3-iodopropyl triethoxysilane, to yield 5.1 g (85%) of the pure solid product (decomposition—250 °C).

FTIR (KBr): 3070, 2972, 2922, 2885, 1562, 1445, 1294, 1163, 1076, 956, 783, 639 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 0.48 (4H, t, J=8.0 Hz), 1.07 (t, 18H, J=7.2 Hz), 1.89 (4H, m), 3.67 (12H, q, J=7.2 Hz), 4.24 (4H, t, J=7.2 Hz), 7.33 (2H, s), 9.85 (1H, s) ppm.

^{13}C NMR ($CDCl_3$): δ 6.9, 18.2, 24.3, 51.7, 58.5, 122.4, 135.9 ppm.

MS: (M^+) 604. Anal. Calcd for $C_{21}H_{45}N_2O_6Si_2$: C, 52.79; H, 9.49; N, 5.86. Found: C, 52.81; H, 9.46; N, 5.85%.

*4.4. Synthesis of Pd–NHC complex (**IV**)*

To a solution of 1 g of $Pd(OAc)_2$ (0.0045 mol) in 100 mL dry THF, 5.4 g of 1,3-*N*,*N*-bis(3-(triethoxysilyl)propyl)-imidazolium iodide (**III**) (0.009 mol) was added and reaction mixture was stirred at room temperature for 1.5 h and then refluxed for 3 h. The formation of Pd–carbene complex was confirmed by in situ NMR. After completion of reaction, THF was evaporated to yield the crude oily product, which can be solidified after tituration by hexane and yielded 2.9 g of orange colored Pd–NHC complex (73%).

FTIR (KBr): 3121, 2974, 2929, 2885, 1458, 1079, 949, 794, 713 cm^{-1}.

^{1}H NMR ($CDCl_3$): δ 0.6 (8H, m), 1.16 (t, 36H, J=7.2 Hz), 2.1 (8H, m), 3.77 (24H, q, J=7.2 Hz), 4.3 (8H, m), 7.87 (4H, s) ppm.

^{13}C NMR ($CDCl_3$): δ 7.6, 18.3, 23.5, 40.7, 53.3, 58.4, 120.9, 162.9 173.1 ppm.

MS (FAB$^+$): (M$^+$) 1315. Anal. Calcd for $C_{42}H_{90}I_2N_4O_{12}$-$PdSi_4$: C, 38.34; H, 6.89; N, 4.26. Found: C, 38.31; H, 6.92; N, 4.24%.

4.5. Synthesis of Pd–NHC organic silica (**V**)

The oily Pd–carbene complex (**IV**) after evaporation of THF (in above procedure) was dissolved in 4 mL of THF and 1.5 mL of 0.5 N NH_4F was added to this solution. Gelification of mixture occurred at room temperature within 10 min, which was allowed to stand for 24 h. The solid orange colored organic silica (**V**) was then washed with ethanol and dried under vacuum at 80 °C.

Yield: 2.4 g.

FTIR (KBr): 3120, 2930, 2863, 1126, 1001, 876, 691 cm^{-1}.

^{29}Si CP-MAS: δ −59 (T^2), −66 (T^3) ppm. ^{13}C CP-MAS: δ 11.1, 18.4, 24.6, 53.3, 57.8, 128.9, 166.1 ppm.

BET: porosity 5 m^2/g.

4.6. Typical experimental procedure for Heck reaction

The aryl halide (1 mmol), alkene (1.2 mmol), triethylamine (1.5 mmol), and 0.1 g of Pd–NHC silica (**V**) (0.004 g of Pd) were added to 1 mL DMF in a 10 mL crimp-sealed thick-walled glass tube equipped with a pressure sensor and a magnetic stirrer. The reaction tube was then placed inside the cavity of a microwave oven, operated at 120±5 °C (temperature monitored by a built-in infrared sensor), power 40–140 W and pressure 40–70 psi for 30 min. After completion of the reaction, the reaction mixture was filtered and crude was subjected to column chromatography to afford pure Heck product.

4.7. Typical experimental procedure for Suzuki reaction

The aryl halide (1 mmol), boronic acid (1.2 mmol), K_2CO_3 (1.5 mmol), and 0.1 g of Pd–NHC silica (**V**) (0.004 g of Pd) were added to 1.5 mL DMF/H_2O (1:2) in a 10 mL crimp-sealed thick-walled glass tube equipped with a pressure sensor and a magnetic stirrer and similar procedure as describe above was followed at 100 °C for 10 min.

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2008.02.098.

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