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Heterogeneous Catalysis

High Catalytic Activity of Palladium(II)-Exchanged Mesoporous Sodalite and NaA Zeolite for Bulky Aryl Coupling Reactions: Reusability under Aerobic Conditions**

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Palladium-catalyzed cross-coupling reactions, such as Suzuki, Heck, and Sonogashira reactions, are very important as a versatile route to aryl compounds that are highly useful as pharmaceuticals and fine chemicals.[1] Various Pd complexes have been used as homogeneous catalysts, but the limited reusability of expensive Pd has been a serious problem in industrial applications.[2,3] In this regard, heterogeneous Pd catalysts are a promising option. Such heterogeneous catalysts can be prepared by grafting ligated Pd complexes onto polymer resins and metal oxides.[4] Alternatively, ligand-free catalysts can be prepared by supporting Pd^0 nanoparticles or Pd^{2+} ions on porous solid materials, such as carbon,[5] zeolites,[6–9] mesoporous silica,[9,10] and metal oxides.[11–13] The ligand-free system is preferable in heterogeneous catalysis, owing to economic preparation and high stability in air.[14–18] However, the use of ligand-free catalysts is often limited by Pd leaching, and also by changes in the chemical state of the Pd species.[1,19]

The limited success of ligand-free, heterogeneous Pd catalysts is attributed to the unique reaction mechanism involving a Pd^0 state. There have been numerous works indicating that the catalytic active state is a Pd^0 species in coupling reactions.[6,9,14–18] In cases where Pd^{II} is used, in situ reduction to Pd^0 is known to occur during the reaction. De Vries and Reetz provided the evidence that monomeric or dimeric Pd^0 species, being in equilibrium with nanoparticulate Pd^0, is the catalytically active species.[14,15] Similar results were also reported by Schmidt at around the same time.[17,18] Notably, it was reported that the reduced Pd^0 species were more easily leached into the reaction media than the Pd^{II} species.[20] The reversible dissolution and redeposition of Pd^0 can result in the agglomeration of Pd^0 species into large Pd nanoparticles or Pd black, causing a loss of metal dispersion and surface area.[14,15] Thus, a heterogeneous catalyst, free of Pd leaching and agglomeration, is highly desirable for achieving high activity and catalyst reusability.

Herein, we report that Pd^{2+}-exchanged mesoporous sodalite and NaA zeolite are suitable as heterogeneous catalysts, which meet the aforementioned requirements. We chose the highly mesoporous sodalite and NaA zeolites as a support for Pd because the mesoporous structure (pore diameter > 5 nm) can allow much-enhanced diffusion of bulky aryl substrates as compared with solely microporous zeolites (< 0.72 nm). Most importantly, the catalysts were reusable without Pd leaching and agglomeration, as long as the reactions were carried out in air.

The mesoporous sodalite and NaA zeolite were synthesized by the addition of organosilane surfactant into the conventional synthesis compositions of sodalite and NaA zeolite (see the Supporting Information).[21–23] The resultant sodalite and NaA zeolite exhibited framework compositions of $Si/Al = 1.0$ and $Na^+/Al = 1.0$, which are consistent with those of their conventional counterparts. XRD patterns (Figure 1 a) correspond well to the highly crystalline sodalite and NaA. N_2 adsorption isotherms (Figure 1 b) revealed the presence of highly mesoporous structures with a narrow mesopore distribution centered at 8 and 10 nm for sodalite and NaA, respectively. The highly mesoporous morphologies were also confirmed by scanning electron microscopy (SEM; see Figure S1 in the Supporting Information). The materials exhibited high mesopore surface areas (187 $m^2\,g^{-1}$ for soda-

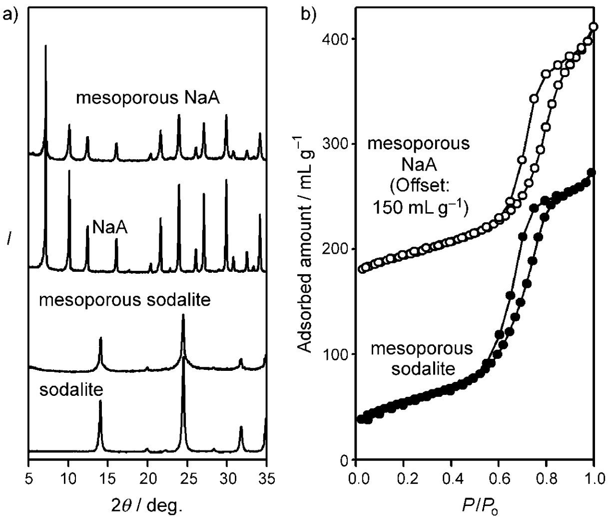

Figure 1. a) XRD patterns and b) N_2 adsorption–desorption isotherms of mesoporous sodalite and NaA zeolite.

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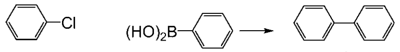
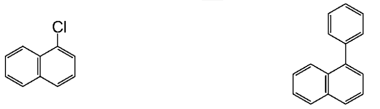
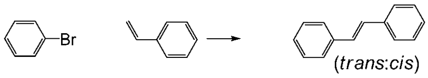
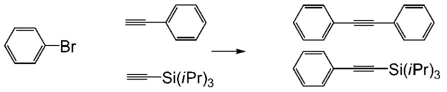
lite, 155 $m^2 g^{-1}$ for NaA) and mesopore volumes (0.42 and 0.38 $mL g^{-1}$). The *t*-plot analyses revealed solely mesoporous structures in these materials, with no appreciable microporosities. Notably, even N_2 (0.41 nm in size) cannot enter the narrow pore apertures of sodalite (0.22 nm in diameter) and NaA (0.40 nm) zeolite.

Owing to the Al-rich compositions (Si/Al = 1.0, Na^+/Al = 1.0), the mesoporous sodalite and NaA zeolite provided a large number of ion-exchange sites. Various cations, including as alkali (e.g., Li^+ and K^+), alkaline earth (e.g., Mg^{2+}, Ca^{2+}, and Sr^{2+}), and transition metal ions (e.g., Pd^{2+}, Ru^{3+}, Pt^{2+} and La^{3+}), can penetrate the 6-membered pore aperture (0.22 nm diameter) of the regular sodalite cage.[24,25] However, Cs^+ is too large to enter the aperture, leading to a negligible exchange in conventional sodalite ($Cs^+/Al < 0.01$).[25] Conversely, the mesoporous sodalite exhibited a considerable ion-exchange capacity for Cs^+ ($Cs^+/Al = 0.17$). The result indicated that as much as 17 % of the total ion-exchange sites are accessible to bulky Cs^+ ions at the mesopore walls of the sodalite. A similar conclusion might be drawn for the mesoporous NaA zeolite.

Owing to the highly mesoporous structure and the significant ion-exchange capacity at the mesopore walls, the zeolites can be modified into highly active catalysts for C–C coupling reactions, including Suzuki, Heck, and Sonogashira reactions. Pd^{2+}-exchanged mesoporous sodalite and NaA zeolite were prepared by ion exchange in a 0.01 M aqueous solution of $Pd(NO_3)_2 \cdot x H_2O$, with the Pd^{2+} loading corresponding to 2 % of total Al sites. The Al-rich zeolites exhibited an extremely high ion-selectivity for Pd^{2+}; more than 99 % of the loaded Pd^{2+} was exchanged onto the frameworks (product composition: $Pd^{2+}_{0.02}Na^{+}_{0.96}Si_{1.0}Al_{1.0}O_{4.0}$). To investigate the effect of pore structure on catalytic properties, conventional NaX zeolite, with a solely microporous structure, was also ion-exchanged in the same way (product composition: $Pd^{2+}_{0.02}Na^{+}_{0.96}Si_{1.2}Al_{1.0}O_{4.4}$). The catalytic properties of zeolites in the various C–C coupling reactions are summarized in Table 1. All of the reactions were carried out in air.

The zeolite catalysts all gave high catalytic conversions in reactions involving small aryl substrates (Table 1, entries 1–3 and 8). The reagents and products in these reactions are sufficiently small so that the reactions can take place even inside the supercages of NaX zeolite (diameter ≈ 0.73 nm). With bulky substrates (other entries in Table 1), however, the mesoporous catalysts exhibited much higher catalytic activities than NaX zeolite. The results indicated that reagents and/or products in these reactions were larger than the aperture of the NaX supercage, and hence the reactions could only occur at the external surface of NaX. Notably, the NaX zeolite supercage structure has one of the largest pore apertures among zeolite materials, and hence this zeolite has been most frequently investigated as a support for Pd catalysts.[6–9] The present results indicate that the aperture of NaX is still too small to host coupling reactions that produce such bulky aryl compounds. As a result of facile molecular diffusion to the catalytically active sites, the aforementioned mesoporous catalysts exhibited high catalytic activities even for aryl bromides and chlorides in the Heck reaction, whereas the ordinary NaX zeolite only exhibited considerable activity for couplings of aryl iodides. Furthermore, the mesoporous zeolites were highly active even without the use of an external base cocatalyst (Table 1, entries 1 and 3). Conventionally, C–C coupling reactions were carried out in the presence of base

Table 1: Catalytic properties of Pd^{2+}-exchanged zeolites in Suzuki (entries 1–4), Heck (entries 5–7), and Sonogashira (entries 8, 9) coupling reactions in air. Unless stated otherwise, reactions were carried out without external base cocatalysts.

Entry	Reaction[a]	Pd cat. [mol %]	Temp. [°C]	Time [h]	Conversion [%][b]		
					Mesoporous sodalite	Mesoporous NaA	NaX
1[c]		1.0	80	12	96	95	88
2[c]		0.1	100	24	84	89	45
3		1.0	80	12	95	91	84
4		1.0	80	12	83/4[d]	85/6[d]	27/22[d]
5		1.0	100	3	90/7[e]	92/8[e]	87/8[e]
6		1.0	120	12	86/6[e]	89/6[e]	23/3[e]
7		3.0	120	24	41/4[e]	38/3[e]	5/–[e]
8[f]		1.0	80	12	94	91	83
9[f]		1.0	80	15	84	86	16

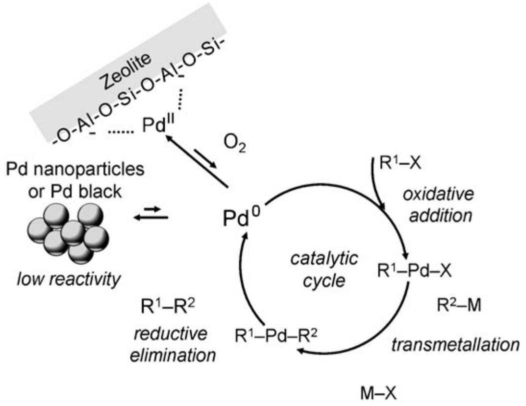
[a] Reaction conditions, unless otherwise stated: aryl halide (2.0 mmol), another substrate (2.4 mmol), DMF/H_2O (3 mL, 1:1 v/v), and Pd catalyst (approx. 0.1–3.0 mol %), Sonogashira reaction was carried out in Cu–free conditions;[26] [b] Yield was determined by GC based on the amount of aryl halide, using *n*-dodecane as an internal standard; [c] with Na_2CO_3 (1.0 mmol); [d] heterocoupling/homocoupling selectivity (homocoupling product is biphenyl); [e] *trans*/*cis* selectivity; [f] DMF/H_2O (3 mL, 4:1, v/v).

cocatalysts, such as Na_2CO_3, K_2CO_3, and K_3PO_4, to increase catalytic activity and neutralize acidic byproducts (HCl, HBr or HI).[1] In the absence of such bases, the homogeneous Suzuki reaction mediated by $Pd(NO_3)_2 \cdot x H_2O$ resulted in a catalytic conversion no greater than 7%. The marked difference in the catalytic activities of $Pd(NO_3)_2 \cdot x H_2O$ and the Pd^{2+}-exchanged zeolites indicates that, in the case of the zeolite catalysts, the catalytic reaction occurred due to the intrinsic basicity of Al-rich zeolite frameworks.[7,27]

In the absence of external base, the mesoporous zeolites exhibited high reusability under the reaction conditions with an aryl halide/Pd molar ratio of 100:1. The initial activity was completely maintained during five recycling experiments (see the Supporting Information, Figure S2), and no leaching of Pd was detected by inductively coupled plasma (ICP) emission spectroscopy. With higher aryl halide/Pd molar ratios, however, excessive generation of acid byproducts (HCl, HBr and HI) caused the destruction of zeolite frameworks, leading to a significant loss of catalytic activity and reusability. The destruction of zeolite frameworks could be prevented by addition of an external base. For example, the mesoporous zeolites were highly active even at an aryl halide/Pd molar ratio of 1000:1, when Na_2CO_3 was added as an external base (Table 1, entry 2). The catalyst also completely maintained catalytic activity during five recycling experiments.

The presence of O_2 in the reaction media played a crucial role in catalyst reusability. When the Suzuki reaction (Table 1, entry 3) was carried out under an N_2 atmosphere instead of air, catalytic conversion gradually decreased to 52% after the 5th cycle (91% in the first cycle).To investigate the role of O_2, the chemical state of Pd in the mesoporous sodalite was analyzed by X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure spectroscopy (EXAFS) studies, before and after the Suzuki coupling (Table 1, entry 3) in N_2 and air. The Pd^{II} zeolite showed exactly the same XANES pattern before and after the Suzuki reaction in air (see the Supporting Information, Figure S3), which was similar to that of $Pd(NO_3)_2 \cdot x H_2O$. According to the EXAFS analysis, no peaks corresponding to the nearest Pd–Pd distance in the metallic state (approximately 2.8 Å) were detected in the radial distribution (see the Supporting Information, Figure S3). This result indicated that the Pd^{2+} ions remained highly stabilized against metal reduction when exchanged onto the zeolitic framework, without agglomeration to Pd^0 nanoparticles. This observation is remarkable, whereas Pd^0 nanoparticles or Pd black (bigger agglomerates) were often detected after reactions in both homogeneous and heterogeneous systems.[6,9,14–18] Contrary to the result in air, the reaction in N_2 produced Pd^0 nanoparticles. The XANES patterns indicated a change from Pd^{II} to Pd^0 states during the reaction, and a distinct peak corresponding to the Pd–Pd distance occurred at 0.28 nm in the radial distribution function. The results indicated that O_2 in air can effectively suppress the reduction of Pd^{II} and subsequent agglomeration into Pd^0 nanoparticles. Bubbling of O_2 in the reaction mixture also stabilized the Pd^{II} state during the Suzuki reaction (Table 1, entry 3), although the catalytic conversion (34%) decreased compared to the reaction in air (95%).

Based on these results, we propose that the catalytic reaction is carried out by a molecular Pd^0 species that is generated in situ under the reaction conditions. The Pd^0 species is immediately re-oxidized into Pd^{II} by O_2, before agglomeration to Pd^0 nanoparticles can take place (Scheme 1). According to this mechanism, O_2 in the reaction medium prevents the formation of less reactive Pd^0 nanoparticles by shifting the equilibrium toward Pd^{II}. The equilibrium seems to be highly shifted toward the Pd^{II} state as a result of the strong electrostatic stabilization of Pd^{2+} ions by the negatively charged zeolite surface. However, an excessively high concentration of O_2 (or O_2 pressure in the gas phase) can suppress the in situ generation of the molecular Pd^0 species, causing decreased activity.



Scheme 1. Proposed reaction mechanism for Pd^{2+}-exchanged zeolite catalysts under aerobic atmosphere.

In this mechanistic consideration, the solubility of the in situ-generated molecular Pd^0 species is a very important issue. Zeolites have long been used by Djakovitch and Koehler for aryl-coupling reactions.[6] In many cases, although Pd is initially supported on the zeolite, it is not clear whether the Pd was leached to solution so that the reactions were catalyzed homogeneously by the dissolved Pd species.[6–9] Traces of soluble Pd were detected in a sufficient concentration to afford catalytic activity. Conversely, the present Pd catalyst seemed to catalyze the coupling reactions in a truly heterogeneous manner. This conclusion was based on the following observations. 1) During the reaction, we removed the Pd-exchanged zeolite by microfiltration and allowed the reaction to continue. The conversion stopped increasing immediately (see the Supporting Information, Figure S4). If a trace amount of soluble Pd species had been the active species, the catalytic conversion should have increased further, even after the removal of the zeolite catalyst. 2) We tested the coupling reactions in the presence of poly(4-vinylpyridine),[28] which is well known as a solid poison to trap homogeneous Pd species in the solution phase through chelation. However, no significant change in catalytic activity was detected (see the Supporting Information, Figure S4). 3) Mesoporous zeolites exhibited much higher activity than the solely microporous NaX zeolite catalyst, especially for reactions involving bulky molecular species. If the reactions were catalyzed by dissolved Pd species, such size-selectivity would be very difficult to explain.

In summary, we have demonstrated that Pd^{2+}-exchanged mesoporous sodalite and NaA zeolite can be used as a highly efficient heterogeneous catalyst for various C–C coupling reactions of bulky aryl compounds. Notably, Pd^{2+} ions exchanged on the zeolite frameworks were highly stabilized against metal agglomeration, maintaining the high catalytic activities during a number of recycles under aerobic environments. It was proposed that the catalytic reactions were carried out by a Pd^0 species, which was generated in situ under the reaction conditions. This species seemed to be immediately oxidized back to the initial Pd^{II} state when the reaction was carried out in the presence of O_2, preventing the formation of Pd^0 nanoparticles. The present strategy, preventing the formation of large Pd nanoparticles using air or O_2, would provide a versatile and economic way to achieve high catalytic activity and reusability, even for other heterogeneous Pd catalysts.

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