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Pillar[5]arene-Based [2]Rotaxane: Synthesis, Characterization, and Application in a Coupling Reaction

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ABSTRACT: Mechanically interlocked molecules are a class of smart supramolecular species because of their interesting topological structure and application in various areas, such as biology and nanoscience. In this work, we used "multicomponent reaction" to fabricate a new [2]rotaxane based on pillar[5]arene from different small-sized molecules. The molecular structure of the obtained [2]rotaxane **R** was confirmed by ¹H and ¹³C NMR, high-resolution electrospray ionization mass spectrometry, two-dimensional nuclear Overhauser effect spectroscopy, and density functional theory studies. Interestingly, the [2]rotaxane-based organometallic cross-linked catalyst (Pd@**R**) was easily constructed via the coordination between triazole groups and Pd(NO₃)₂. Pd@**R** proved to be a good catalyst for the Suzuki–Miyaura coupling reaction with excellent stability and repeatability.

M echanically interlocked molecules (MIMs) are a type of smart supramolecular species because of their interesting topological structure and wide application in biology and nanoscience areas.¹ [2]Rotaxane, which contains a dumbbelllike architecture with a macrocycle sliding along a linear axle, is a popular MIM and can be treated as an ideal candidate for molecular machines and devices. Currently, on the one hand, many well-know macrocycle compounds, such as crown ethers, cyclodextrins, calixar[n]arenes, and cucurbiturils, have been applied as wheel components to fabricate [2]rotaxanes.² On the other hand, various molecular recognition motifs, such as crown ethers/ammonium salts, have been utilized to investigate the [2]rotaxane-based molecular motions.³

Pillar[5] arenes, a new class of "popular" macrocyclic hosts, were designed and prepared by Ogoshi and co-workers in 2008. During the past decade, the synthetic methods, host–guest properties, and applications of pillar[5] arenes have been developed rapidly.⁴ On the one hand, pillar[*n*] arenes possess a more rigid structure than crown ethers and calixar[*n*] arenes, which made a large number of guests suitable for pillar[*n*]-arenes. On the other hand, it is easier to prepare and functionalize pillar[*n*] arenes than cyclodextrins and cucurbiturils. Stoddart and co-workers designed and developed the first pillar[5] arene-based [2] rotaxane in 2011 with pillar[5]-arene as the wheel, 1,8-diaminooctane as the axle, and 3,5-di-*tert*-butylbenzaldehyde as the stopper.⁵

After this pioneer, various types of pillar[5]arene-based [2]rotaxanes have been fabricated by other research groups.⁶ However, when constructing pillar[5]arene-based [2]-rotaxanes, most of the previous methods used a large-sized stopper that reacted with the linear axle (Scheme 1); this significantly restrained the diversity of [2]rotaxanes. Therefore, it is quite necessary to develop a new strategy to fabricate pillar[5]arene-based [2]rotaxanes. Furthermore, the investigation of rotaxane's application has rarely been reported.⁷ In this article, we used a "multicomponent reaction" to fabricate a new

Scheme 1. Classical Large Size Stoppers in Construction Pillar[5]arene-Based [2]Rotaxanes



pillar[5]arene-based [2]rotaxane from different small-sized molecules (Scheme 2a). Interestingly, [2]rotaxane-based organometallic cross-linked catalyst (Pd@R) was easily constructed via the coordination between triazole groups and Pd(NO₃)₂. Pd@R proved to be a good catalyst for the Suzuki–Miyaura coupling reaction with excellent stability and repeatability (Scheme 2b).

The synthetic process of pillar[5]arene-based [2]rotaxane **R** was shown in Scheme 2. At first, the aliphatic chain axle **G** was successfully prepared in two steps. The substitution reaction of dibromohexane and sodium azide was dispersed in dimethyl-formamide (DMF) with tetra-*n*-butylammonium bromide (TBAB) as a phase-transfer catalyst to give the desired diazoalkanes, which in turn reacted with 4-(prop-2-yn-1-yloxy)benzaldehyde according to the copper-catalyzed azide-alkyne cycloaddition (CuAAC) reaction to give the desired axle **G**. As we know, **G** and perethylpillar[5]arene can form a stable complex in a solvent (Figure S13).¹⁰ Then, for the construction of pillar[5]arene-based [2]rotaxane, the traditional threading-stopper method was employed. The mixture



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Scheme 2^{*a*}



"(a) The synthetic route to [2]rotaxane based on pillar[5]arene (**R**) and the chemical structure of compound **1**. (b) Cartoon representation of the formation of Pd@R and its application in the coupling reaction.

of G and perethylpillar[5]arene was stirred in $CHCl_3$ and CH_3CH_2OH at room temperature for 12 h, which enabled the axle to be threaded into the cavity of perethylpillar[5]arene.

Then the three-component reaction, in refluxing ethanol, of dimedone, malononitrile, and benzaldehyde catalyzed by piperidine was applied as the stopper formation reaction. The expected [2]rotaxane **R** was successfully prepared in a moderate yield. The molecular structure of the obtained [2]rotaxane **R** was thoroughly investigated by ¹H NMR, ¹³C NMR, two-dimensional (2D) nuclear Overhauser effect spectroscopy (NOESY), high-resolution electrospray ionization mass spectrometry (HR-ESI-MS), and density functional theory (DFT) studies.

From the ¹H NMR spectra we found that Hb, Hc, Hd, and He in the linear axle of **R** showed obvious upfield shifts $(-\Delta\delta)$ = 0.52-3.03 ppm) compared with those of compound 1 (Figure 1a,b). On the one hand, this phenomenon can be explained by the encapsulation-induced shielding effects. On the other hand, the Hi of wheel pillar[5]arene showed downfield shifts compared with free pillar[5]arene because of the deshielding effects. What's more, Hd and He also located below 0 ppm after being heated in the highly polar solvent deuterated dimethyl sulfoxide (DMSO-d₆) at 75 °C overnight (Figure S2), indicating that the stopper constructed by multicomponent reaction is bulky enough. 2D NOESY NMR spectroscopy also gives credible evidence for the formation of [2]rotaxane. As shown in Figure 2, the 2D NOESY NMR spectroscopy of **R** in DMSO- d_6 showed strong nuclear Overhauser effect (NOE) correlation signals between the pillar[5]arene wheel (Hh, Hi, Hg, and Hf) and the compound 1 axle (Hb, Hc, Hd, and He), indicating that the alkyl chain on the axle penetrated into the perethylpillar[5]aren cavity to form a host-guest complex. Furthermore, the exact mass of the obtained [2]rotaxane was given by HR-ESI-MS (Figure S6). A relative peak was found at 1756.9103, which corresponded to $C_{103}H_{123}N_{10}O_{16}([M + H]^{+})$ for **R**.

To better understand the topological structures of the [2]rotaxane, a theoretical calculation using the density



Figure 1. ¹H NMR spectra (rt, 400 MHz, DMSO-d₆) of (a) compound 1, (b) [2]rotaxane R, and (c) perethylpillar[5]arene.



Figure 2. NOESY spectrum of [2]rotaxane R (rt, 400 MHz, DMSO-d₆).

functional theory for **R** was also performed. As shown in Figure 3, the calculated results gave direct evidence that the aliphatic



Figure 3. (a) Side view, (b) top view, and (c) space-filling view of the calculated structure of **R3** at the B3LYP/6-31G(D) level using the polarizable continuum model in DMSO, where only the hydrogens in question are given for clarity. The gray dashed lines indicate $C-H\cdots\pi$ interactions and H bonds.

chain on 1 was located in the perethylpillar[5]arene cavity to form stable [2]rotaxane. The distances of the C–H··· π and H bonds are from 2.3 to 2.9 Å, which is shorter than 3.05 Å. What's more, the angles of C–H··· π were larger than 90°, indicating the formation of multiple C–H··· π interactions. All the ¹H NMR, 2D NOESY, HR-ESI-MS, and DFT results confirmed the construction of pillar[5]arene-based [2]-rotaxane.

From the structural features of our [2]rotaxane, we can see that there are two triazole units on the axle; the triazole units can act as anchoring sites for metal-based catalysts. Taking **R** as an example, $Pd(NO_3)_2$ was conveniently introduced to form Pd^{2+} -loaded supramolecular polymeric materials through the coordination interaction between the triazole groups and the Pd ions. After the addition of $Pd(NO_3)_2$ into the solution of **R**, polymeric materials (Pd@R) were created immediately. A transmission electron microscopy (TEM) image showed that it was formed by hinges of small particles with a diameter of 50 nm (Figure 4a). Further, energy-dispersive X-ray spectroscopy



Figure 4. (a) TEM image of Pd@R. (b) The corresponding EDX spectrum of Pd@R.

(EDX), powder X-ray diffraction (XRD) analysis, and scanning electron microscopy (SEM) mapping provided direct evidence for the incorporation of Pd in the polymeric materials (Figures 4b, S11, and S12).⁸

With Pd@R in hand, the Suzuki coupling reaction was selected to investigate its catalytic capability.⁹ As shown in Table 1, the catalytic activity of Pd@R is ~95% overnight. What's more, the Pd@R catalyst can be reused for several

 Table 1. Suzuki-Miyaura Coupling Reaction^a Catalyzed by

 Pd Catalysts



^aReaction conditions: Phenyl-OTf (1.00 mmol), 4-boronic acid pyridine (1.50 mmol), K_2CO_3 (2.00 mmol), catalyst (0.50 mol % Pd), DMF (5 mL), 100 °C. Yields were determined by gas chromatography/mass spectrometry (Agilent 1260).

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cycles without any loss of conversion ratio. From the X-ray photoelectron spectroscopy (XPS) analysis, we found that, after the coupling reaction, Pd(II) in the catalyst transformed into Pd(0); however, the Pd(0) particles were still incorporated in the polymeric materials, so after the catalyst was cycled three times, the XPS spectra did not show any changes compared with the catalyst used after the first time (Figure S16). A TEM image also confirmed that Pd(0) particles were incorporated in the polymeric catalyst after three times cycling and that the polymeric catalyst maintained its spherical morphology (Figure S17). Furthermore, different substrates were investigated in the coupling reaction, all giving good yields (Table S2). For comparison, $Pd(NO_3)_2$ and the Pd/compound 1 complex (Pd@1) were also used to catalyze the coupling reaction under the same conditions. On the one hand, it was found that the use of $Pd(NO_3)_2$ instead of Pd@Rcaused the conversion of the coupling reaction to decrease to 30%. Moreover, it is difficult to recover and reuse $Pd(NO_3)_2$. On the other hand, the conversion of Pd@1 as catalyst was ~66% under the same conditions. Although polymeric Pd@Ris nonporous with Brunauer-Emmett-Teller surface area (S_{BFT}) of 8.45 m² g⁻¹ (Figure S18), it is also larger than the surface area of Pd@1. A possible reason for this may be that the existence of the large-sized pillar[5]arene framework inhibits the close stacking of the molecules. What's more, Pd@R can adsorb a decent amount of substrates, indicating it is a good reaction carrier (Figures S15 and S19).

In conclusion, pillar[5] arene-based [2] rotaxane was constructed efficiently via a multicomponent reaction through a "multicomponent reaction". The structure of the obtained [2] rotaxane was characterized by various methods, such as ¹H NMR, ¹³C NMR, NOESY, HR-ESI-MS, and DFT calculation. Moreover, the polymeric materials prepared from Pd²⁺ and **R** through the coordination interaction between the triazole groups and Pd ions were used to catalyze the Suzuki–Miyaura coupling reaction. Compared with Pd(NO₃)₂ and Pd@1, Pd@ **R** showed better catalytic activity and recyclability. We hope the fusion of pillar[5] arene-based [2] rotaxane and metal ions will expand the application in supramolecular polymeric materials in many other areas, such as asymmetric catalysis and organic optical materials.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.inorgchem.0c01752.

Syntheses methods of **R** and **R@Pd**, structure characterization, catalytic property of **R@Pd** (PDF)

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Notes

The authors declare no competing financial interest.

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