A Crystalline Porous Coordination Polymer Decorated with Nitroxyl Radicals Catalyzes Aerobic Oxidation of Alcohols

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S *Supporting Information*

ABSTRACT: A porous coordination polymer (PCP) has been synthesized employing an organic ligand in which a stable free radical, isoindoline nitroxide, is incorporated. The crystalline PCP possesses one-dimensional channels decorated with the nitroxyl catalytic sites. When O_2 gas or air was used as the oxidant, this PCP was verified to be an efficient, recyclable, and widely applicable catalyst for selective oxidation of various alcohols to the corresponding aldehydes or ketones.

Porous coordination polymers (PCPs), assembled from metal ions and organic linkers, have been successfully created as intriguing platforms united with chemistry, physics, and material sciences. The modular synthesis of PCPs with a variety of metal nodes and tunable organic ligands provides their vastly diverse porous structures with desired pore sizes and functionalities[1] directed to various applications such as chemical separation,[2] gas storage,[3] sensing,[4] and catalysis.[5] On the other hand, stable free radicals constantly attract great interest because of their manifestation of polymerization,[6] spin labeling,[7] and organic magnets.[8] It is expected that the combination of PCPs and stable free radicals will afford novel materials with multiple functionalities and extraordinary properties. However, very few PCPs decorated with radicals[9] have been reported because of synthetic challenges, such as the instability of the radicals and the bulky structure of the ligands. To our delight, nitroxyl radicals, which possess the whole radical character with additional catalytic oxidation properties, are very stable and relatively designable. Great efforts have been continuously devoted to the development of nitroxyl radical compounds as homogeneous catalysts for the oxidation of alcohols to their corresponding carbonyl compounds, which is a fundamental and pivotal transformation in organic chemistry.[10] Although impressive advances have been made, there is still plenty of room to develop the ideal catalysts.

As the ultimate goal of catalysis research, the ideal catalysts would be highly active, efficient, recyclable, and environmentally benign with good selectivity and simple workup procedures. This goal is readily realized by rationally designed PCPs incorporated with catalytic sites on the pore surfaces because of their ability to engage the advantages of both homogeneous and heterogeneous catalysts while alleviating their limitations. Several PCPs with unique catalytic properties, including asymmetric catalysis, have been reported to date.[5] Compared with the homogeneous catalysts, the remarkable features of heterogeneous catalysts are that they can be easily isolated by filtration to simplify the workup procedures and their robustness usually enables recyclability. Moreover, in contrast with other immobilized catalytic systems, PCPs bearing large surface areas, uniform pores, and extremely dense active sites generally exhibit good efficiency and selectivity. Their highly ordered crystalline structures can be solved by single-crystal X-ray diffraction (SXRD) and well-characterized, which will benefit further rational designs. Herein we report a new free-radical-decorated PCP (FRPCP) with the formula $[Cu(DPIO)_2(SiF_6)]$, where DPIO is 4,7-bis(4-pyridyl)-1,1,3,3-tetramethylisoindolin-2-yloxyl. The elegant DPIO ligand possesses pyrroline nitroxide in the central moiety as a stable free radical with two 4-pyridyl groups symmetrically placed on two sides to act as linear linkers (Figure 1a). The DPIO ligands are thus periodically integrated into a porous framework and decorate the pore surface with free radicals. The resulting FRPCP featuring large 1D channels catalyzes an efficient, selective oxidation of a variety of alcohols to their corresponding aldehydes or ketones under an O_2 or air atmosphere and mild conditions.

The DPIO pillar ligand was designed and successfully synthesized in five steps starting from the reported 3,6-dibromophthalic anhydride and finally employing Suzuki–Miyaura coupling of a key intermediate, 4,7-dibromo-1,1,3,3-tetramethylisoindolin-2-yloxyl (DBIO), with 4-pyridinylboronic acid [see the Supporting Information (SI)]. Although the total yield was only 9.3%, we were able to obtain DPIO on a gram scale. DPIO was characterized by high-resolution mass spectrometry and SXRD. The length of DPIO calculated from the distance between the two pyridyl nitrogen atoms is 11.4 Å (Figure 1b). Moreover, the radical character of DPIO was probed by electron paramagnetic resonance (EPR) spectroscopy and exhibited a typical three-line signal centered at $g = 2.006$ in CH_2Cl_2 solution (see the SI).

With DPIO in hand, we then used it to build an analogue of the well-known PCPs $[M(4,4'\text{-bipyridine})_2(SiF_6)]_n$ (M = Zn, Cu),[11]
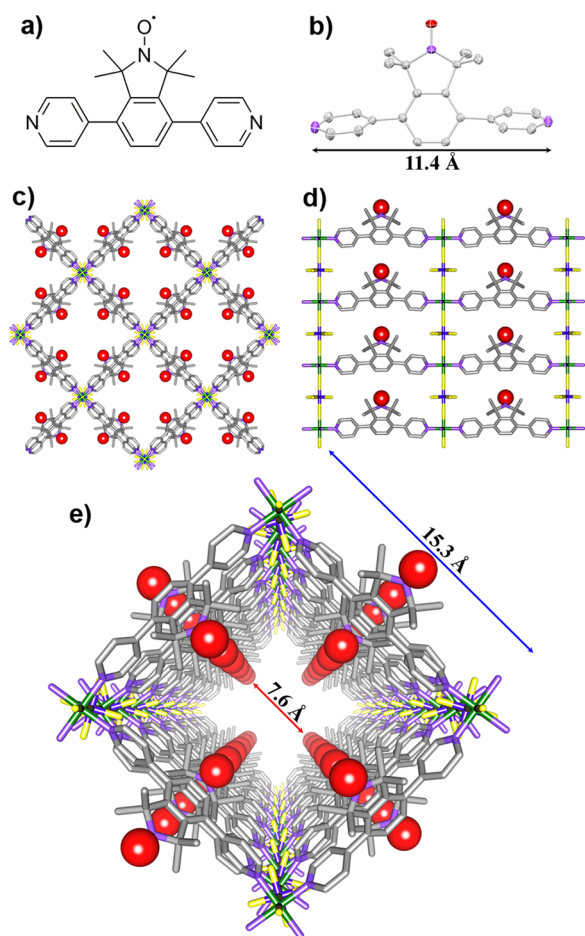
Figure 1. (a) Chemical structure of the DPIO ligand. (b) Crystal structure of DPIO. (c) View of the FRPCP along the c axis (red balls represent O atoms). (d) View of the FRPCP along the a or b axis. (e) View of the 3D porous structure of the FRPCP along the c axis. Atoms: Cu (green), Si (blue), F (yellow), N (purple), O (red), C (gray). H atoms and guest water molecules have been omitted for clarity.

since they usually offer robustness and large 1D channels that are quite appealing for catalytic reactions. Dissolving DPIO in EtOH and layering this solution onto an aqueous $CuSiF_6$ solution afforded the FRPCP as violet single crystals. The crystallographic structure clearly reveals a non-interpenetrated three-dimensional (3D) framework with octahedral coordination of the Cu(II) centers in which each Cu(II) is coordinated by four N atoms of DPIO ligands to generate $[Cu(DPIO)_2]_n$ squares in the ab plane and the squares are axially linked by SiF_6^{2-} groups to provide channels (Figure 1c,d). The channel dimensions calculated from the neighboring Cu atoms linked by DPIO are 15.3 Å × 15.3 Å. As the isoindoline moieties form a dihedral angle of 43.7° with respect to the channel walls, the narrowest cross-section size and its diagonal length considering the van der Waals radii are calculated to be 7.6 Å × 12.4 Å and 14.4 Å, respectively (Figure 1e and Figure S1 in the SI). Thus, with the radical species appended regularly in the pores, the FRPCP possesses 51.5% void space based on PLATON calculations.[12] Interestingly, all of the nitroxyl moieties in this crystal adopt the same orientation along the c axis (Figure 1d). Along the a and b axes, the windows are almost closed by the isoindoline nitroxide groups (Figure S1). The simulated powder X-ray diffraction (PXRD) pattern from SXRD of the FRPCP is in good agreement with that of the freshly obtained crystals and samples activated at 60 °C for 24 h

under high vacuum (Figure S2). Thermogravimetric analysis (TGA) revealed that the guest molecules were completely removed and that the frameworks are stable up to 200 °C (Figure S3).

To investigate the porosity of the activated FRPCP, gas sorption studies of N_2, O_2, and CO_2 were conducted at different temperatures (Figures 2 and S4). All of the isotherms at low
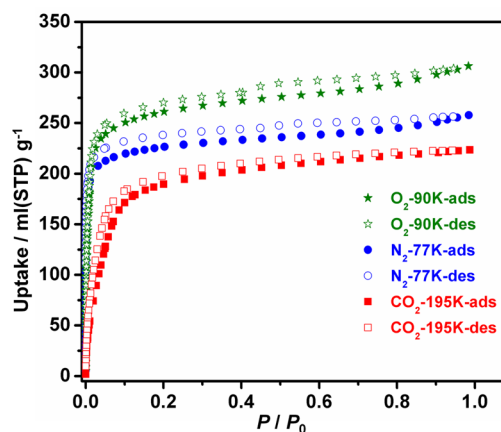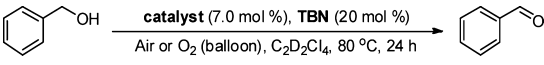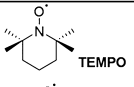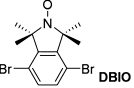

Figure 2. Sorption isotherms of CO_2 (195 K), N_2 (77 K), and O_2 (90 K) on the FRPCP. STP and P_0 denote standard temperature and pressure and saturated vapor pressure, respectively.

temperature are type I, and little hysteresis was observed, suggesting a robust structure and no strong interactions between the nitroxyl radicals and gas molecules. The Brunauer−Emmett−Teller (BET) surface area was calculated to be 822 m²/g from the N_2 gas sorption at 77 K.

The proper structural features, good thermal stability, and extremely high radical density (∼1.8 mol/L) of the FRPCP encouraged us to employ it for catalytic reactions. Among catalytic oxidation systems for the transformations of alcohols to the corresponding carbonyl compounds, the recently reported TEMPO/*tert*-butyl nitrite (TBN) system is prominent because the reaction can be performed under neutral conditions, avoiding general acid or base reagents.[10d] Using similar reaction conditions, we first examined the oxidation of benzyl alcohol. The reactions were carried out in NMR tubes with 3.5 mol % FRPCP (7.0 mol % loading of DPIO ligand) or 7.0 mol % of other catalysts, 20 mol % TBN, and 0.75 mL $C_2D_2Cl_4$ as the solvent under air or O_2 at 80 °C. As shown in Table 1, comparable to TEMPO, our ligand intermediate DBIO also gave a high yield of 96%, indicating the high activity of isoindoline nitroxide (entries 1 and 2). Although using the FRPCP under air afforded a lower yield than DBIO, the yield is still quite impressive (79%) considering that the reaction is heterogeneous (entry 3). Improvement in the yield was achieved by utilizing O_2 gas instead of air (entry 4). It is also noteworthy that the FRPCP gave much higher yields than another heterogeneous catalyst, siliacat@TEMPO, under the same conditions (entries 5 and 6).

To study whether the oxidation occurs inside the pores or only on the outer surface, ground and unground FRPCP samples were used in the catalytic reactions. Typically, if the reaction occurs only on the surface of the crystals, the ground sample should show a much higher yield than the unground sample because the grinding process decreases the particle size, resulting in an increased outer surface area. However, the unground sample with a particle size of ∼1 mm afforded an 79% yield and the ground sample with much smaller particle size showed a comparable

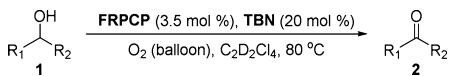**Table 1. Catalytic Oxidation of Benzyl Alcohol under Various Reaction Conditions**[a]

entry	catalyst	oxidant	yield[b]
1[c]	TEMPO	Air	95%
2	DBIO	Air	96%
3	FRPCP	Air	79%
4[d]	FRPCP	O₂	94%
5	Siliacat@TEMPO	Air	44%
6	Siliacat@TEMPO	O₂	80%
7	FRPCP (ground)	Air	80%
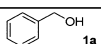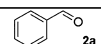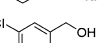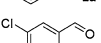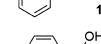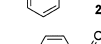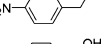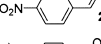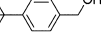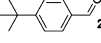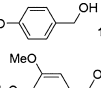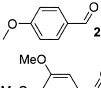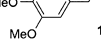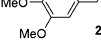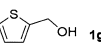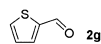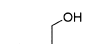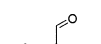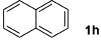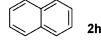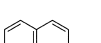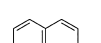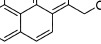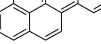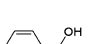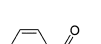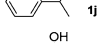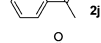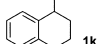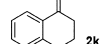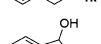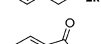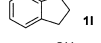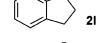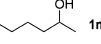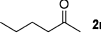
[a]The reactions were performed in an NMR tube with 0.016 mmol of alcohol. [b]Determined by ^{1}H NMR spectroscopy. [c]The reaction time was 12 h. [d]The recycled catalyst gave yields of 86% and 72% in the second and third runs, respectively.

yield of 80%, suggesting that the oxidation reaction primarily occurs in the pores, although partial degradation of the sample upon grinding should be considered (Table 1).

The confinement effect of the FRPCP for catalytic reactions was examined by experiments using different catalyst/substrate (C/S) ratios. At C/S = 1/14, both the FRPCP and DBIO gave almost quantitative conversions (94% vs 96%). When the C/S ratio was decreased from 1/14 to 1/5000, the conversion almost vanished (decreasing from 96% to 0.3%) with DBIO as the catalyst. On the other hand, with FRPCP as the catalyst, the yield decreased, but a 4% yield of product was still obtained (see the SI). The >13 times higher conversion for FRPCP compared with DBIO at the lower C/S ratio suggested that the confinement of the reactants in the nanospace of PCP renders its high reactivity for the catalytic oxidation. Moreover, the catalyst was found to be recyclable. After the reaction was completed, the catalyst was recovered by filtration, and this solid was used for the next run. The three runs gave yields of 94%, 86%, and 72%, respectively. The preserved PXRD pattern of the recovered PCP further confirmed its recyclability (Figure S2). Conversion to the product completely ceased after removal of the FRPCP crystals, indicating that the reactions are catalyzed heterogeneously (Figure S5).

A wide range of alcohols were successfully oxidized to the corresponding carbonyl compounds under the following conditions: 0.016 mmol of alcohol, 3.5 mol % activated FRPCP crystals, 20 mol % TBN, ~1 atm of O₂ (gas balloon), 0.5 mL of C₂D₂Cl₄, 80 °C (Table 2). Substituted benzyl alcohols were easily oxidized to the corresponding aldehydes in almost quantitive yields (entries 2−6). Electron-donating substituents on the phenyl group (i.e., methoxy and *tert*-butyl) accelerated the reaction, while reactions of alcohols with electron-withdrawing groups (e.g., nitro) required longer reaction times. Some other aromatic substrates such as **1g** and **1h** were readily oxidized in excellent yields (entries 7−9). Oxidation of secondary alcohols **1j**−**l** gave yields of 99%, 90%, and 63%, respectively. However, the oxidation of aliphatic alcohols in 4 days afforded lower yields (entries 13−16).

Table 2. FRPCP-Catalyzed Oxidation of Various Alcohols[a]

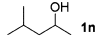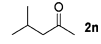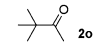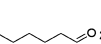| entry	alcohol	product	time	yield[b]
1	1a	2a	24 h	94%
2	1b	2b	44 h	90%
3	1c	2c	30 h	97%
4	1d	2d	12 h	99%
5	1e	2e	12 h	100%
6	1f	2f	3 h	100%
7	1g	2g	24 h	99%
8	1h	2h	24 h	97%
9	1i	2i	24 h	99%
10	1j	2j	24 h	99%
11	1k	2k	24 h	90%
12	1l	2l	24 h	63%
13	1m	2m	96 h	94%
14	1n	2n	96 h	64%
15	1o	2o	96 h	48%
16	1p	2p	96 h	27%
17	1q	2q	8 h	100%
18	1r	2r	24 h	100%
19[c]	1q : 1r (50% : 50%)	2q / 2r	6 h	48% / 33%
20	1s	2s / 2s' / 2s''	8 h	55% / 18% / 19%

[a]The reactions were performed in an NMR tube with 0.016 mmol of alcohol. [b]Determined by ^{1}H NMR spectroscopy. [c]The reactant was a mixture of 0.008 mmol of **1q** and 0.008 mmol of **1r**.

The specificity of PCPs compared with other solid materials is that they host well-defined pores that facilitate size or shape selectivity for the substrates.[13] By the use of PCPs constructed from ligands with catalytic sites, this special selectivity will be grafted onto the reactions. Indeed, higher branched alcohols led to lower yields in the same reaction time catalyzed by our FRPCP (entries 13−15), and the linear benzylic alcohol **1q** is easier to

oxidize than its isomer **1r**, as shown by the reaction using a 1:1 mixture of **1q** and **1r** as the reactant (entries 17−19). To evaluate the chemoselectivity,[10e,f] diol **1s** was subjected to this reaction system, and we found that the primary benzylic alcohol was selectively oxidized over the secondary alcohol (entry 20). All of the primary alcohols were selectively oxidized to their corresponding aldehydes without overoxidation to the carboxylic acids.

One of the advantages of heterogeneous reactions is the easy removal of the catalyst. More than that, our system led to a very simple workup procedure based on the high yield and the volatile side products (i.e., H_2O, t-BuOH). For the oxidation of **1f** as an example, after the reaction, the reaction mixture was filtered to remove the solid catalyst, and all of the volatiles (H_2O, t-BuOH, $C_2H_2Cl_4$) were removed by evaporation under reduced pressure to afford the pure product in 93% isolated yield (see the SI for details). This simple workup procedure is quite appealing to industrial applications.

In summary, using the newly designed free-radical ligand as the organic linker, we synthesized a novel PCP decorated with nitroxyl radicals. The full investigation of this PCP and its application to catalytic reactions proved that this PCP could be a mild, efficient, and recyclable catalyst for selective oxidation of a variety of alcohols to aldehydes or ketones. We envision that these results will provide inspiration for the further design and synthesis of PCPs as ideal catalysts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental details, characterization data, crystal data (CIF), gas sorption isotherms, XRD patterns, and TGA curves. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
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