Cation exchange reversibly switches rotor speed and is monitored by a networked fluorescent reporter†

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Framework 1, a freely rotating turnstile, is transformed by sequential metal ion addition into the coordination-based double-minimum rotors \([\text{M}_2(1)]^{2n+}\) that operate at 8 kHz (\(M = \text{Zn}^{2+}; \ n = 2\)) and 30 kHz (\(M = \text{Cu}^+; \ n = 1\)). In a network with the fluorescent receptor 2, the metal ion exchange at \([\text{M}_2(1)]^{2n+}\) and thus indirectly the rotor speed is reported by distinct fluorescence changes at 2.

Among the many types of molecular devices,1 thermally activated turnstiles2 and rotors3 allow us to study and comprehend the relationship between motion and smart molecular properties,4 as lately demonstrated in catalytic rotary machinery.5 The finding that product inhibition and catalytic activity directly depend on the machine speed5 suggests that one does not need a unidirectional motor for sophisticated effects in catalysis. Such results ask for a more systematic exploration of rotor systems with speed regulation.6

Despite recent advances,6 reversible toggling of rotational speed in rotors needs further exploration, in particular when the course of switching is to be reported by an optical signal. As shown by Hosseini, it is possible to control the motion of turnstiles by addition of metal ions (stop-go) and monitor the process by luminescence changes.2a,2c For instance, in a turnstile containing a bis-pyridyl terminated rotator and a tridentate-appended stator, drastic emission changes in the open vs. closed state (with Ag+ and Pd2+) allowed monitoring of the reversible ON/OFF switching of motion.2b

Implementation of speed regulation in rotors linked with optical monitoring requires matching of two functions in one device at the same time. Due to our expertise in networking devices8 we considered another approach, i.e. to link an external optical reporter to the rotor by chemical signalling. Such protocol constitutes an adaptable toolbox that could be applied to a variety of rotor and optical reporter systems.

Here, we report on a networked system in which the two-state behaviour of rotor 1 that is reversibly regulated from slow to fast motion by addition/exchange of different metal ions is monitored by luminescence changes at a remote receptor 2 (Scheme 1). Our design was guided by the following considerations: intrinsic rotation within the framework 1 occurs about a tolane unit9 and thus should proceed without a sizable barrier as in a typical turnstile. The situation ought to change once metal ions (\(\text{Zn}^{2+}\) or \(\text{Cu}^+\)) ions are added, since the pyridine terminals are expected to bind to the metal-loaded phenanthroline stations via HETPYP-I (HETeroleptic PYridine and Phenanthroline Metal)10 complexation. Now the arm is expected to exchange at defined speed between the two degenerate metal-loaded stations. The luminescent aza-crown ether 2 was designed for communication with 1 as we expected different emission for the free and cation-loaded receptor.

Scheme 1 Communication between nanorotor 1 and reporter 2 upon sequential addition of Zn2+ and Cu+ ions.
Before addressing the precise design (Scheme 1) of the rotor and luminescence reporter, we optimized the involved binding sites by studying various two-step self-sorting events. We observed that the 1 : 1 : 1 blending of the shielded phenanthroline 3, aza-crown ether 4 and 4-iodopyridine (5) in presence of one equivalent of Zn$^{2+}$ (Scheme 2) cleanly furnished the HETPPY-1$^{+}$ complex [Zn(3)]$^{2+}$. In the $^1$H NMR, all phenanthroline protons of 3 were downfield shifted while those of pyridine, e.g. $\alpha$-protons, were moved upfield from 8.25 to 7.78 ppm (Fig. 1a and b). The aza-crown ether 4 remained unaltered attesting a two-fold incomplete$^{11}$ self-sorting. In the second self-sorting, addition of Cu$^+$ triggered a translocation of Zn$^{2+}$ from [Zn(3)]$^{2+}$ to aza-crown ether 4 to furnish [Zn(4)]$^{2+}$, while copper(I) coordinated to phenanthroline 3 (85%). Importantly, as the binding of Cu$^+$ to phenanthroline 3 in CH$_2$Cl$_2$ (log $K = 5.42 \pm 0.10$, see Fig. S63) is stronger than that of Zn$^{2+}$ (log $K = 4.58 \pm 0.58$, see Fig. S64), copper(I) replaced zinc(II) at the phenanthroline binding site of 3 in CD$_2$Cl$_2$ : CD$_3$CN (98 : 2). In the $^1$H NMR all proton signals of phenanthroline 3 were shifted upfield while both aromatic and aliphatic protons of aza-crown ether 4 showed downfield shifts as a result of zinc(II) binding (Fig. 1c). Finally, two equiv. of cyclam were added for removal of Cu$^+$ and Zn$^{2+}$ in order to regenerate the initial state represented by the free ligands 3, 4 and 5 (see NMR, Fig. 1d).

Guided by this model study, the design of the rotor and reporter was finalized (Scheme 1). In scaffold 1 the pyridine arm and shielded phenanthroline stations are covalently connected preventing the possibility of pyridine translocation in presence of Zn$^{2+}$ and Cu$^+$ as in the model self-sorting.

Scaffold 1 was synthesized through a series of Sonogashira couplings in 15 steps and characterized by NMR, ESI-MS and elemental analysis (Scheme 3, ESI†). Characteristic signals in the $^1$H NMR proved the formation of 1, e.g. peaks of the pyridine protons $\alpha$-H and $\beta$-H appeared at 8.57 and 7.44 ppm in addition to distinctive phenanthroline proton signals. The MS peak at $m/z = 1270.8$ showed the expected mass for [1 + H]$^+$. For fluorescence monitoring, the aza-crown receptor in 2 was decorated with an anthracene unit. It was synthesized as described in the ESI† and characterized by spectroscopic methods and ESI-MS. After excitation at $\lambda = 410$ nm, the system 2 showed a bright yellow emission at $\lambda = 552$ nm (vide infra).

Firstly, [Zn$_2$(1)]$^{4+}$ was prepared by mixing 1 and Zn(OTf)$_2$ in a 1 : 2 ratio. Phenanthroline protons 4-H to 8-H shifted downfield owing to zinc(II) ion coordination, while signals of pyridine protons $\alpha$-H broadened and moved upfield, indicating that the zinc(II)-bound pyridine terminal was located in the shielding region of the mesityl groups of the zinc(II) phenanthroline stations (Fig. 2a and b). ESI-MS confirmed the formation by a peak at $m/z = 858.0$ representing [Zn$_2$(1)(H$_2$O)(OTf)]$^{2+}$. Its hydrodynamic radius was calculated to 11 Å by using $D = 4.7 \times 10^{-10}$ m$^2$ s$^{-1}$ from DOSY measurements (the DFT-computed theoretical radius is 9.6 Å). The single set of signals in the $^1$H NMR suggested fast exchange of the pyridine arm between both zinc(II)-loaded phenanthroline stations. The kinetics of motion in [Zn$_2$(1)]$^{4+}$ was determined by a VT $^1$H NMR study from 25 °C to −75 °C in CD$_2$Cl$_2$/CD$_3$CN (80 : 20) (Fig. 3a); the solvent mixture$^{12}$ was required to keep the complex [Zn$_2$(1)]$^{4+}$ soluble. At 25 °C the single set of signals for the phenanthroline protons attested fast exchange,
Table 1 Experimental activation parameters of nanorotors and rotational frequency at 25 °C

<table>
<thead>
<tr>
<th>Nano-rotors</th>
<th>$\Delta H^\ddagger$ (kJ mol$^{-1}$)</th>
<th>$\Delta S^\ddagger$ (J mol$^{-1}$ K$^{-1}$)</th>
<th>$\Delta G^\ddagger$ (kJ mol$^{-1}$)</th>
<th>$k_{25}$ (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\text{Zn}_{2}(\text{II})]^{4+}$</td>
<td>53.4 ± 0.4</td>
<td>9.7 ± 2.0</td>
<td>50.5</td>
<td>8000</td>
</tr>
<tr>
<td>$[\text{Cu}_{2}(\text{I})]^{2+}$</td>
<td>50.4 ± 0.3</td>
<td>9.9 ± 1.2</td>
<td>47.4</td>
<td>30000</td>
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</table>

Table 2 $^1$H NMR shift comparison of some characteristic protons of ligand 1, $[\text{Zn}_{2}(\text{II})]^{4+}$ and $[\text{Cu}_{2}(\text{I})]^{2+}$ (ligand 1 and $[\text{Cu}_{2}(\text{I})]^{2+}$ were measured in CD$_2$Cl$_2$ and $[\text{Zn}_{2}(\text{II})]^{4+}$ was measured in CD$_2$Cl$_2$:CD$_3$CN (96:4))

<table>
<thead>
<tr>
<th>Protons</th>
<th>$\delta$/ppm ligand 1</th>
<th>$\delta$/ppm $[\text{Zn}_{2}(\text{II})]^{4+}$</th>
<th>$\delta$/ppm $[\text{Cu}_{2}(\text{I})]^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-H</td>
<td>8.57</td>
<td>6.56</td>
<td>6.67</td>
</tr>
<tr>
<td>b-H</td>
<td>7.44</td>
<td>7.01</td>
<td>7.10</td>
</tr>
<tr>
<td>c-H</td>
<td>8.49</td>
<td>8.94</td>
<td>8.77</td>
</tr>
<tr>
<td>4-H</td>
<td>7.91, 7.80</td>
<td>8.27, 8.17</td>
<td>8.13, 8.06</td>
</tr>
<tr>
<td>5 and 6-H</td>
<td>8.32</td>
<td>8.87</td>
<td>8.66</td>
</tr>
<tr>
<td>7-H</td>
<td>7.57</td>
<td>7.97</td>
<td>7.90</td>
</tr>
<tr>
<td>9 and 9'-H</td>
<td>6.97, 6.96</td>
<td>6.94</td>
<td>6.96</td>
</tr>
</tbody>
</table>

Fig. 2 Partial $^1$H NMR (500 MHz, 25 °C) of (a) 1 and 2 (1:2 ratio) in CD$_2$Cl$_2$: (b) after ZnOTf$_2$ addition to a: $[\text{Zn}_{2}(\text{II})]^{4+}$ and 2 in CD$_2$Cl$_2$:CD$_3$CN (98:2), (c) after $[\text{Cu}(\text{CH}_3\text{CN})_4]PF_6$ addition to b: $[\text{Cu}(\text{II})]^{2+}$ and $[\text{Zn}_{2}(\text{II})]^{4+}$ in CD$_2$Cl$_2$:CD$_3$CN (98:2), (d) after cyclam addition to c: 1 and 2 in CD$_2$Cl$_2$:CD$_3$CN (98:2) (*: Corresponding proton signals of $[\text{Zn}_{2}(\text{II})]^{4+}$ from which 9% of Zn$^{II}$ was not translocated).

Fig. 3 Partial VT $^1$H NMR (600 MHz) at various temperatures of (a) $[\text{Zn}_{2}(\text{II})]^{4+}$ in CD$_2$Cl$_2$:CD$_3$CN (80:20), (b) $[\text{Cu}_{2}(\text{I})]^{2+}$ in CD$_2$Cl$_2$.

While rotational exchange slowed down visibly at −25 °C. Now two sets of signals emerged for phenanthroline proton 4-H, one resonating at 8.92 ppm for the pyridine

Two sets of signals emerged for phenanthroline proton 4-H, which split into copper(I)-loaded (8.74 ppm) and pyridine protons were shifted upfield upon Cu$^+$ coordination while the pyridine protons were shifted downfield (Table 2). In the ESI-MS a signal at 255, 438 and 458 nm, characteristic of receptor

To test the communication via metal translocation, two equiv. of $[\text{Cu}(\text{CH}_3\text{CN})_4]PF_6$ were added. $^1$H NMR results suggested that 91% of the copper(I) $[\text{Cu}_{2}(\text{I})]^{2+}$ formed while parallel Zn$^{II}$ was translocated to receptor 2 (Fig. 2c). The NMR signals of 2 changed on the way to $[\text{Zn}_{2}(\text{II})]^{4+}$, e.g. proton k-H shifted downfield from 6.71 to 6.87 ppm. At the same time, the UV-vis analysis equally validated that Zn$^{II}$ had translocated to receptor 2 to afford $[\text{Zn}_{2}(\text{II})]^{4+}$ (Fig. 4b), because absorption bands
as rotator, whose rotational barrier at room temperature is estimated as 2.4–2.7 kJ mol$^{-1}$.\textsuperscript{9} Nanorotor [Zn$_2$(1)$^{4+}$], formed upon addition of Zn$^{2+}$, operates at $k_{25} = 8000$ Hz and the Cu$^{-}$-loaded system [Cu$_2$(1)$^{2+}$] rotates at $k_{25} = 30000$ Hz. The three-step transformation of 1 ($\to$10$^8$ kHz) $\to$ [Zn$_2$(1)$^{4+}$] (8 kHz) $\to$ [Cu$_2$(1)$^{2+}$] (30 kHz) was achieved by the sequential addition of zinc(II) and copper(I) ions with the last transformation being monitored by 2 as fluorescence reporter. While the ensemble of rotor [Zn$_2$(1)$^{4+}$] and free receptor 2 exhibited an emission at 552 nm, the addition of copper(I) triggering zinc(II) translocation ($t_{1/2} = 762$ s) to afford receptor [Zn(2)$^{2+}$] shifted the emission to $\lambda = 448$ and 475 nm. Fully reversible ion exchange between 1 and receptor 2 was demonstrated over two cycles, indicating that multifunctional (i.e. rotation & emission) and multicomponent systems work in a reliable and coherent manner.

Fig. 4 Comparison of UV-vis spectra (25 °C, 0.2% CH$_3$CN in CH$_2$Cl$_2$) of (a) 2 and [Zn(2)$^{2+}$] at 5.00 μM, (b) 1 (2.50 μM) + 2 (5.00 μM), [Zn(2)$^{2+}$] and and 1 + 2 + [Cu(cyclam)$^{2+}$] + [Zn(cyclam)$^{2+}$]; comparison of emission spectra (25 °C, $\lambda_{exc} = 410$ nm, 0.2% CH$_3$CN in CH$_2$Cl$_2$) of (c) 2 and [Zn(2)$^{2+}$] at 1.25 μM, (d) 1 (0.625 μM) + 2 (1.25 μM), [Zn(2)$^{2+}$] + 2, [Cu(2)$^{2+}$] + [Zn(2)$^{2+}$] and 1 + 2 + [Cu(cyclam)$^{2+}$] + [Zn(cyclam)$^{2+}$].

Conflicts of interest
There are no conflicts to declare.

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Notes and references


