Homeomorphic Isomerization as a Design Element in Container Molecules; Binding, Displacement, and Selective Transport of MCl$_2$ Species (M = Pt, Pd, Ni)

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S *Supporting Information*

ABSTRACT: The dibridgehead diphosphine $\overline{P}$-$((CH_2)_{14})_3\overline{P}$ (1) can rapidly turn inside-out (homeomorphic isomerization) to give a mixture of *in,in* and *out,out* isomers. The *exo* directed lone pairs in the latter are able to scavenge Lewis acidic MCl$_2$; cagelike adducts of the *in,in* isomer, *trans*-$\overline{MCl_2(P((CH_2)_{14})_3P)}$ (M = **2**/Pt, **3**/Pd, **4**/ Ni), then form. The NiCl$_2$ unit in **4** may be replaced by PtCl$_2$ or PdCl$_2$, but **2** and **3** do not give similar substitutions. U-tubes are charged with CH$_2$Cl$_2$ solutions of **1** (lower phase), an aqueous solution of K$_2$MCl$_4$ (charging arm; M = Pt, Pd), and an aqueous solution of excess KCl (receiving arm). The MCl$_2$ units are then transported to the receiving arm until equilibrium is reached (up to 22 d). When the receiving arm is charged with KCN, transport is much faster (ca. 100 h) and higher K$_2$MX$_4$ equilibrium ratios are obtained ($\geq$96$\leq$4). Analogous experiments with K$_2$PtCl$_4$/K$_2$PdCl$_4$ mixtures show PdCl$_2$ transport to be more rapid. A similar diphosphine with longer methylene chains, P$((CH_2)_{18})_3$P, is equally effective. No transport occurs in the absence of **1**, and other diphosphines or monophosphines assayed give only trace levels.

Figure 1. U-tube apparatus often used to assay guest transport in host/guest chemistry.

A variety of types of "container molecules" have been developed.[1] By definition, they are capable of encapsulating suitable guest molecules, often with objectives such as sequestration or transport/release.[1f] The nature of the container/guest interaction can vary widely, ranging from modest van der Waals forces[1a−e,j] to much stronger covalent bonds.[1h] One means of acquiring transport data involves triphasic U-tube experiments, as illustrated in Figure 1.[2] The container molecule is commonly localized in a lower liquid phase, and the guest molecule equilibrates from an orthogonal liquid phase in one arm to the same phase in the other.

We have described the syntheses and a limited range of reactions of the *in/out* isomers of the dibridgehead diphosphine P$((CH_2)_{14})_3$P (1),[3,4] which feature 30-membered macrocycles. These molecules have a fascinating ability to turn themselves inside out, which has been termed homeomorphism.[5] As shown in Scheme 1, this rapidly interconverts *in,in*-**1** (more stable) and *out,out*-**1** (less stable). Phosphorus inversion, which would initially give *in,out*-**1**, only occurs at much higher temperatures.
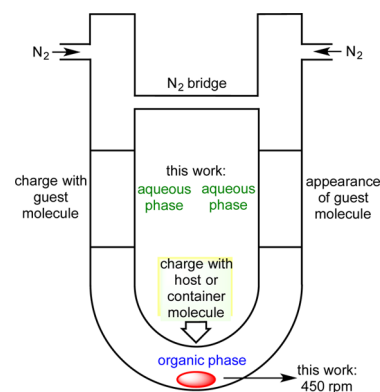
Since the lone pairs are directed in an *exo* sense in *out,out*-**1** and an *endo* sense in *in,in*-**1**, we thought that such diphosphines might be used to scavenge suitable Lewis acids and possibly transport them as payloads to an orthogonal phase. Hence, a proof of principle was sought. Accordingly, in this communication, we report that CH$_2$Cl$_2$ solutions of *in,in*/*out,out*-**1** can transport MCl$_2$ fragments between aqueous phases in U-tubes, and with appreciable selectivities (PdCl$_2$ > PtCl$_2$).

In an initial set of experiments, basic binding properties of *in,in*/*out,out*-**1** were established. As shown in Scheme 1, CH$_2$Cl$_2$ solutions were treated with PtCl$_2$, PdCl$_2$, or NiCl$_2$ (all insoluble in CH$_2$Cl$_2$). Workups gave the corresponding 1:1 adducts *trans*-$\overline{MCl_2(P((CH_2)_{14})_3P)}$ (M = Pt/**2**, Pd/**3**, Ni/**4**) in 93%, 94%, and 68% yields, respectively. The generation of **2** by this route has already been reported.[6] In the case of **3**, this represents a new synthesis of an independently prepared complex.[6] In the case of **4**, this represents a new complex. High yields of **2**−**4** were also obtained when the soluble complexes MCl$_2$(NCCH$_3$)$_2$ were used in place of MCl$_2$. All of these adducts gave distinct ^{31}P NMR chemical shifts, and the new complex **4** was fully characterized as described in the Supporting Information (SI). The crystal structure was also determined. As shown in Figure 2, the "filled container" has a roughly ovoid shape.

To set the stage for transport experiments, equilibrations involving the MCl$_2$ moieties were attempted. First, the Ni
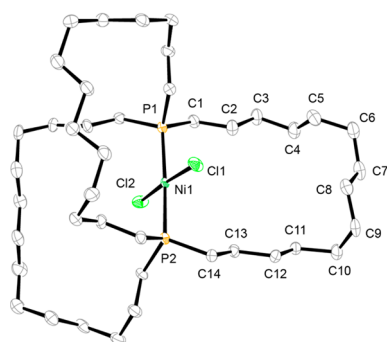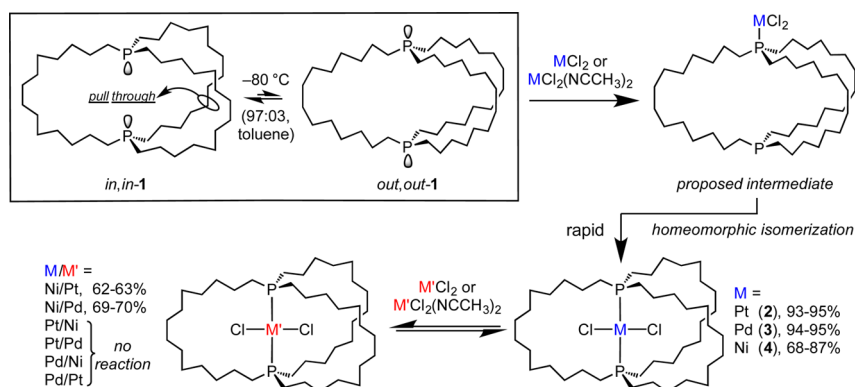
Scheme 1. Dibridgehead Diphosphine 1: *in,in* and *out,out* Isomers and Proposed Mode of MCl₂ Binding

Figure 2. Thermal ellipsoid plot of structure of **4** (50% probability level).

complex **4** was treated either with $PtCl_2$ or $PdCl_2$ (1.2 equiv, CH_2Cl_2, heterogeneous, 5 d) or with $PtCl_2(NCCH_3)_2$ or $PdCl_2(NCCH_3)_2$ (1.2 equiv, THF, homogeneous, 2 d). Workups gave the Pt and Pd complexes **2** and **3** in 62−63% and 69−70% yields, respectively. Analogous experiments were conducted with all other possible combinations of Ni, Pd, and Pt reactants. However, the $PtCl_2$ and $PdCl_2$ moieties in **2** and **3** could not be replaced by any other MCl_2 source. Identical results were obtained when $PdCl_2/PtCl_2$ exchange was attempted in CH_3CN at 70 °C (6 d). Hence, the binding enthalpy of $NiCl_2$ to *in,in*-**1** is lower than those of $PdCl_2$ or $PtCl_2$, but the relative affinities of the last two fragments remain unknown.

Next, attention was turned to the U-tube experiments represented in Figure 3. Thus, 0.246 mmol of *in,in/out,out*-**1** was dissolved in CH_2Cl_2 (40 mL), and 0.361 mmol of a $PtCl_2$
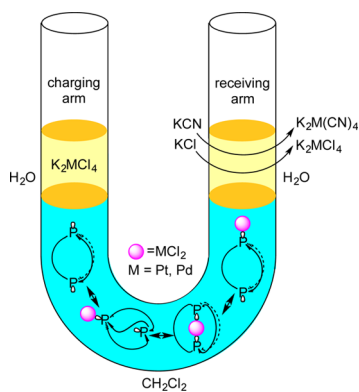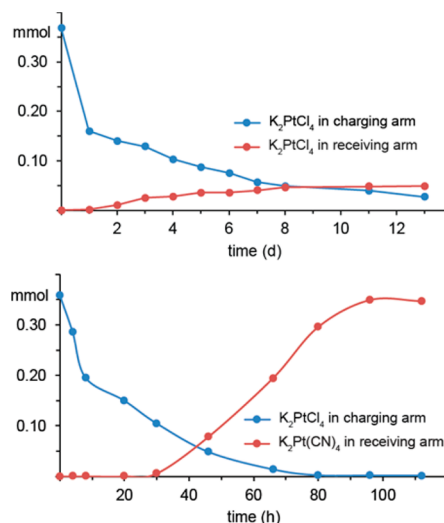

Figure 3. Transport of MCl_2 from aqueous K_2MCl_4 to aqueous KCl or KCN via CH_2Cl_2 solutions of *in,in/out,out*-**1**.

Figure 4. Data for Figure 3. Top: disappearance of K_2PtCl_4 from the charging arm (blue; 0.361 mmol) and appearance of K_2PtCl_4 in the receiving arm (red; 3.68 mmol KCl) using *in,in/out,out*-**1** (0.246 mmol) in the CH_2Cl_2 phase. Bottom: disappearance of K_2PtCl_4 from the charging arm (blue; 0.357 mmol) and appearance of $K_2Pt(CN)_4$ in the receiving arm (red; 3.59 mmol KCN) using *in,in/out,out*-**1** (0.245 mmol) in the CH_2Cl_2 phase.

source, K_2PtCl_4, was dissolved in water (7.0 mL). The former solution was added to the U-tube (bottom), and the latter was added to the charging arm. The receiving arm was loaded with an aqueous solution of KCl (3.68 mmol in 7.0 mL) to regenerate K_2PtCl_4 from the transported $PtCl_2$. Since this represents only a 5-fold excess above the 0.722 mmol needed for complete conversion and a 50:50 equilibrium distribution, there is only a modest "driving force" for transport. Furthermore, the *in,in/out,out*-**1** would be expected to retain an equilibrium quantity of $PtCl_2$ in the CH_2Cl_2 phase.

The CH_2Cl_2 phase was stirred (450 rpm, all experiments), and the slow disappearance/appearance of the K_2PtCl_4 in the charging/receiving arms was monitored by UV−visible spectroscopy as detailed in the SI. As shown in Figure 4 (top), after 1 day there was a drop in concentration in the charging arm roughly equal to the amount of *in,in/out,out*-**1** in the CH_2Cl_2 phase. This suggested the saturation of the host molecules with $PtCl_2$ to give **2**. Subsequently, slow $PtCl_2$ transport to the receiving arm began, with equal concentrations of K_2PtCl_4 realized after 8−11 days. Yet, the low values suggested that the *in,in/out,out*-**1** remained saturated with $PtCl_2$ in the CH_2Cl_2 phase.
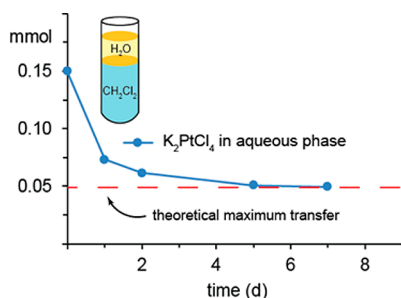
Figure 5. Equilibration of $PtCl_2$ between an aqueous solution of K_2PtCl_4 (blue; 0.150 mmol, 3.5 mL) and a CH_2Cl_2 solution of *in,in/out,out*-**1** (0.101 mmol, 20 mL) in an "I-tube".

To support this hypothesis, an aqueous solution of K_2PtCl_4 (0.150 mmol in 3.5 mL) was layered onto a CH_2Cl_2 solution of *in,in/out,out*-**1** (0.101 mmol in 20 mL) in an "I tube". As can be seen in Figure 5, the K_2PtCl_4 concentration decreased on the same time scale as in the transport experiment in Figure 4. The data indicate that, after 1 and 7 d, >76% and >99% of the *in,in/out,out*-**1** has been converted to **2**, as verified by ^{31}P NMR spectra of aliquots. The expected amount of K_2PtCl_4 (0.049 mmol) remained in the aqueous phase.

The slow time scale in Figure 4 (top) is typical of U-tube experiments.[2] Nonetheless, in the interest of accelerating $PtCl_2$ transport, a stronger driving force was sought. When K_2PtCl_4 and KCN (4.0 equiv) are combined in water, complete conversion to the tetracyanide complex $K_2Pt(CN)_4$ rapidly occurs.[7] The formation constants (log β_4, $\beta_4 = [MX_4^{2-}]/[M][X^-]^4$: $PtCl_4^{2-}$, 16; $Pt(CN)_4^{2-}$, 41)[8] indicate a much higher thermodynamic stability for the latter. Thus, the preceding experiment was repeated, but with the receiving arm charged with an aqueous KCN solution (3.59 mmol in 7.0 mL). As shown in Figure 4 (bottom), over 24 h there was a similar drop in concentration of K_2PtCl_4 in the charging arm. But now transport was faster, with an equal concentration of platinum in the two arms after 43 h. With additional time, all of the platinum was carried from the charging to the receiving arm. No color or detectable amount of **2** (^{31}P NMR) remained in the CH_2Cl_2 phase.

Next, experiments analogous to those in Figure 4 were conducted with the palladium salt K_2PdCl_4 in the charging arm. Although minor differences were evident, transport rates were very close to those obtained with K_2PtCl_4, with both KCl and KCN in the receiving arm (Figure 6). However, similar experiments with K_2NiCl_4[9] did not give any $NiCl_2$ transport, even though the viability of the required intermediate **4** has been unambiguously demonstrated (Scheme 1, Figure 2). The reason appears to involve the facile aquation of $NiCl_2$ to give the very stable blue complex $NiCl_2 \cdot 6H_2O$ (*trans*-$NiCl_2(H_2O)_4 \cdot 2H_2O$).[10]

We wondered whether *in,in/out,out*-**1** might be able to selectively transport one of several MCl_2 species. Thus, the experiments in Figures 4 and 6 were repeated, but with 50:50 K_2PtCl_4/K_2PdCl_4 mixtures. That conducted with KCN in the receiving arm gave the more striking results and is presented in Figure 7 (see Figure s3 (SI) for that with KCl in the receiving arm). After an initial drop in both the K_2PdCl_4 and K_2PtCl_4 concentrations in the charging arm (10 h), the former was much more rapidly consumed, reaching parity with $K_2Pd(CN)_4$ in the receiving arm after 50 h (0.015 mmol) and dropping to <0.003 mmol after 120 h. In contrast, appreciable amounts of K_2PtCl_4 remained in the charging arm after 50–120 h (0.069–0.020 mmol). These trends were mirrored by the $K_2Pd(CN)_4$ and
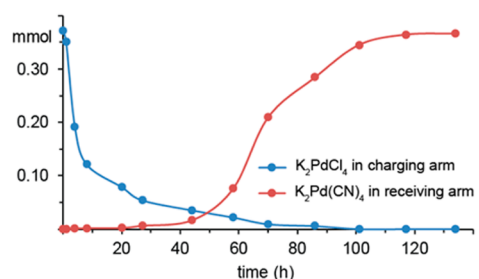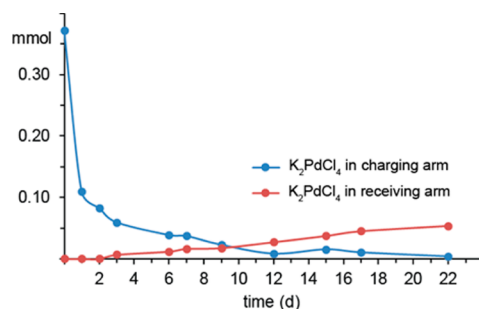

Figure 6. Additional data for Figure 3. Top: disappearance of K_2PdCl_4 from the charging arm (blue; 0.371 mmol) and appearance of K_2PdCl_4 in the receiving arm (red; 3.66 mmol KCl) using *in,in/out,out*-**1** (0.244 mmol) in the CH_2Cl_2 phase. Bottom: disappearance of K_2PdCl_4 from the charging arm (blue; 0.371 mmol) and appearance of $K_2Pd(CN)_4$ in the receiving arm (red; 3.70 mmol KCN) using *in,in/out,out*-**1** (0.244 mmol) in the CH_2Cl_2 phase.
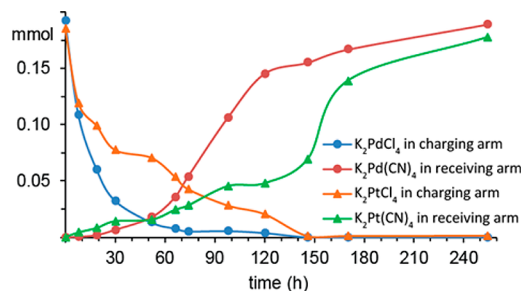

Figure 7. Additional data for Figure 3. Disappearance of K_2PtCl_4 (orange, 0.185 mmol) and K_2PdCl_4 (blue, 0.192 mmol) from the charging arm and appearance of $K_2Pt(CN)_4$ (green) and $K_2Pd(CN)_4$ (red) in the receiving arm (3.67 mmol of KCN) using *in,in/out,out*-**1** (0.243 mmol) in the CH_2Cl_2 phase.

$K_2Pt(CN)_4$ quantities in the receiving arm, with the former greatly dominating at 75–150 h (0.054–0.158 mmol). At 254 h, nearly all of the K_2PdCl_4 and K_2PtCl_4 had been transferred to the receiving arm (98% and 96%). Thus, $PdCl_2$ transport is favored kinetically, in line with the rate trends observed for many substitution reactions.[11]

A final issue concerns the breadth of phosphorus donor ligands that are effective for MCl_2 transport. Can homologues of *in,in/out,out*-**1**, or even acyclic diphosphines or simple monophosphines, behave similarly? First, a dibridgehead diphosphine with four additional carbon atoms in each methylene chain, *in,in/out,out*-$P((CH_2)_{18})_3P$ (*in,in/out,out*-**5**), was similarly synthesized as described in the SI. The types of experiments with K_2PtCl_4 in Figure 4 were repeated. That conducted with KCN in the receiving arm gave the more striking results and is presented in Figure 8 (see Figure s4 (SI) for that with KCl in the receiving arm). Importantly, the time scale and extent of $PtCl_2$ transport are very close to that with *in,in/out,out*-**1**.
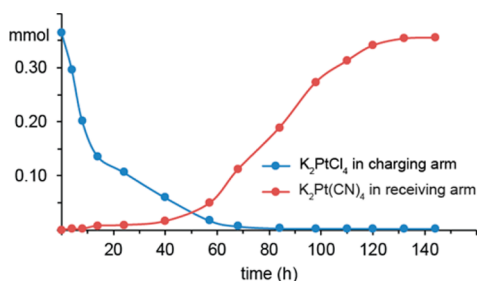
Figure 8. Additional data for Figure 3. Disappearance of K_2PtCl_4 from the charging arm (blue; 0.365 mmol) and appearance of $K_2Pt(CN)_4$ in the receiving arm (red; 3.67 mmol KCN) using *in,in/out,out*-**5** (0.249 mmol) in the CH_2Cl_2 phase.

U-tube experiments were conducted with 1,2-bis(dimethyl-phosphino)ethane (DMPE) and (*n*-Oct)$_3$P. As shown in Figures s5 and s7, no transport was observed after 12 d when KCl was used in the receiving arm, although DMPE did extract an equivalent of PtCl$_2$ into the CH_2Cl_2 phase. When KCN was used in the receiving arm, very low levels of transport could be detected (DMPE, 8% after 12 d; (*n*-Oct)$_3$P, 7% after 12 d (Figures s6 and s8)). In both cases, significant quantities of PtCl$_2$ were extracted into the CH_2Cl_2 phases. Finally, when the amounts of *in,in/out,out*-**1** in the CH_2Cl_2 phases in Figure 4 were decreased, the transport rates also decreased.

As a concluding perspective, we note that container molecules span a diverse range of architectures. Major classes include assemblies derived from H-bonded subunits,[1a−d] and Platonic or Archimedean solids composed of metal-based corners and organic linkers.[1g,i,j] In both cases, encapsulation is achieved by partial disassembly and reassembly. The new host systems reported herein do not require disassembly, but rather incorporate guests by an uncommon dynamic process, homeo-morphism.[3,5] Our data clearly establish the viability of guest transport, together with some thermodynamic (PtCl$_2$/PdCl$_2$ > NiCl$_2$) and kinetic (PdCl$_2$ > PtCl$_2$) selectivity trends. Although the experiments in Figures 3−8 operate on the time scales of hours or days, this is an artificial distinction, as faster rates would be attained at higher temperatures with less volatile solvents. Indeed, container molecules based upon noncovalent bonding are likely to be entropically destabilized at higher temperatures, but the dibridgehead diphosphines *in,in/out,out*-**1** and -**5** are thermally robust. Since potential real world applications for binding and transport of metallic species can involve extreme conditions, this class of compounds has exceptional promise.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b12788.

Experimental details, figures with data from additional U-tube experiments (PDF)
Crystallographic data for **4** (CIF)

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Notes
The authors declare no competing financial interest.

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