Cation-Controlled Olefin Isomerization Catalysis with Palladium Pincer Complexes

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Supporting Information Placeholder

ABSTRACT: A series of palladium(II) pincer complexes with different substituents on the amine donor has been prepared and studied in olefin isomerization catalysis. Installing a macrocycle into the pincer ligand enables cation-switchable positional olefin isomerization: no reaction is observed with the catalyst alone, while in the presence of Li\(^+\) salts isomerization proceeds cleanly. Mechanistic studies implicate a key role of highly electrophilic Pd centers with accessible olefin binding sites in catalysis.

INTRODUCTION

The prevailing strategy for optimizing organometallic catalysts involves synthesizing new ligand–metal combinations with distinct structures until the desired reactivity is found. Just one elegant example of this approach comes from the development of palladium and nickel α-diamine catalysts by Brookhart and coworkers.\(^1,2\) Whereas phenanthroline Pd complexes oligomerize olefins, complexes with more sterically encumbered α-diamine supporting ligands give highly branched polymers.\(^2,3\) When even bulkier ligands are employed, internal olefins are released from the metal center, leading instead to selective positional isomerization to yield 2-alkenes.\(^4\)

An alternative approach to optimizing catalysis involves designing controllable catalysts, with activity or selectivity modulated by external additives.\(^5–7,8,9\) Our group has been developing cation-responsive olefin isomerization catalysts. The iridium catalysts of Scheme 1 feature pincer-crown ether ligands that enable cation-controlled catalysis. An aza-crown ether macrocycle is incorporated into a phenylphosphinite chelate to enable ether oxygen interactions either with the catalytic active site or external cationic additives.\(^8,9\) This approach has been leveraged to achieve on/off switchable and rate-tunable allylbenzene isomerization, wherein salts control rate by modulating the extent of substrate binding (Scheme 1A).\(^10,11\) The positional selectivity of olefin isomerization can also be controlled with similar catalysts, with 2-selective isomerization in the absence of Na\(^+\) salts, but 3-selective isomerization when Na\(^+\) salts are added.\(^12\)

Scheme 1. Previous studies of iridium pincer-crown ether catalysts (A) and current studies of palladium catalysts (B) for olefin isomerization.

A Previous work: Iridium hydride complexes

![Scheme 1: Previous studies of iridium pincer-crown ether catalysts (A) and current studies of palladium catalysts (B) for olefin isomerization.](image)

B This work: Hydride-free palladium complexes

![Scheme 1: Previous studies of iridium pincer-crown ether catalysts (A) and current studies of palladium catalysts (B) for olefin isomerization.](image)
the low Allred-Rochow electronegativity of Pd. We were therefore interested in exploring cation-controlled catalysis based on these strong cation-crown interactions. There is a rich history of catalysis and small molecule activation chemistry mediated by palladium pincer complexes, but surprisingly limited olefin isomerization reactivity. There is, however, extensive literature on alkene isomerization by palladium complexes, including simple salts. We wondered if such reactivity could be controlled through cation-crown interactions, particularly given the likely differences in mechanism of isomerization between iridium complexes and palladium complexes.

Herein we report the synthesis of palladium(II) complexes supported by three different aminophosphinite pincer ligands (Scheme 1B). These complexes are catalysts for double bond positional olefin isomerization, with the crown ether group enabling on/off activity switching with Li$^+$ salts. Mechanistic studies reveal a pathway that is distinct from prior iridium pincer catalysts, featuring highly electrophilic Pd centers that mediate isomerization.

**RESULTS AND DISCUSSION**

**Synthesis of Palladium Complexes.** The target palladium complexes were prepared according to Scheme 2. The three ligands were prepared according to recently reported procedures. The methoxy group in the backbone was selected to prevent unwanted metalation at the site ortho to the phosphinite (para to the amine donor). Refluxing Pd(COD)Cl$_2$ with the ligand produced square planar palladium(II) chloride complexes with tridentate NCOP pincer coordination. The structures are similar to other palladium NCP pincer complexes.

The aza-ether-containing chloride complex ($^{15}$C$_5$NCOP)PdCl, which is closely related to a previously published variant without a methoxy group in the backbone, features a crown ether. The four ether oxygen atoms in the macrocycle could interact with either the Pd center or cationic additives during catalysis, which might enable controlled catalysis. The diethylamine-containing complex has no ethers near the Pd center, so no controlled catalysis would be expected. The bis(methoxyethyl)amine-containing complex also has an acyclic amine but contains two ether groups that could potentially in engage in cation interactions. The structure of ($^{15}$NCOP)PdCl derived from X-ray diffraction of crystals grown from hexanes at $-35$ °C is shown in Figure 1.

**Scheme 2.** Synthesis pincer-crown ether palladium chloride complexes.

![Scheme 2](attachment:image2.png)

**Figure 1.** Molecular structure of one of the two unique ($^{15}$NCOP)PdCl molecules in the asymmetric unit from single-crystal X-ray diffraction, with ellipsoids shown at 50% probability. Hydrogen atoms omitted for clarity. Distances (Å) and angles (°): Pd–P 2.1943(5), Pd–C(Ar) 1.954(2), Pd–N 2.189(2), Pd–Cl 2.3892(6); P–Pd–Cl 101.99(2), Cl–Pd–N 95.36(5), N–Pd–C(Ar) 82.30(8), C(Ar)–Pd–P 80.45(7)

Prospective catalysts for olefin isomerization were targeted next. Hypothesizing that an accessible olefin binding site would be needed, the chloride ligand
was removed to produce a series of cationic complexes with weakly bound ligands trans to the phenyl backbone.

When crown-ether-containing palladium halide complexes ($^{15}$C-NCOP)Pd(X) were treated with salts of sodium, potassium, thallium, or trityl cation in an attempt to abstract the halide, spectroscopic studies supported either partial conversion or salt interactions without halide abstraction. The use of AgPF$_6$ did lead to full conversion to a new species assigned as [κ$^4$-($^{15}$C-NCOP)Pd][PF$_6$] based on high-resolution mass spectrometry. However, persistent silver impurities hampered purification.

**Scheme 3.** Synthesis of cationic palladium complexes.

An alternative route to cationic palladium complexes was devised based on silylum salts as halide abstractors. As shown in Scheme 3, treating ($^{15}$C-NCOP)PdCl with [Et$_3$Si][B(C$_6$F$_5$)$_3$]$_4$-$^{31}$-$^{33}$ (generated in situ from Et$_3$SiH and [Ph$_3$C][B(C$_6$F$_5$)$_3$])$^{33}$ produced [κ$^4$-($^{15}$C-NCOP)Pd][B(C$_6$F$_5$)$_3$]$_4$ as a white powder in 80% yield, following pentane washes and passage through a short alumina column to remove Ph$_3$CH, Et$_3$SiCl, and other impurities.

The use of a slight excess of silylium proved critical. Utilization of less than one equivalent [Et$_3$Si][B(C$_6$F$_5$)$_3$]$_4$ resulted in formation of a distinct species with broad $^1$H NMR signals. The same species was produced upon mixing equimolar amounts of neutral ($^{15}$C-NCOP)PdCl and the cationic [$^{15}$C-NCOP]Pd][B(C$_6$F$_5$)$_3$]$_4$ in CD$_2$Cl$_2$. Based on this result and comparisons with other pincer complexes in the literature,$^{29,34}$ we tentatively assign this species as the mono-halide-bridged dipalladium complex [{κ$^3$-($^{15}$C-NCOP)Pd}$_2$-µ-Cl][B(C$_6$F$_5$)$_3$] (Scheme 3).

With a tractable halide abstraction strategy in hand, cationic complexes with varying amine donors were sought. Treating the diethylamino-substituted complex (Et$_2$N)PdCl with [Et$_3$Si][B(C$_6$F$_5$)$_3$]$_4$ and Et$_2$O in PhCl produced a mixture of three species according to $^1$H NMR and $^3$P[$^1$H] NMR spectroscopy (Scheme 3). The major ion peak by ESI-MS was the three-coordinate cation [(Et$_2$N)Pd]$^+$, suggesting the presence of weakly coordinating ligands such as Et$_2$O or PhCl. Reactions with the strong donor ligand acetonitrile confirm the presence of labile ligands: addition of ca. 100 equiv acetonitrile converted the mixture to [(Et$_2$N)Pd(NCCH$_3$)]$^+$ as a single well-defined species assigned as the cationic acetonitrile complex. The mixture was therefore considered a suitable precatalyst based on the presence of easily displaced ligands, and was used without purification.

Treating (BME)NCOP)PdCl with [Et$_3$Si][B(C$_6$F$_5$)$_3$]$_4$ produced the cationic complex [(BME)NCOP]Pd][B(C$_6$F$_5$)$_3$]$_4$ in 73% yield, Scheme 3. The solution molecular symmetry of [(BME)NCOP]Pd$^+$ is $C_s$, consistent with rapid exchange between the bound and free oxygen donors. The same behavior was observed for nickel pincer-crown ether complexes.$^{35}$

**Cation-Controlled Isomerization of 1-hexene.** Positional isomerization of olefins was examined using the three cationic palladium complexes. Palladium complexes have long been recognized as active catalysts for olefin isomerization.$^{36}$ In many cases, no hydride ligand is needed in the precatalysts, in contrast to the NCOP iridium hydride catalysts we previously studied for cation-controlled isomerization. We hypothesized that cation-crown interactions could still gate substrate access to the Pd center, regardless of the specific mechanism of isomerization. The double-bond positional isomerization of 1-hexene was monitored by $^1$H NMR spectroscopy. Standard conditions called for 5 mM Pd (1.7 mol%), 5 mM
LiBAR$_4^+$3Et$_2$O, 70 mM Et$_2$O, 300 mM 1-hexene, and 50 mM mesitylene internal standard at 25 ºC.

5 mM Pd catalyst + 5 mM LiBAR$_4^+$
70 mM Et$_2$O
50 mM mesitylene int. std.
CD$_2$Cl$_2$, 25 ºC

The run was monitored using different batches of catalyst revealed moderate variance in rates (TOF = 1.37±0.60 h$^{-1}$ for 5 data sets under identical conditions). Time-normalized kinetic analysis showed good overlays, however, consistent with a robust catalyst (Figure S25).

These results demonstrate cation control over isomerization. No activity is apparent except when LiBAR$_4^+$ is included as an additive. In comparison to the previously studied NCOP iridium catalysts, the Pd catalyst is slower in the absence of Li$^+$ (no detectable activity), but also in the presence of Li$^+$.

The diethylamine-substituted catalyst [(5$^{\text{t}}$NCOP)Pd][B(C$_6$F$_5$)$_4$] was explored next. With no oxygen donors on the amine group capable of binding to the Pd center, we expected the catalyst to be active for isomerization even in the absence of salts. Indeed, isomerization of 1-hexene proceeded smoothly over 15 h without salt additives (TOF 8.1 h$^{-1}$). In the presence of one equivalent of LiBAR$_4^+$, isomerization of 1-hexene proceeded slightly slower (TOF 5.7 h$^{-1}$). The rates of isomerization by [(1$^{\text{c}}$NCOP)Pd]$^+$ and [(1$^{\text{t}}$c$^{\text{t}}$NCOP)Pd]$^+$ in the presence of LiBAR$_4^+$ are very similar. It is not clear why LiBAR$_4^+$ addition modestly decelerates the isomerization reaction. Although the Li$^+$ salt contains Et$_2$O, experiments with additional Et$_2$O did not show signs of inhibition (Figure S28).

Finally, isomerization was also examined with the bis(methoxyethyl)amine-based catalyst [k$^4$-(BME-NCOP)Pd]$^+$. The run-to-run variations in kinetic profile were more pronounced with this catalyst in the absence of salts, so those conditions are omitted. The catalyst was better behaved when LiBAR$_4^+$ was present, with uncertainty in TOF derived from initial rates in the presence of salts gave TOF = 0.59±0.28 h$^{-1}$ (Figure S27). It is striking that the rate is almost

Figure 2. Isomerization of 300 mM 1-hexene catalyzed by [(1$^{\text{c}}$c$^{\text{t}}$NCOP)Pd][B(C$_6$F$_5$)$_4$] (A), [(5$^{\text{t}}$NCOP)Pd][B(C$_6$F$_5$)$_4$] (B), and [(BME-NCOP)Pd][B(C$_6$F$_5$)$_4$] (C) with no salt additive (empty symbols) and with 5 mM LiBAR$_4^+$ (filled symbols).
within error of the crown-containing complex, despite the expectation of weak interactions between Li$^+$ and the methoxyethyl groups. In the relatively nonpolar and noncoordinating chlorinated solvent, however, some degree of ion-dipole interactions must still be present. In support of this notion, treating [κ^4-(BME NCOP)Pd(NCCH_3)]\(^+\) LiBar\(^{F_4}\) resulted in NMR changes consistent with a host-guest interaction in CD_2Cl_2 (Figure S31).

The catalytic studies show that the catalyst with a crown ether group is the only one capable of switchable behavior, with two different states of different activity. The diethylamino-based catalyst was highly active but not controllable, as expected.

**Probing the Mechanism of Isomerization.** The two primary mechanisms of positional isomerization of olefins are (A) the “π-allyl” mechanism, in which an allylic C–H bond is activated to form an η^3^-allyl π-complex; and (B) the “insertion-elimination” mechanism, in which a Pd–H intermediate facilitates olefin 1,2-insertion and α-hydrogen elimination. Electrophilic cationic palladium salts have been proposed to isomerize via formation of a bound carbocation that is readily deprotonated to enter the π-allyl pathway.\(^{37,38}\)

In situ monitoring revealed no evidence for a palladium(II) hydride intermediate, and there is no obvious way for hydride to form. Thus, the insertion-elimination pathway was considered unlikely. Instead, an electrophilic mechanism is consistent with a variety of experimental observations.

**Scheme 5.** Proposed mechanism of olefin isomerization.
allylbenzene produced β-methylstyrene initially, followed by formation of a range of products that included cycloaluminized indenes (Scheme 4C). The olefin cis-stilbene was employed as a mechanistic probe (Scheme 4D). Because it has no allyl C–H bonds, it cannot form a η3-allyl complex. Yet, nearly complete conversion to trans-stilbene was observed when pure cis-stilbene contacted [(BME NCOP)Pd]⁺.

We propose that stilbene coordination leads to a significant contribution from the carboxylation resonance form, leading to free rotation and cis/trans isomerization. Indeed, the mechanisms for stereochemical and positional isomerization may well be different, with an η3-allyl involved in the latter but not the former. Positional isomerizations would commence from the same coordination step, which would render allylic protons acidic enough for facile deprotonation to form the key η3-allyl complex intermediate.

Scheme 5 summarizes the proposed mechanisms for stereochemical and positional isomerization. These align with earlier proposals for dicationic Pd salts.37,38 The presence of carboxylation intermediates may explain the sensitivity of these reactions to impurities or other run-to-run differences. Control reactions containing LiBARt but omitting the Pd complex resulted in no detectable reaction after one week at room temperature, supporting the notion that Pd and Li⁺ work synergistically.

CONCLUSIONS

The cationic palladium pincer-crown ether complex [(15c5 NCOP)Pd]⁺ exhibits cation-controlled reactivity with alkenes. In the absence of Li⁺, no reaction is observed, while isomerization of 1-hexene to internal olefins occurs upon addition of a Li⁺ salt. Other alkenes react in a manner indicative of carboxylation intermediates, producing oligomers, polymers, or Friedel-Crafts-type cyclization products. The cationic palladium centers with weakly bound ligands are proposed to be sufficiently electrophilic to build up carboxylation character. The amine ligand may also serve to facilitate proton transfer reactions.

Comparisons can be made between the new palladium catalysts and previously studied pincer-crown ether iridium catalysts. The iridium catalyst contains a hydride ligand and proceeds via an insertion/elimination mechanism for positional isomerization. In contrast, the palladium catalyst appears to proceed via an electrophilic π-allyl mechanism. Substrate binding to the metal center is essential in each catalyst, however, and the pincer-crown ether ligand enables cation control over substrate binding in each system. A key difference is that the palladium catalyst shows no activity without salts, whereas the iridium catalyst slowly isomerizes olefins even without additives. This could be due to stronger binding of the crown ether oxygens by the more electrophilic Pd center.

ASSOCIATED CONTENT

Supporting Information
Experimental details, NMR spectra and crystallographic details (PDF).

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How does supporting ligand structure influence cation switchable catalysis?