


# Mechanistic Studies of SCS-Pd Complexes Used in Heck Catalysis

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**Abstract:** Air-stable SCS palladacycles that can be used to promote C–C coupling chemistry were studied mechanistically. Using a small library of electronically varied SCS ligands, a collection of palladacycles was synthesized. Kinetic studies showed that these complexes all had induction periods, induction periods that were effected by concentration of substrates, products and trace impurities. Hammet correlations showed that electronically diverse palladacycles had identical  $\rho$  values, values that suggested that aryl halide electrophilic addition to a Pd species was not the rate-determining step. Phosphine addition experiments led to increased reactivity of the starting palladacycles, possibly by trapping an *in situ* generated Pd(0) species. Studies that examined reactivity in biphasic thermomorphic reactions showed residual activity in phases that do not contain polymer-bound

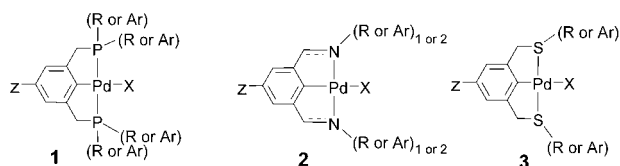
palladacycle and provided convincing evidence that palladacycles are not the actual catalyst. Poisoning experiments using mercury metal to test for the presence of a Pd colloid were very effective with low molecular weight palladacycles, completely suppressing Heck chemistry. Similar studies with polymer-bound palladacycles showed mercury poisoning too. However, since so little decomposition of the palladacycle occurred, the polymer-bound palladacycle could still be recycled multiple times. However, mercury poisoned subsequent cycles of the experiment too. The conclusion is that SCS palladacycles are actually reservoirs of a catalytically active but ill-defined form of palladium(0).

**Keywords:** C–C coupling, Heck reaction, homogeneous catalysis, mechanism, metallacycles, palladium

## Introduction

Pincer complexes of various transition metals have been of interest in organometallic catalysis and synthesis<sup>[1–5]</sup> and in materials chemistry.<sup>[6]</sup> Palladacycles are the palladium subset of this larger group of metallacycles and have been used to promote Pd-catalyzed cross-coupling reactions.<sup>[7]</sup> Palladium pincer compounds are characterized by a metal-carbon bond and two coordinating heteroatoms that chelate the metal in a cyclic fashion (e.g., **1–3**). The most common heteroatoms are P, N, and S. The SCS palladacycles discussed here were first described by Shaw<sup>[8]</sup> and they and their N- and P-substituted analogues have emerged as an interesting, actively investigated family of organometallic complexes that have been used as a palladium source for various catalytic reactions.<sup>[7,9–12]</sup> The mechanistic studies below focus on a limited subset of these complexes, the so-called SCS-Pd pincer complexes that have two sulfur atoms of a bis(benzyl thioether) chelating the carbon-bound palladium. Our interest in these compounds grew out of our work developing strategies for recovering and re-

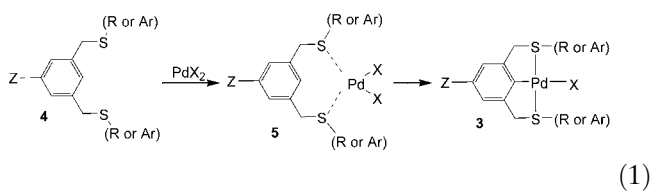
cycling catalysts<sup>[13,14]</sup> and from the initial observations that these SCS-Pd compounds like their PCP analogues exhibit improved oxygen and thermal stability compared to more common phosphine-ligated Pd(0) complexes that are used as sources of Pd for Heck catalysis.<sup>[2,6,10,11]</sup> We subsequently used these SCS-Pd complexes covalently bound to various soluble polymer supports in Pd-catalyzed cross-coupling reactions.<sup>[15–18]</sup> In these studies, the SCS-Pd species behave like palladium catalysts – the covalent polymer-bound palladium species are recovered quantitatively and can be reused in multiple reaction cycles. However, while metal analyses of product solutions in these systems have generally failed to detect leaching of Pd, such studies do not distinguish between the SCS-Pd species serving as a molecular catalyst or as a precursor of some unknown Pd species that is the actual active catalyst. Indeed, there is evidence that suggests that these metallacycles like other bi- and tridentate Pd complexes are catalyst precursors and not catalysts themselves and that Pd(0) species are the actual catalysts.<sup>[10b,12,19–26]</sup> This work includes studies of SCS palladacycles by our group and by the Jones and



Weck groups<sup>[19,20]</sup> as well as mechanistic studies of similar PCP-Pd complexes.<sup>[21]</sup> Together these studies provide convincing evidence that these SCS palladacycles and other palladacycles are neither the catalytically active species nor a reversibly formed rest state of an active catalyst for Heck catalysis but rather a precursor of another undefined but quite active catalyst.

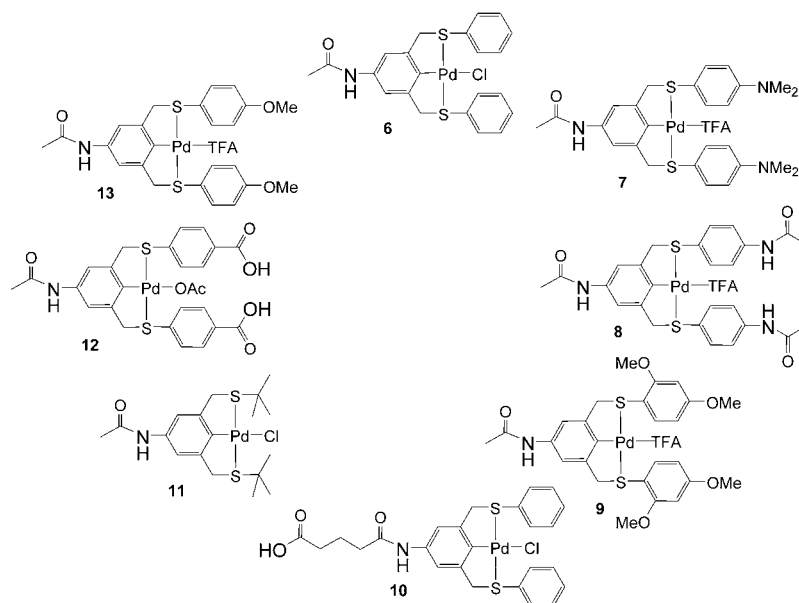
## Results and Discussion

We prepared a variety of palladacycles (Figure 1) from a bisbenzyl thioether *via* an S,S-Pd(II) coordination complex (**5**) [Eq. (1)] using chemistry like that used in earlier work.<sup>[8,10]</sup>



The resulting SCS-Pd complexes were shown to promote Heck reactions of aryl iodides but were less effective with aryl bromides. If the palladacycle formation

were complete (i.e., if there was no coordination complex **5** present), the S-aryl SCS palladacycles (**6**, **7**, **8**, **9**, **10**, **12**, or **13**) could be used in Heck chemistry without formation of any visible palladium black. If the coordination complex were present as a mixture with the palladacycle or if the coordination complex itself were used, palladium black invariably formed. In certain cases,<sup>[10a,22]</sup> palladium black also formed from a palladacycle too. While it is difficult to exclude the presence or involvement of low levels (<10%) of the coordination complex in any reaction promoted by an SCS-Pd complex, our success in multiple recycling of SCS-Pd complexes that were bound to soluble polymers<sup>[15–17]</sup> and our failure to effect similar recycling of S,S-Pd coordination complexes bound to the same polymers suggests that the catalytic activity seen in any of these reactions is not due solely to these S,S coordination complexes or the products of S,S coordination complex decomposition. Heck chemistry with aryl bromides was confined to complexes **8**, **9**, **11**, and **13** and was typically seen only with activated bromoarenes. Table 1 lists the results of these studies. Higher loadings of palladacycles **8**, **9** and **13** in the presence of 50 mol % of tetrabutylammonium bromide using K<sub>2</sub>CO<sub>3</sub> as a base were also successful in complete conversion of bromobenzene to a Heck product although the reaction times were long. These results contrast with the reported activity of PCP-Pd complexes<sup>[11a]</sup> and indicate either that those species generate a different actual catalyst or that they react in some different manner. Reactivity of a palladium species only toward activated aryl halides has been suggested by Du Pont to be evidence for Pd(0) colloidal catalysis in reactions promoted by palladium complexes.<sup>[26]</sup>



**Figure 1.** Electronically diverse SCS palladacycles prepared using metallation of an S,S-Pd(II) coordination complex [Eq. (1)].

**Table 1.** Heck reactions of aryl bromide with various palladacycles.<sup>[a]</sup>

Aryl Bromide	Palladacycle	Time [h]	Yield [%] <sup>[b]</sup>
4-(NO <sub>2</sub> )-C <sub>6</sub> H <sub>4</sub> -Br	<b>8</b>	5.5	92
	<b>9</b>	4	96
	<b>10</b>	4	90
4-(CN)-C <sub>6</sub> H <sub>4</sub> -Br	<b>8</b>	4	89
	<b>9</b>	5	86
	<b>10</b>	14	81
4-(CH <sub>3</sub> CO)-C <sub>6</sub> H <sub>4</sub> -Br	<b>8</b>	26	70
	<b>9</b>	28	72
	<b>10</b>	36	63
C <sub>6</sub> H <sub>5</sub> Br	<b>8</b>	51	100 <sup>[c]</sup>
	<b>9</b>	25	100 <sup>[c]</sup>

<sup>[a]</sup> These reactions were carried out using 0.1 mol % of the SCS-Pd complex at 120 °C in DMF using Et<sub>3</sub>N as the base.

<sup>[b]</sup> These yields are isolated yields.

<sup>[c]</sup> These yields are GC conversions based on aryl bromide from reactions at 140 °C using DMF as the solvent and K<sub>2</sub>CO<sub>3</sub> as the base in the presence of 50 mol % of Bu<sub>4</sub>NBr.

### Mechanistic Investigations

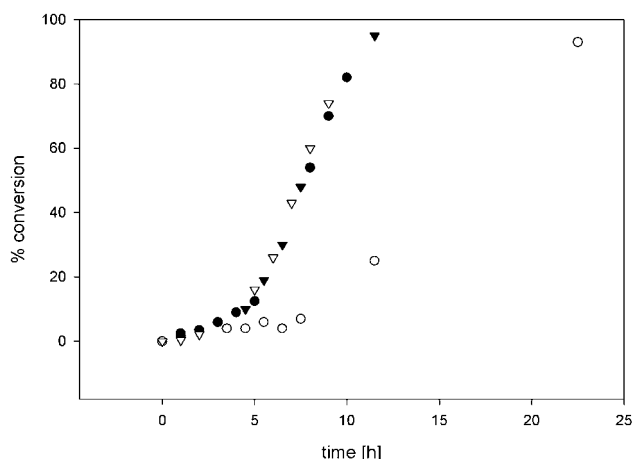
The development of palladacycles including the SCS palladacycles described above and their effective use in Pd-catalyzed C–C bond forming reactions has led to a growing interest in the mechanism by which these organometallic complexes catalyze coupling reactions.<sup>[27–34]</sup> This interest was heightened by the suggestion that a mechanism involving a Pd(II)–Pd(IV) cycle could supplement the textbook Heck mechanism involving a Pd(0)–Pd(II) cycle. In the most simplistic view, substituting the Pd(0) catalyst with a Pd(II) in a palladacycle like the SCS-Pd species discussed here would mean that the Pd center is oxidized to Pd(IV) during the reaction. Pd(IV) complexes are known and have been extensively studied by Canty's group,<sup>[35]</sup> and the rather high activity of some members of the palladacycle family made the possibility of a different mechanism seem possible even for the SCS palladacycles described above. However, irreversible or reversible formation from these palladacycles of a Pd(0) species that is the actual active catalyst has never been excluded. Indeed, many examples where a Pd(II)–Pd(IV) cycle was suggested have been shown to instead involve reduction of the initial Pd(II) complex during the reaction to a Pd(0) species. For example, Bohm and Herrmann have reported a study in which they compared a dimer, phosphine-based palladacycle with a phosphine-ligated Pd(0) counterpart<sup>[33]</sup> and concluded that the two catalysts behave similarly enough to preclude a Pd(IV) intermediate. The actual catalyst formed from the palladacycle was not defined.

The utility of soluble polymer-supported SCS palladacycles in Heck, Suzuki and Sonogashira reactions and the fact that mechanistic role of these SCS palladacycles

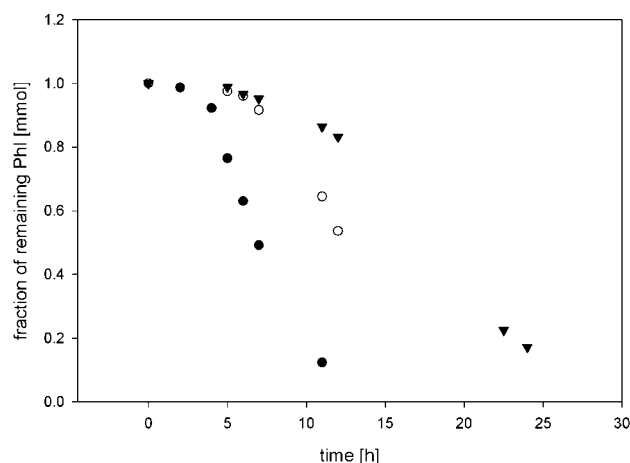
was still speculative prompted us to perform our own investigations into how SCS palladacycles function in these catalytic reactions.<sup>[19]</sup> We hoped to show that the SCS species are molecular catalysts as it would be more satisfying to be recycling a molecular catalyst rather than a catalyst precursor. However, we recognized that while we could recover up to 99.9% of the charged 0.1–1.0 mol % Pd introduced as an SCS-Pd soluble polymer bound species, very high Pd recovery does not mean that SCS-Pd compounds themselves are the catalysts. Given the range of electronically varied palladacycles above, we reasoned that these species would have differing reactivities in the Heck reaction – reactivities that might allow us to probe the nature of the actual catalyst to determine if these SCS-Pd species are molecular catalysts, species that reversibly generate a molecular catalyst, or merely novel repositories of a precursor form of some unspecified but highly active homeopathic Pd(0) catalyst.

One approach to study whether the original SCS-Pd compound was actually a catalyst or merely a catalyst precursor would be to recover the SCS-Pd compound and determine if the trifluoroacetate group (or the chloride group) had exchanged with iodide formed in these Heck reactions. However, most of our experiments used relatively low amounts (often 0.1 mol %) of the SCS palladacycle to promote the reaction, so this was not practical. The only case where this issue was studied was an example where 10 mol % of the SCS palladacycle **9** was used in a reaction to form methyl cinnamate from iodobenzene and methyl acrylate. In that instance, examination of the product by <sup>1</sup>H NMR spectroscopy showed changes (upfield shifts in the aryl methoxy groups and the aryl C–H signals) that suggested that the recovered palladacycle was not the starting trifluoroacetate. However, we did not unambiguously show that this palladacycle product was in fact the expected iodide exchange product.

To study the effect of electronically different *S*-aryl groups on Heck chemistry, we carried out Heck reactions under pseudo-first order conditions using 2 mmol of iodobenzene, 20 mmol of methyl acrylate, and 20 mmol of Et<sub>3</sub>N, using 0.001 mmol of an SCS palladacycle at 100 °C. Aliquots were removed at regular intervals (0.5–1 [h]) and analyzed by GC. Reactions were run with palladacycles **6** (*S*-phenyl), **7** [bis(dimethylamino)], **8** [bis(acetamido)], and **12** [bis(benzoic acid)]. Plotting the conversion of PhI vs. time showed remarkable similarity between the first three complexes (Figure 2). The graphs overlap quite well indicating that the electronics of the ligand do not significantly affect the reaction. The exception to this trend was the reaction using the bis(dimethylamino) palladacycle **7**. This reaction converted iodobenzene to product more slowly than the other palladacycles. We speculate that this may be a result of reaction of the nucleophilic dimethylamino groups with the Heck acceptor which is an alkylating agent, chemis-



**Figure 2.** Conversion vs. time using various SCS palladacycles. ▼ bis(*S*-phenyl) **6**; ○ bis(dimethyl amino) **7**; ▽ bis(acetamido) **8**; ● bis(benzoic acid) **12**.



**Figure 3.** Comparison of induction periods using differing amounts of PhI. ● 1 mmol of PhI; ○ 2 mmol of PhI; ▼ 5 mmol of PhI.

try which could affect the palladacycle or palladacycle decomposition in a complex way.

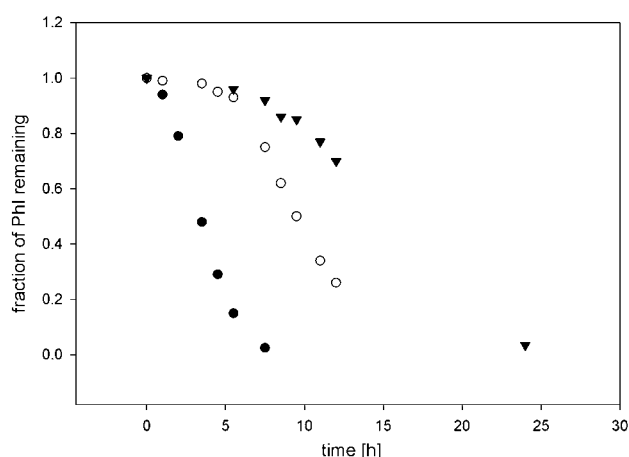
The kinetic data shown in Figure 2 also show that there is an induction period in these reactions. The conversion of iodobenzene to product is slow for the first 15–20% of the reaction and then increases. After the first reaction reached completion, a second portion of reagents was added. This second cycle did not exhibit an induction period. The presence of an induction period when using palladacycles has been reported by others. Pfaltz and Blackmond investigated a dimeric, nitrogen-based palladacycle,<sup>[33,34]</sup> and observed an induction period with this complex and with the dimeric phosphine palladacycle previously synthesized by Herrmann.<sup>[36,37]</sup> Similar results were noted by Gladysz in his studies of a recyclable Pd species that was also a Heck catalyst precursor rather than a catalyst.<sup>[24]</sup> However, the presence of an induction period does not provide definitive evidence that the palladacycles are decomposing as the presence of an induction period could indicate that the complex is altered in some minor fashion to provide the actual catalyst or it could indicate that a species is generated in the reaction that acts as an accelerant.

We performed several experiments to test the effect of substrates and other additives on reaction rates and induction periods. For example, we varied the amount of either iodobenzene or acrylate in the reaction. Three reactions were set up for each experiment. In three vials 1 mmol, 2 mmol, and 5 mmol of PhI were each combined with 20 mmol of methyl acrylate and 20 mmol of Et<sub>3</sub>N. The *S*-phenyl SCS palladacycle **6** (0.001 mmol) was added and the reaction mixtures were heated at 100 °C. Aliquots were removed periodically and analyzed by GC. The data from these experiments (Figure 3) showed that the reaction containing 1 mmol of PhI had the shortest induction period while the reaction containing 5 mmol of PhI had the longest induction pe-

riod. A similar experiment studied differing acrylate concentrations using three reactions with a constant 2 mmol of PhI, 20 mmol of Et<sub>3</sub>N, 0.001 mmol of the palladacycle **6**, and either 2.2 mmol, 5 mmol, or 20 mmol of methyl acrylate added. As these reactions were monitored, the reaction with the smallest excess of methyl acrylate had the shortest induction period while the reaction with the largest excess of methyl acrylate exhibited the longest induction period (the Figure for this experiment is provided in the Supporting Information). A third set of experiments probed the effect of other trace species on the reaction rate.

These experiments were prompted by Pfaltz and Blackmond's investigations of dimeric, nitrogen-based palladacycles<sup>[33,34]</sup> where they observed a longer induction period in the presence of added water. We performed similar experiments using 2 mmol of PhI, 20 mmol of methyl acrylate, 20 mmol of Et<sub>3</sub>N and 0.001 mmol of palladacycle **6** in 10 mL DMF with 0.5 mL of water, adventitious water from the DMF solvent, or with predried solvent (drying over molecular sieves for 24 h). Interestingly, the 'wet' reaction had the shortest induction period and the 'dry' reaction had the longest induction period, indicating that the catalyst formation step is sensitive to the amount of water present (Figure 4). The reasons for the effect of aryl iodide, acrylate or water on the induction period are not clear to us. One possibility is that the aryl iodide or acrylate might be coordinating to the SCS-Pd species, preventing it from forming the actual more active catalyst. Water then would have to be promoting the formation of the actual active catalyst.

The data above could be explained by decomposition of the SCS palladacycle to form the active catalyst. However, there are alternative explanations that are consistent with these data that do not require the palladacycle to decompose to form another unspecified catalyst. For



**Figure 4.** Comparison of induction periods with varying amounts of water. ● 'wet'; ○ 'normal'; ▼ 'dry'.

example, Shaw<sup>[31,32]</sup> envisioned a possible pathway where the olefin first coordinates to the Pd center and a nucleophile then attacks the olefin, forming a palladium-alkyl complex. Shaw proposed that the increased electron density of this newly formed complex facilitates the oxidative addition of the aryl halide. This mechanism provides possible explanations for both the observed induction period and the accelerating effect of water. The induction period could be the product of the generation of iodide, a potential nucleophile. In the early stages of the reaction, the concentration of iodide is low. As the reaction progresses, the concentration of iodide increases, facilitating the formation of the palladium-alkyl complex until a limiting concentration of iodine is reached. Water could also serve as a nucleophile, thereby explaining the shortened induction period in the presence of water.

We tested this idea using a set of experiments where tetrabutylammonium iodide was added. If the chemistry proceeded according to Shaw's mechanism, the added iodide should eliminate or greatly reduce the induction period. Three reactions were set up using 2 mmol of PhI, 20 mmol of methyl acrylate, and 20 mmol of Et<sub>3</sub>N in the presence of 0.001 mmol of *S*-phenyl palladacycle **6**. The first reaction was performed without additives, the second with 10 mol % (relative to the aryl iodide) of Bu<sub>4</sub>NI, and third with 20 mol % of Bu<sub>4</sub>NI. The reactions with added Bu<sub>4</sub>NI exhibited increased induction periods (see Supporting Information Figure 2). There was little difference in the induction periods for the two reactions containing differing amounts of Bu<sub>4</sub>NI. All three reactions eventually went to completion. The extended induction period in the presence of added iodide was inconsistent with Shaw's mechanism. Crabtree's group has reported a similar experiment in which they added NaF to a Heck reaction catalyzed by a bis-carbene, pincer-type palladacycle.<sup>[38]</sup> They reasoned that if fluoride nucleophilically attacked the olefin, the strong C–F

bond would prevent the subsequent elimination of halide that is part of Shaw's mechanism. They did not detect fluoride-containing products and they also concluded that fluoride does not attack the olefin during the reaction.

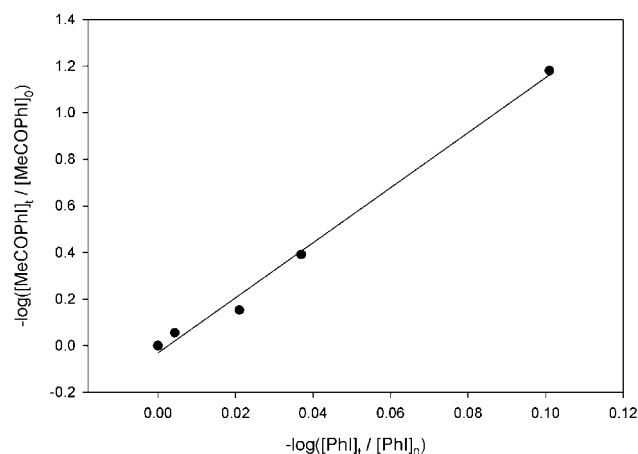
We also considered the possibility that acid generated during the reaction might in some way be accelerating the reactions. In reactions like those described above, 0, 10, or 20 mol % of concentrated HCl was added (HCl was chosen instead of HI because HI has a tendency to liberate I<sub>2</sub> and it was unclear how the presence of iodine might affect the reaction). Like the reactions in which Bu<sub>4</sub>NI was added, the reactions containing added HCl showed longer induction periods compared with the reaction containing no additives. These experiments with added iodide or protons suggest the species generated during the Heck reaction are probably not assisting the reaction and that the nucleophilic assistance described by Shaw is not part of the catalytic cycle. Why the induction period is affected by the presence or absence of additives is not clear. However, the notion that the SCS-Pd species is not the actual catalyst but rather is decomposing under Heck reaction conditions to form the actual catalyst is the simplest explanation of these experiments.

### Using Substrates as Mechanistic Probes

We studied the reactivity of different aryl iodides in Heck reactions promoted by different SCS palladacycles in the hope that Hammett plots would provide useful information. These competition experiments were performed in two ways.<sup>[39]</sup> In the first method, a substituted iodoarene like iodoacetophenone and iodobenzene (2 mmol each) were combined in a flask containing 20 mmol of methyl acrylate and 20 mmol of base. The reaction was carried out using 0.002 mmol of a palladacycle at 100 °C. Periodically, aliquots were removed from the reaction and analyzed by GC. The fraction remaining of each iodoarene was calculated at each time interval. The reaction was run until the one of the iodoarenes was completely consumed. Then the log of the calculated fraction of iodoarene at each time interval was plotted against the log of the fraction of iodobenzene at the same time interval, producing a straight line (Figure 5). The slope of that line is the relative reactivity of the iodoarene vs. iodobenzene. Separate reactions were performed using iodoacetophenone, iodotoluene, and iodoanisole and relative reactivities were determined in each reaction.

The second method combined all four iodoarenes in the same reaction. The amount of each iodoarene was reduced to 1 mmol to maintain a total of 4 mmol of iodoarene in the reaction. The other parameters were identical as those described above. In this method, the reaction was allowed to continue until the iodobenzene





**Figure 5.** Plot derived from competition experiment between iodobenzene and iodoacetophenone.

had been consumed. The fractions remaining for each iodoarene were calculated and the data for iodoarenes were plotted against that for iodobenzene. This method provided equivalent results as those obtained by the previous method but shortened the amount of time necessary to collect all the data.

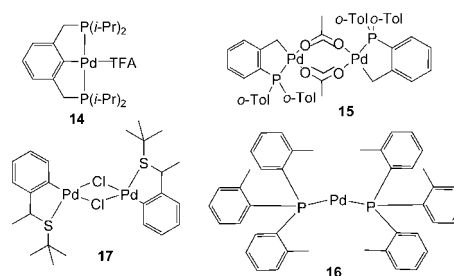
The reactivity ratios measured in these experiments were used to construct Hammett plots using both  $\sigma$  and  $\sigma^-$  substituent constants. Good linearity was achieved when using  $\sigma$  values ( $r^2=0.96$ ) but a better fit was obtained using  $\sigma^-$  values ( $r^2=0.99$ ). This small difference may indicate that a direct resonance interaction exists between the *para* substituent and the reactive center. The slope of both graphs was positive, indicating that electron-withdrawing groups facilitate the reaction. The value of  $\rho$  for the plot derived using  $\sigma$  values was 1.86 while a value of 1.2 was obtained using  $\sigma^-$  values. In a similar way, reactivity ratios were determined using bis(dimethylamino) SCS **7** and bis(*tert*-butyl) SCS **11** (Table 2). The reaction constants for Heck reactions using these Pd species were identical to the reaction constant measured for reactions using **6**.

These  $\rho$  values are comparable to those obtained by other groups. Milstein<sup>[11a]</sup> reported a  $\rho$  value of 1.39 vs.  $\sigma$  values for the reaction of aryl iodides catalyzed by tridentate PCP palladacycle **14**. Herrmann<sup>[27]</sup> reported a  $\rho$  value of 1.58 vs.  $\sigma^-$  values with aryl bromides using bidentate phosphapalladacycle **15**. In the same article, he reported that a tri-*o*-tolylphosphine ligated Pd(0) catalyst **16** produced a  $\rho$  value of 1.01 (vs.  $\sigma^-$  values) for the same substrates. Using bidentate sulfur-based palladacycle **17**, Dupont<sup>[10e]</sup> reported that in a competition experiment iodoacetophenone, iodobenzene, and iodoanisole are converted to their corresponding cinnamate products in a ratio of 7:2:1, respectively. This result translates to a Hammett plot with a  $\rho$  of 1.13 vs.  $\sigma$  values. Our results are thus consistent with similar catalysts. The  $\rho$  values obtained are different from phosphine-ligated

**Table 2.** Reactivity ratios obtained with various SCS palladacycles.<sup>[a]</sup>

Aryl iodide	<b>7</b>	<b>6</b>	<b>11</b>
iodoacetophenone	11.8	12.4	11.5
iodobenzene	1	1	1
iodotoluene	0.67	0.66	0.69
iodoanisole	0.56	0.59	0.62

<sup>[a]</sup> In these experiments, 4 mmol of an iodoarene mixture was allowed to react with 20 mmol of methyl acrylate and 20 mmol of triethylamine base in the presence of 0.002 mmol of the indicated SCS palladacycle at 100 °C. Aliquots were periodically removed from the reaction and analyzed by gas chromatography.



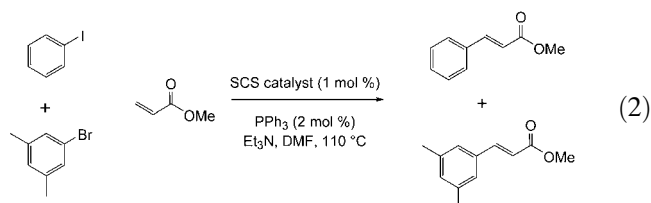
Pd(0) catalysts, suggesting that the palladacycle catalysts are not the same. The values obtained here also do not seem to be high enough to indicate that the oxidative addition of the aryl halide is the rate-determining step. Milstein's group studied the addition of aryl chlorides to a Pd(0) catalyst ligated with bidentate phosphines.<sup>[40]</sup> They performed competition experiments with substituted aryl chlorides and obtained  $\rho$  values of approximately 5, so showing that the oxidative addition of the aryl chloride is rate-determining. The observation that palladacycles do not exhibit a similar  $\rho$  value casts doubt on the oxidative addition step being rate determining.

### Added Phosphine Experiments

To test the possibility that the organometallic compounds simply act as 'reservoirs' of Pd(0) species like those present in phosphine ligated Pd(0) catalysts, we carried out a Heck reaction using iodobenzene and 3,5-dimethylbromobenzene in the presence of methyl acrylate and triethylamine.<sup>[41,42]</sup> *S*-Phenyl palladacycle **6** was used as the Pd source and 2 equivs. (relative to the palladacycle) of triphenylphosphine were also added. If a Pd(0) species were formed, we reasoned that the phosphine could coordinate to the Pd(0), forming a catalyst that is active for the coupling of aryl bromides and acrylates. Since the SCS complex used does not convert 3,5-dimethylbromobenzene to a Heck product, any observed conversion of the aryl bromide would be evi-

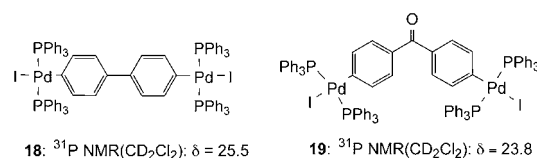
dence for phosphine-ligated Pd(0) formation due to decomposition of the starting SCS palladacycle.

The reaction was performed under nitrogen using 0.5 mmol of each aryl halide, 1.1 mmol of methyl acrylate in DMF at 110 °C in the presence of SCS palladacycle **6** (1 mol % relative to total aryl halide), PPh<sub>3</sub> (2 mol %) and Et<sub>3</sub>N (1.1 mmol) [Eq. (2)]. The reaction was monitored by GC. As the reaction was followed, the iodobenzene was consumed but the 3,5-dimethylbromobenzene remained untouched. The bromoarene was not converted to the cinnamate product over the course of 94 h. However, using the *S*-*t*-Bu SCS palladacycle **11**, we did observe some conversion of the aryl bromide. Approximately 15% of the 3,5-dimethylbromobenzene was consumed in 16 h when **11** was used as the Pd source. The formation of some 3,5-dimethylbromobenzene-derived product using a phosphine ligand with SCS palladacycle **11** is consistent with earlier observations that this palladacycle is not stable under the conditions of Heck catalysis.<sup>[10a,25]</sup>



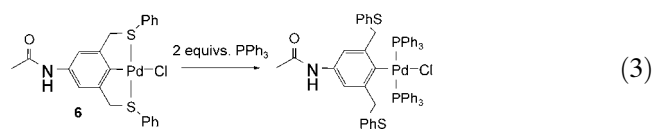
Although conversion of 3,5-dimethylbromobenzene was not observed in the experiment using *S*-phenyl palladacycle **6**, it is possible that the amount of Pd(0) formed (and consequently the concentration of a PPh<sub>3</sub> ligated Pd species) was too low to affect detectable conversion of 3,5-dimethylbromobenzene in a reasonable amount of time. We therefore repeated this experiment using the bulky ligand, tri(*tert*-butyl)phosphine. Palladium catalysts using this phosphine are active enough to convert aryl chlorides even at room temperature,<sup>[43]</sup> so we reasoned that this phosphine would be more sensitive test of Pd(0) formation. Using the previously defined conditions and *S*-phenyl palladacycle **6**, P(*t*-Bu)<sub>3</sub> was substituted for PPh<sub>3</sub>. In contrast to the reaction above, this experiment did show a 10% conversion of 3,5-dimethylbromobenzene to a Heck product in 14 h.

While these experiments with added phosphine ligands provide additional support to the notion that SCS-Pd complexes are catalyst precursors, the observations above are complicated by the fact that added phosphine is not an innocent spectator in the presence of a palladacycle. Shaw's group had earlier noted that PPh<sub>3</sub> coordinates to the palladium center of an SCS complex.<sup>[8]</sup> van Koten has also shown that unmetallated PCP ligands can react with metallated NCN complexes in a *trans*-cyclometallation reaction.<sup>[8,44]</sup> During this reaction, the nitrogen ligands of the NCN complexes are displaced by the phosphorus atoms of the PCP ligand,



and ultimately the metal center is transferred from the NCN moiety to the PCP ligand.

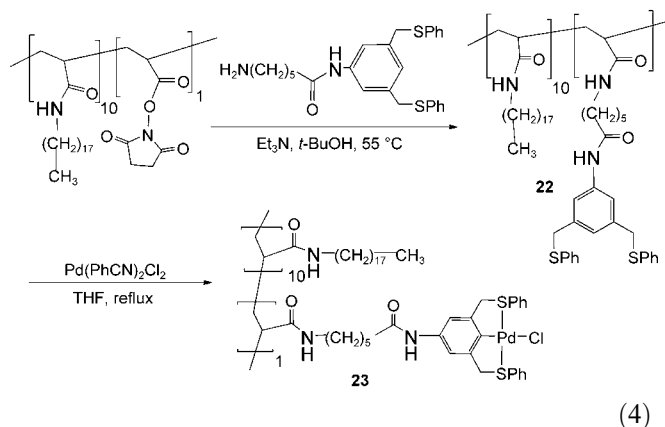
Since the reaction of an added phosphine with the SCS palladacycles would confuse the simple suggestion that phosphines like Ph<sub>3</sub>P or (*t*-Bu)<sub>3</sub>P trap an SCS palladacycle Pd(0) decomposition product, we dissolved the *S*-phenyl SCS palladacycle **6** in DMSO-*d*<sub>6</sub> along with 2 equivs. of PPh<sub>3</sub> and studied the resulting mixture by NMR spectroscopy. A <sup>1</sup>H NMR spectrum of this sample showed that the signal corresponding to the benzyl protons had moved from  $\delta = 4.8$  to  $\delta = 4.1$  ppm. The signal assigned to the amide N-H at  $\delta = 9.85$  was shifted upfield to  $\delta = 9.4$ , and the acetamido CH<sub>3</sub> signal moved from  $\delta = 2.0$  to  $\delta = 1.95$  ppm. Two peaks were seen in the <sup>31</sup>P NMR spectrum – one at  $\delta = 26.6$  and one at  $\delta = 23.1$ . One peak is likely triphenylphosphine oxide. The second peak's chemical shift is similar to the shifts observed by Stang<sup>109</sup> for the phosphine aryl-palladium complexes **18** and **19**. Given that PPh<sub>3</sub> evidently reacts with the palladacycle **6**, we cannot unambiguously conclude that the phosphine addition experiments really do show that Pd(0) formation is occurring. It is instead equally possible that added phosphine is displacing the sulfur atoms and coordinating to the Pd center [Eq. (3)] to form a pseudo-PCP catalyst that reductively eliminates to unintentionally form a phosphine-ligated Pd(0) species that in turn converts 3,5-dimethylbromobenzene to Heck products.



Although the above experiments all suggest that SCS palladacycles decompose to form some other Pd species that is the actual catalyst in cross-coupling reactions promoted by SCS-Pd palladacycles, each experiment has an alternative explanation. Since we have not been able to unambiguously detect Pd colloids or identify some other species as the actual catalyst,<sup>[25]</sup> we sought to develop other experiments that might more definitively show that SCS palladacycles on polymer supports are not the actual catalysts. These experiments involved using biphasic studies of polymer-supported SCS palladacycles where the actual catalyst has a lower phase selective solubility than the polymer-bound SCS palladacycle catalyst precursor or where the phase separability of the polymer-bound SCS palladacycle from heterogeneous Pd(0) colloid traps [Hg(0)] allowed us to show that recy-

cled palladacycles generate species whose activity is poisoned by elemental mercury.

These experiments used the polymer-bound ligands **20** and **22** and the polymer-bound SCS palladacycles **21** and **23**. Such species have been used by us previously in Heck catalysis<sup>[15–18]</sup> and are accessible by chemistry like that shown in Eq. (4). The studies below were carried out in a thermomorphic system of heptane and 90% DMA.<sup>[45,46]</sup>

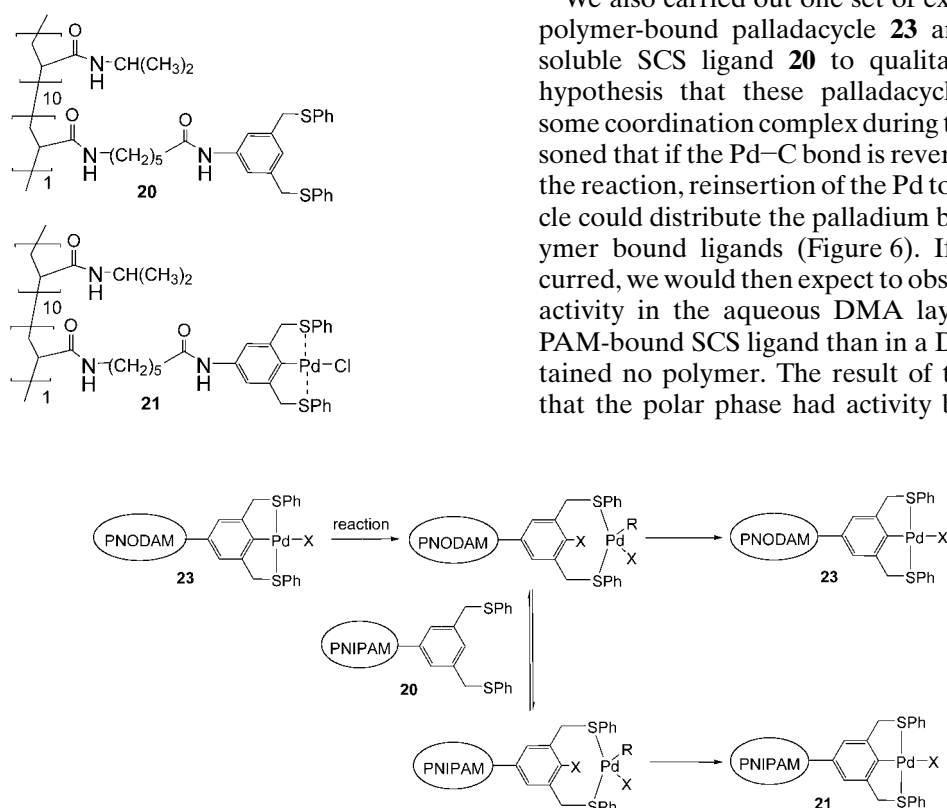


Aqueous DMA was used to avoid solubility problems observed with the PNIPAM-SCS system. In this system, PNODAM polymers are exclusively (> 10,000:1) solu-

ble in the heptane-rich phase at 25 °C. In contrast, PNIPAM polymers are exclusively (> 10,000:1) soluble in the DMA-rich phase at 25 °C.<sup>[47]</sup>

In the first experiment, the PNIPAM-SCS-Pd species **21** (0.2 mol %) was used in a Heck reaction of iodobenzene and methyl acrylate (100 °C, 6 h, Et<sub>3</sub>N as the base). After the iodoarene was consumed, the hot single phase reaction mixture was cooled to form a biphasic mixture. The top heptane-rich phase was shown to have < 0.1 ppm Pd (ICP analysis). Furthermore, addition of fresh substrates to this phase and heating led to no Heck chemistry. A second experiment was then carried out with the same substrates using PNODAM-SCS-Pd **23** (0.2 mol %) as the Pd source. Again, Heck chemistry occurs in the thermomorphic mixture (6 h for complete conversion of iodobenzene). On cooling, the polar DMA-rich phase was isolated and analyzed for Pd. Again, no Pd (< 0.1 ppm) was detected by ICP analysis. However, addition of fresh substrates to this phase and heating did lead to Heck catalysis. Such activity was also observed for the polar phase of a second cycle when the heptane soluble **23** was reused in a thermomorphic system. While the Heck reaction seen with these polar phases was slower (14 h for complete conversion of iodobenzene), the observation of any activity in a phase that contains no polymer and hence no palladacycle is unambiguous evidence that Pd dissociates from the polymer and that the palladacycle is not required for catalysis.

We also carried out one set of experiments using the polymer-bound palladacycle **23** and the polar phase soluble SCS ligand **20** to qualitatively examine the hypothesis that these palladacycles reversibly form some coordination complex during the reaction. We reasoned that if the Pd–C bond is reversibly cleaved during the reaction, reinsertion of the Pd to reform a palladacycle could distribute the palladium between the two polymer bound ligands (Figure 6). If this exchange occurred, we would then expect to observe higher catalytic activity in the aqueous DMA layer containing PNIPAM-bound SCS ligand than in a DMA layer that contained no polymer. The result of this experiment was that the polar phase had activity but that the activity



**Figure 6.** Potential scrambling pathway between PNODAM and PNIPAM-bound SCS ligands.



was the same as that of a polar phase where no polymer was present.

The species that is generated in these reactions could be a palladium colloid. To examine this issue, we followed the lead of others who have used mercury metal as a trap for a colloidal metal species.<sup>[20,21,48–50]</sup> Such experiments have successfully implicated Pd colloids in Heck couplings using PCP-Pd complexes and more recently in SCS-Pd complexes. Our results agreed with these other findings.

Several experiments were performed. One reaction used iodobenzene, methyl acrylate, 0.1 mol % palladacycle **6**, and an excess (with respect to the palladacycle) of Hg. The reaction mixture was heated at 100 °C and monitored but no conversion of the starting materials to product was observed. A similar reaction without Hg did form products. This second Hg-free reaction however, stopped if Hg were added. More complex results were seen in Heck chemistry with the polymer-bound palladacycle **23**. In a Heck reaction of methyl acrylate and iodobenzene with 0.1 mol % of **23** without Hg, the iodobenzene and methyl acrylate were smoothly and completely converted to methyl cinnamate. However, in the reaction containing Hg, the reaction reached 20% conversion in 18 h but did not continue past this point. The polymer might be shielding the colloidal palladium for a short time, allowing some conversion of the starting materials. In this case, the polymeric species could still be recovered by heptane extraction and the recovered **23** could be used in a second cycle, promoting Heck chemistry of these same substrates. The reactivity of **23** in this second cycle was qualitatively unchanged from its reactivity in an Hg-free first cycle. Reactivity of the recycled **23** was, however, again poisoned on the addition of Hg. These results, like the results throughout these studies are again consistent with these palladacycles being relatively stable species that under Heck reaction conditions generate an undefined, possible colloidal Pd, catalyst.

## Conclusions

Electronically varied tridentate SCS ligands and palladacycles were synthesized and were active in promoting the Heck reaction of aryl iodides but were less active in Heck chemistry of aryl bromides. Mechanistic investigations using these palladacycles showed that electronically different palladacycles had the same reactivity. Reactions with these palladacycles exhibited induction periods that were dependent in a complex way on the starting material concentration, adventitious water and other additives. Competition experiments between various aryl iodides yielded Hammett plots that remained consistent from palladacycle to palladacycle. Phosphine addition that led to reactivity uncharacteristic of the palladacycle was consistent with the trapping of a Pd(0) inter-

mediate. A definitive experiment for decomposition of the palladacycle to some other active catalyst was the residual catalytic activity in the separated phase of a thermomorphic system. The observed catalytic activity in a solution that was separated from the polymer-bound SCS palladacycle even with recycled polymer-bound palladacycles is a strong indication that some other non-supported palladium catalyst is formed *in situ*. The work by other groups on other palladacycles where Hg poisoning is seen and in our work where Hg retardation of a polymer-bound palladacycle's reactivity implicates the presence of Pd(0) colloids or nanoparticles as the actual catalytic species.

The conclusion that some palladium species other than the palladacycle (e.g., a palladium nanoparticle or colloid) is the actual catalytic species is something of a disappointment as it indicates that our earlier work recycled a catalyst precursor and not the catalyst itself. That having been said, it must be remembered that these palladacycles are active for the Heck reaction at fairly low loadings. Moreover, these SCS palladacycles have been successfully used in recycling strategies on different polymer supports by a variety of groups and Pd loss in these experiments is inconsequential. Based on this recycling work and palladium analysis, the amount decomposition of the palladacycle is low. Less than 1% of the original palladacycle is transformed during the reaction. For a palladacycle loading of 0.2 mol % this translates to a turnover number of 50,000 or better for the actual catalyst.

## Experimental Section

### General

Reagents and solvents were obtained from commercial sources and were generally used without further purification. Gas chromatographic analyses were performed on a Shimadzu instrument equipped with a 15-m SPB-5 [poly(5%-diphenyl-95%-dimethylsiloxane)] normal phase fused silica capillary column (0.53 ID). <sup>1</sup>H NMR spectra were recorded on Varian spectrometers at 300 or 500 MHz. Chemical shifts are reported in ppm using hexamethyldisiloxane (HMDS, 0.055 ppm) as the internal standard. <sup>13</sup>C NMR spectra were recorded at 75 MHz or 125 MHz with CDCl<sub>3</sub> (77.0 ppm) or DMSO-*d*<sub>6</sub> (39.5 ppm) as the internal reference. Solid state NMR spectra of **23** were obtained using a Bruker MSL-300 MHz NMR spectrometer. Infrared spectra were recorded as thin films between NaCl plates or as pressed KBr pellets using a Mattson Galaxy 4021 FT-IR spectrometer. Metal analyses were performed using a Beckman Spectra Span VI operating with the AdaM VI software package. Melting points were determined with a Thomas-Hoover Unimelt capillary melting point apparatus and were uncorrected. S,S ligands and SCS-Pd complexes not explicitly described below were prepared using literature procedures.<sup>[10a,15,16]</sup>

**PNODAM-NASI**

Benzene (50 mL) was bubbled through with nitrogen for 30 min. Octadecylacrylamide (4.5 g, 13.9 mmol) and *N*-acryloxysuccinimide (0.24 g, 1.39 mmol) were added. The reaction mixture was warmed to 80 °C and a solution of AIBN (12.6 mg, 0.077 mmol) in 2 mL of benzene was added. The mixture was stirred at 80 °C under nitrogen for 36 h. The solvent was removed and the residue taken up in 30 mL of chloroform and precipitated into 150 mL of cold methanol to give a white powder; yield: 4.1 g (87%). IR (KBr):  $\nu$  = 1812, 1783, 1737, 1654, 1542  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  = 0.8 (t, 30H), 1.2 (br s, 395H), 1.5 (br s, 27H), 2.8 (br s, 4H), 3.1 (br s, 20H).

PNIPAM-SCS (**20**) and PNIPAM-SCS-Pd (**21**) were prepared following a literature procedure.<sup>[15]</sup>

**PNODAM-SCS (22)**

In 30 mL of *tert*-butanol, PNODAM-NASI **21** (300 mg, 0.089 mmol) was dissolved. Separately, amine-terminated SCS ligand **51**<sup>[64]</sup> (50 mg, 0.089 mmol) was dissolved in 10 mL of *tert*-butanol with 0.5 mL of  $\text{Et}_3\text{N}$ . This solution was transferred to the polymer solution and the reaction mixture was stirred at 55 °C for 4 h. The solvent was removed under reduced pressure. The residue was taken up in 6 mL of chloroform and precipitated into 40 mL of methanol to afford the polymer as a white powder; 310 mg (93%).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  = 0.9 (t, 30H), 1.2–1.5 (br m), 3.1 (br s, 20H) 4.0 (br s, 3H), 6.9 (br s, 1.5H), 7.1–7.3 (br m, 8H), 7.5 (br s, 1.5H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  = 175.4, 139.0, 138.3, 136.3, 129.6, 128.7, 126.1, 124.5, 119.0, 42.4, 39.7, 38.8, 31.8, 29.7, 29.4, 29.3, 28.0, 27.2, 22.6, 13.9.<sup>[16]</sup>

**PNODAM-SCS-Pd (23)**

PNODAM-SCS **22** (256 mg, 0.068 mmol) was dissolved in 20 mL of THF. To this was added a solution of  $\text{Pd}(\text{NPh})_2\text{Cl}_2$  (26 mg, 0.068 mmol) in 5 mL of THF. The solution was stirred at room temperature for 1 h, then brought to reflux for 24 h. The solvent was removed on a rotary evaporator and the residue dissolved in 6 mL of  $\text{CHCl}_3$  and precipitated into 40 mL of methanol affording a brownish powder; yield: 246 mg (94%).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  = 0.9 (t, 30H), 1.1–1.5 (br m), 3.1 (br s, 31H), 4.5 (br s, 2.4H), 7.3 (br s, 2.5H), 7.8 (br s, 1H);  $^{13}\text{C}$  NMR (solid state):  $\delta$  = 152.2 (*ipso* carbon).<sup>[16]</sup>

**Thermomorphic Heck Reaction**

In a screw cap vial, 2 mL of a heptane solution of PNODAM-5 (7.5 mg/mL, 0.004 mmol Pd total) was diluted to 5 mL with heptane. Iodobenzene (2 mmol), acrylic acid (2.5 mmol), and  $\text{Et}_3\text{N}$  (6 mmol) were dissolved in 10 mL of DMA and added to the vial. The reaction mixture was heated at *ca.* 100 °C. After the reaction, the vial was cooled and the layers allowed to separate. The lower DMA phase was removed, poured into water and acidified with HCl to precipitate the product. The product was then filtered and dried. Fresh reactants in DMA were then added for the next cycle. The same procedure was used with PNIPAM-SCS-Pd complex, the difference being that the PNIPAM-bound complex was recovered in the polar phase.

***N*-Acetyl-3,5-bis((*p*-dimethylaminophenyl)thiomethyl)aniline**

A 200-mL flask with attached condenser was purged with nitrogen. Acetone (50 mL) was bubbled through with nitrogen for 15 min. Dimethylaminothiophenol (590 mg, 3.85 mmol),  $\text{K}_2\text{CO}_3$  (604 mg, 4.38 mmol), and *N*-acetyl-3,5-bis(benzyl chloride)<sup>[10a]</sup> (407 mg, 1.75 mmol) were combined in the 200-mL flask and dissolved in 100 mL of acetone. The reaction mixture was protected from light and refluxed for 48 h. The reaction mixture was filtered and the solvent removed. The residue was dissolved in chloroform and washed with water and brine. The solvent was evaporated and the residue purified by chromatography on silica gel (ethyl acetate: $\text{CH}_2\text{Cl}_2$ , 1:9) to afford a white solid; yield: 574 mg (70%); mp 115–116.5 °C.  $^1\text{H}$  NMR ( $\text{DMSO}-d_6$ ):  $\delta$  = 1.99 (s, 3H), 2.83 (s, 12H), 3.90 (s, 4H), 6.60 (dd, 4H), 6.78 (s, 1H), 7.17 (dd, 4H), 7.39 (s, 2H), 9.84 (s, 1H);  $^{13}\text{C}$  NMR ( $\text{DMSO}-d_6$ ):  $\delta$  = 24.0, 39.9, 40.4, 112.7, 117.8, 119.8, 124.1, 133.2, 138.6, 139.2, 149.7, 168.2; IR (KBr):  $\nu$  = 3292, 1664, 1594  $\text{cm}^{-1}$ ; HRMS:  $m/z$  calcd. for  $\text{C}_{24}\text{H}_{21}\text{O}_5\text{NS}_2$  [ $\text{M} + \text{H}^+$ ]: 466.1987; found: 466.1984.

***N*-Acetyl-3,5-bis((*p*-acetamidophenyl)thiomethyl)aniline**

*N*-Acetyl-3,5-bis(benzyl chloride) (0.5 g, 2.15 mmol), *p*-acetamidothiophenol (880 mg, 5.25 mmol), and  $\text{K}_2\text{CO}_3$  (725 mg, 5.25 mmol) were combined in a 100-mL flask. Acetone (50 mL) was added and a reflux condenser attached. The flask was covered in foil, flushed with argon and the reaction mixture brought to reflux. After 15 h, the mixture was filtered and the solvent removed under reduced pressure. The resulting solid was broken up, placed on a filter, washed with portions of water, and dried on the aspirator to afford a white powder; yield: 936 mg (88%); mp 163–165 °C.  $^1\text{H}$  NMR ( $\text{DMSO}-d_6$ ):  $\delta$  = 2.0 (overlapping singlets, 9H), 4.08 (s, 4H), 6.91 (s, 1H), 7.22 (dd, 4H), 7.48 (s, 2H), 7.53 (dd, 1H), 9.90 (s, 1H), 9.95 (s, 2H);  $^{13}\text{C}$  NMR ( $\text{DMSO}-d_6$ ):  $\delta$  = 23.8, 117.9, 119.4, 123.9, 129.0, 130.0, 137.8, 138.1, 139.3, 168.1; IR (KBr):  $\nu$  = 3299, 2923, 1664, 1598  $\text{cm}^{-1}$ ; HRMS: ( $m/z$ ) calcd. for  $\text{C}_{24}\text{H}_{21}\text{O}_5\text{NS}_2$  [ $\text{M} + \text{H}^+$ ]: 494.1572; found: 494.1660.

***N*-Acetyl-3,5-bis((benzoxazole)thiomethyl)aniline**

In an argon purged flask, *N*-acetyl-3,5-bis(benzyl chloride) (0.5 g, 2.15 mmol) was dissolved in 40 mL of acetone. To this was added  $\text{K}_2\text{CO}_3$  (743 mg, 5.38 mmol) and a solution of mercaptobenzoxazole (720 mg, 4.74 mmol) in 10 mL of acetone. The reaction mixture was protected from light and refluxed overnight. The mixture was filtered and the solvent removed under reduced pressure. The residue was taken up in chloroform, washed with water, dried and the solvent removed on the rotary evaporator; yield: 659 mg (66%); mp 164–165 °C.  $^1\text{H}$  NMR ( $\text{DMSO}-d_6$ ):  $\delta$  = 10.02 (s, 1H), 7.65 (s, 2H), 7.60 (m, 4H), 7.30 (m, 5H), 4.59 (s, 4H), 2.00 (s, 3H);  $^{13}\text{C}$  NMR ( $\text{DMSO}-d_6$ ):  $\delta$  = 168.3, 163.5, 151.2, 141.1, 139.7, 137.2, 124.5, 124.2, 124.0, 118.5, 118.2, 110.0, 35.4, 23.8.

### ***N*-Acetyl-3,5-bis(*p*-carboxyphenyl)thiomethyl)aniline**

A 100-mL flask and condenser were purged with argon. The flask was charged with *N*-acetyl-3,5-bis(benzyl chloride) (0.5 g, 2.15 mmol), 4-mercaptobenzoic acid (730 mg, 4.73 mmol) and  $K_2CO_3$  (654 mg, 4.73 mmol). Ethanol (20 mL) and water (10 mL) were added, the flask was covered with foil and the reaction mixture refluxed for 2 h. The mixture was concentrated under reduced pressure, acidified with 5 mL of 10% HCl, and 150 mL of water were added. The product was allowed to precipitate as a white solid (2 h) and was then isolated by filtration; yield: 800 mg (80%); mp 212 °C (dec).  $^1H$  NMR (DMSO- $d_6$ ):  $\delta$  = 1.99 (s, 3H), 4.24 (s, 4H), 7.15 (s, 1H), 7.38 (dd, 4H), 7.57 (s, 2H), 7.81 (dd, 1H), 9.95 (s, 1H), 12.9 (s, 2H);  $^{13}C$  NMR (DMSO- $d_6$ ):  $\delta$  = 24.0, 35.4, 118.2, 124.2, 126.4, 127.4, 129.7, 137.5, 139.7, 143.0, 166.9, 168.4; IR (KBr):  $\nu$  = 1687, 1592  $cm^{-1}$ ; HRMS:  $m/z$  calcd. for  $C_{24}H_{21}O_5NS_2$  [ $M + H^+$ ]: 468.0939; found: 468.0959.

### **Palladation of *N*-Acetyl-3,5-bis(*p*-dimethylaminophenyl)thiomethyl)aniline**

In a 50-mL round-bottomed flask, the dimethylamino S,S ligand prepared above (100 mg, 0.215 mmol) was dissolved in 10 mL of acetone.  $Pd(TFA)_2$  (75 mg, 0.225 mmol) was dissolved in 10 mL of acetone and added to the reaction mixture *via* pipette. The mixture was stirred at room temperature for 4 h, then filtered, and the solvent removed to yield **7** as a brownish-red solid that was dried under vacuum; yield: 150 mg (> 99%); mp 185 °C (dec.).  $^1H$  NMR (DMSO- $d_6$ ):  $\delta$  = 1.99 (s, 3H), 2.95 (s, 12H), 4.6 (s, 4H), 6.78 (dd, 4H), 7.20 (s, 2H), 7.66 (dd, 4H), 9.83 (s, 1H);  $^{13}C$  NMR (DMSO- $d_6$ ):  $\delta$  = 24.6, 40.4, 52.1, 113.2, 114.2, 115.8, 134.4, 137.5, 150.5, 152.2, 168.9. HRMS: the mass spectrum was obtained from a dilute acetic acid solution and compound was detected as an acetate complex; [ $M + H_2O + H^+$ ]; calcd. for  $C_{28}H_{36}O_4N_3S_2Pd$ : 648.1182; found: 648.1085.

### **Palladation of *N*-Acetyl-3,5-bis(*p*-acetamidophenyl)thiomethyl)aniline**

To a solution of bis(acetamido) SCS ligand prepared above (200 mg, 0.406 mmol) in 5 mL of DMF was added a solution of  $Pd(TFA)_2$  (135 mg, 0.406 mmol) in 5 mL of DMF. The solution was stirred at room temperature for 5 h. The solvent was removed under reduced pressure to give **8** as a maroon solid; yield: 282 mg (97%); mp 155 °C (dec.).  $^1H$  NMR (DMSO- $d_6$ ):  $\delta$  = 1.99 (s, 3H), 2.05 (s, 6H), 4.7 (s, 4H), 7.20 (s, 2H), 7.64 (dd, 4H), 7.79 (dd, 4H), 9.80 (s, 2H), 10.20 (s, 1H);  $^{13}C$  NMR (DMSO- $d_6$ ):  $\delta$  = 23.9, 24.0, 49.6, 113.6, 119.7, 124.0, 132.7, 136.8, 141.2, 148.9, 168.1, 168.7; IR (KBr):  $\nu$  = 1675, 1592, 1261  $cm^{-1}$ ; HRMS: a mass spectrum was obtained from a dilute acetic acid solution and compound was detected with an acetate ligand; [ $M + H^+ + H_2O$ ] calcd. for  $C_{28}H_{32}O_6N_3S_2Pd$ : 676.08168; found: 676.0551.

### **Palladation of *N*-acetyl-3,5-bis(*p*-carboxyphenyl)thiomethyl)aniline**

The bis(benzoic acid) SCS ligand described above (100 mg, 0.21 mmol) was dissolved in 10 mL of glacial acetic acid.  $Pd(OAc)_2$  was dissolved in 10 mL of glacial acetic acid and added to the ligand solution dropwise from a pipette. A precipitate formed within a few minutes. The suspension was stirred overnight at room temperature and then refluxed for an additional 60 h. The reaction mixture was cooled and filtered. The filtrate was evaporated to dryness and the resulting yellow solid suspended in 10 mL of acetonitrile and refluxed overnight. The reaction mixture was cooled then filtered to afford **12** as a yellow solid; yield: 51 mg (38%); mp > 270 °C.  $^1H$  NMR (DMSO- $d_6$ ):  $\delta$  = 2.0 (s, 3H), 4.82 (s, 4H), 7.26 (s, 2H), 7.95–7.8 (overlapping dd, 8H), 9.82 (s, 1H);  $^{13}C$  NMR (DMSO- $d_6$ ):  $\delta$  = 23.8, 38.1, 49.1, 113.2, 130.0, 136.4, 149.4, 168.0; IR (KBr):  $\nu$  = 3426, 1700, 1592, 1537  $cm^{-1}$ ; HRMS:  $m/z$  calcd. for  $C_{26}H_{23}O_7NS_2Pd$  [ $M + H^+ + H_2O$ ]: 650.0177; found: 649.9864.

### **General Procedure for Heck Reactions using Aryl Halides and SCS-Pd Complexes**

A screwcap vial was charged with aryl bromide (5.0 mmol), methyl acrylate (7.5 mmol), triethylamine (7.5 mmol) and DMF (10 mL). *tert*-Butylbenzene (1.0 mmol) was then added as an internal standard. The catalyst (0.1 mol %) was added as a solution in DMF, and the reaction solution was heated to 120 °C with an oil bath. The reactions were monitored by GC. After completion, the reaction solution was poured into chilled water (150 mL) and the product isolated by filtration.

### **Acknowledgements**

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