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Pd-Catalyzed *Z*-Selective Semihydrogenation of Alkynes: Determining the Type of Active Species

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A protocol was developed to distinguish between well-defined molecular and nanoparticle-based catalysts for the Pd-catalyzed semihydrogenation reaction of alkynes to *Z*-alkenes. The protocol applies quantitative partial poisoning and dynamic light scattering methods, which allow the institution of additional validation experiments. For the quantitative partial poisoning method, tetramethylthiourea (TMTU) was developed as an alternative for the standard poison ligand CS_2, and was found to be superior in its applicability. The protocol and the TMTU poison ligand were validated using the well-described [Pd^{II}(phenanthroline)]-catalyzed copolymerization of styrene and CO, confirming that this system is clearly operating as a well-defined molecular catalyst. The protocol was subsequently applied to three catalyst systems used for the semihydrogenation of alkynes. The first was proposed to be a molecular [Pd^0(IMes)] catalyst that uses molecular hydrogen, but the data gathered for this system, following the new protocol, clearly showed that nanoparticles (NPs) are catalytically active. The second catalyst system studied was an *N*-heterocyclic carbene (NHC) Pd system for transfer semihydrogenation using formic acid as the hydrogen source, which was proposed to operate through an in situ generated molecular [Pd^0(IMes)] catalyst in earlier studies. The investigations showed that only a small fraction of the Pd added becomes active in the catalytic reaction and that NPs are formed. However, despite these findings, a clear distinction between catalytic activity of NPs versus a molecular catalyst could not be made. The third investigated system is based on a [Pd^{II}(IMes)(η^3-allyl)Cl] precatalyst with additive ligands. The combined data gathered for this system are multi-interpretable, but suggest that a partially deactivated molecular catalyst dominates in this reaction.

Introduction

Critical mechanistic studies of molecular catalysis[1–11] and developments in the field of soluble nanoparticle (NP) catalysts[12–22] have demonstrated that under certain circumstances molecular precatalysts may form active NPs or nanocluster catalysts, which consist of a small number of metal atoms. The opposite, in which anticipated NP or nanocluster materials can be precursors for molecular catalysts, has been demonstrated as well.[11,23–26] It is important to know the type of active catalyst, especially for the development of molecular catalysts. These catalysts are developed based on mechanistic understanding.[10,27,28] When, instead of a molecular catalyst, an in situ generated metal-particle-based catalyst is active, the assumed mechanism is incorrect. In that case, altering the reaction conditions, varying the ligand design and computational studies will most likely not lead to any improvements. Studies on the nature of the active catalyst in the Heck-reaction illustrate the importance of knowing the type of a catalyst and the benefits thereof. These investigations provided a rationale for the observed reactivities, disproved wrong mechanistic assumptions, and have realized that the Heck-reaction can now be performed at ultra-low metal loadings.[3,4,29–32]

According to experts in the field of the determination of the type of active species, the number of catalyst systems that are erroneously assumed to be well-defined molecular catalysts is underestimated.[10,11] This holds especially for Pd-catalyzed coupling and hydrogenation reactions,[11,25,33] because many of those reactions can be performed by both transition metal-

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based complexes and metal particles.[4,5,10,34–48] The Pd-catalyzed semihydrogenation of alkynes toward *Z*-alkenes is such a reaction. It is catalyzed by Pd complexes, as well as metal particles such as Pd on carbon and Lindlar's catalyst.[48–52] Chemo- and stereoselectivity of the catalyst system is crucial in this reaction that is applied from laboratory to bulk scale.[45,46,52,53] In such cases an understanding of the type of active species and the reaction mechanism are required to improve catalyst systems that meet the desired chemo- and stereo-selectivities. Therefore, our initial goal was to investigate the type of active catalyst for three catalyst systems; one system for the Pd^0-catalyzed *Z*-selective semihydrogenation of alkynes that uses molecular hydrogen, and two catalyst systems for the Pd^0-catalyzed *Z*-selective transfer semihydrogenation of alkynes using formic acid.

To determine the type of active species for these systems a protocol was developed that uses quantitative partial poisoning and dynamic light scattering (DLS) methods. In relation to this protocol we also propose and employ a new partial poisoning ligand tetramethylthiourea (TMTU). New protocols and poisoning ligands require careful validation. Therefore, we applied the protocol to the [Pd^{II}(phenanthroline)]-catalyzed copolymerization reaction of CO and styrene. We chose this reaction, because NMR and kinetic experiments demonstrated that the true catalyst is a well-defined transition metal complex, hence this reaction may serve for the validation of the protocol for a molecularly catalyzed reaction.

Results and Discussion

In the following three sections, the development of the protocol, the validation of TMTU as a poison ligand in the copolymerization reaction and the determination of the type of active catalyst for the investigated semihydrogenation reactions are discussed respectively.

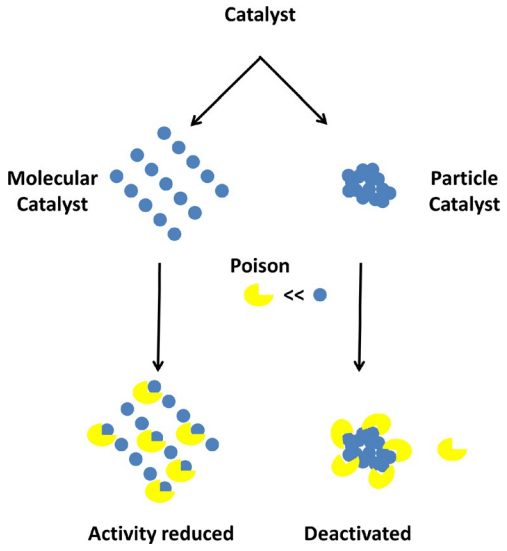
1. Design of the protocol

Several methods have been developed to distinguish between well-defined, molecular catalysts and less-defined systems based on (nano)particles.[1,6,9,21,24,29,33,54–57] Excellent reviews by Finke et al. and Crabtree give an overview of the experiments and methods used for the determination of the type of active catalyst.[10,11] Especially the methodology by Finke et al. has provided a basis in this field.[33] The key to the success of this methodology (and others based thereon) is that multiple determination methods are combined.[3,11,13,33,58,59]

In the protocol described in this paper, DLS and quantitative partial poisoning are combined to study the type of active catalyst of three semihydrogenation reactions. DLS is used to determine the presence of NPs. However, this method does not show whether observed particles are active. Partial poisoning is then used to estimate the number of actively participating Pd atoms in the catalytic reaction. The combination of these methods then allows the determination of the type of active catalyst.

The first advantage of the DLS technique is that it is non-invasive. This means its application does not influence the reaction conditions and does not require sample treatment.[60] DLS is able to detect particles of 1 to ≈250 nm, even at concentrations in the nM range.[10,21,24,61,62] Although its main task is to show the presence or absence of scattering particles, this technique also provides information about the average size of the particles, assuming single scattering conditions, which is generally the case in catalytic reactions. Another advantage is that DLS is a simple and fast technique: it takes about as long as recording an NMR spectrum. The detected particles in a scattering experiment indicate that transition metal-based NPs may be present. However, salts, dust and any other type of particles also cause light-scattering. Hence, to avoid misinterpretations, control reactions are required. These consist of measuring the scattering of all the individual reagents and combinations thereof.

Quantitative partial poisoning gives an estimation of the fraction of active metal atoms by applying ranges of sub-stoichiometric amounts of poison and measuring the corresponding decrease in catalytic activity.[56,63–66] The amount of active metal atoms is indicative for the type of the catalyst. Only the atoms on the outer sphere of NPs are catalytically active, leaving many non-participating metal atoms in the interior of the NP (Scheme 1). Rarely more than 15 percent of the metal



Scheme 1. A representation of a partial poisoning experiment.

atoms participate when NPs are the active catalysts.[67–69] In the case of active molecular catalysts typically most of the metal atoms can participate.

Using quantitative poisoning to determine the type of active species is appealing, because it only has a few experimental constraints, it is a simple method and it does not require additional analytical methods. The quantitative data that this method provides make it more reliable than the more often applied qualitative poisoning methods. Additionally, it uses only sub-stoichiometric amounts of poison, which makes quantitative poisoning less invasive as well.[7,8,54]

However, there are three situations where quantitative poisoning can give misleading results: 1) When the applied poison binds too weakly to the catalyst, a partial poisoning test may erroneously indicate that a molecular catalyst is active, while the activity actually originates from (nano)particles; 2) Experiments may falsely indicate particles as active catalysts when only a small fraction of the precatalyst is converted into an active molecular form; 3) An incorrect estimation of the fraction of active metal atoms is obtained if the poison decomposes a molecular catalyst non-stoichiometrically (or if the catalyst decomposes the poison). To circumvent these three problems, the protocol includes validation experiments, including:

- Testing the poison ligand with authentic NP catalysts to demonstrate sufficient deactivation of the NPs by the poison ligand.
- Isolation of the proposed poisoned molecular species, which is a good indication that the poison ligand does not decompose the active species to form NPs.
- Demonstrating that the reactivity of an isolated poisoned analogue of the proposed molecular catalyst is minimal.

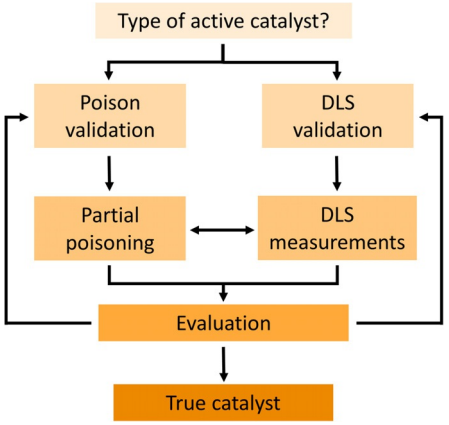
The combination of DLS and quantitative partial poisoning allows the institution of several additional controls, which improve the reliability of the determination of the type of active species. These additional controls are:

- Performing DLS studies on the reaction without poison, with poison, and with the poisoned analogue of the proposed active catalyst. This indicates if the poison ligand facilitates NP formation.
- Verifying that NPs are present if quantitative poisoning shows that only a small fraction of the metal is active.
- Verifying that the percentage of active metal atoms determined by quantitative poisoning is in agreement with the estimated number of surface atoms that is derived from the average particle size. If the poison is appropriate, and the number of surface atoms based on DLS is significantly smaller than the estimated metal fraction, species that are not observed by scattering are most likely active.

The DLS measurements, quantitative poisoning tests and the related validation experiments provide a significant amount of data. A guiding principle in the interpretation of the data is that the type of catalyst should be consistent with *all* the data.[11,33] The protocol derived is shown in Scheme 2.

TMTU as a poison ligand

The selection of an appropriate poison (ligand) is crucial. The reactions investigated in this work are all catalyzed by Pd, which is a soft and electron-rich metal. Sulfur-based poisons are ideal candidates for such type of metals, of which CS_2 is the most commonly used.[11] However, CS_2 has several disadvantages, of which the high volatility, its limited use at elevated temperatures, and high toxicity are the most significant.



Scheme 2. A presentation of the protocol for the determination of the type of active catalyst for soluble (pre)catalysts using DLS and quantitative poisoning as well as their combined validation experiments.

Not surprisingly, research towards alternative poisoning ligands has been noted as one of the key issues for the further development of poisoning tests.[11] To that end, we investigated the use of alternative poison ligands, specifically TMTU (Figure 1). Its strong π-acceptor properties combined with its strong σ-donor properties originate from its resonance structures, which make it a strongly binding ligand for low-valent as well as high-valent complexes (Figure 1).[70]

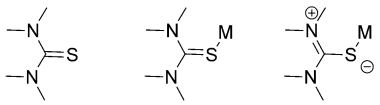
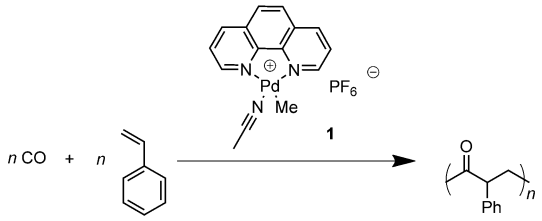


Figure 1. The structure of tetramethylthiourea, its resonance structures and coordination modes.

Thioureas have been exploited as ligands for Pd-complexes,[71–73] Pd-catalyzed reactions,[74–76] the removal of trace metal salts from aqueous solutions[77] and the preparation of coordination polymers.[78] TMTU possesses qualities that are advantageous for poison ligands. It is a stable, inexpensive, commercially available compound; it is a solid at room temperature with a high boiling point and low vapor pressure.[11] In comparison to CS_2, TMTU has only one defined binding mode,[79] is less toxic and is not easily decomposed into fragments that can bind to multiple metal centers. TMTU can also easily be monitored because the thiourea and thiocarbonyl IR-vibrations have high absorption intensities and the frequencies shift significantly upon coordination to a metal.[73,80,81]

2. Copolymerization of styrene and CO by a [Pd^{II}(phenanthroline)] catalyst

We deemed that TMTU is an interesting poisoning ligand, therefore, we experimentally evaluated it in the [Pd^{II}(phenanthroline)]-catalyzed copolymerization of styrene and CO. This is a reaction that provides aromatic polyketones, which are interesting materials both as high-performance plas-

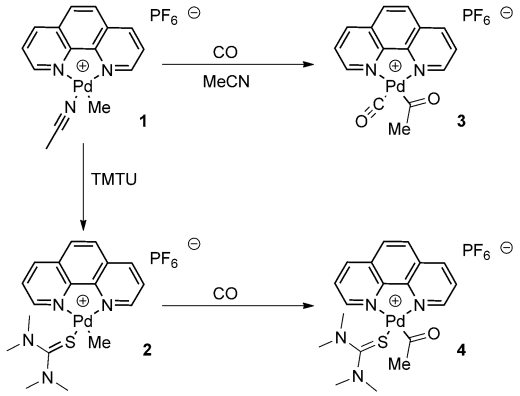


Scheme 3. The copolymerization of CO and styrene by [Pd^{II}(phenanthroline)(Me)][PF_6].

tics and as precursors for polyalcohols, polyamines and polyimines (Scheme 3).[82]

The [Pd^{II}(Phenanthroline)] catalyst system (**1**) was chosen as a first test-case of the partial poisoning method and the applicability of TMTU as a poison ligand for two reasons. First of all, the reaction has been intensely studied and all these studies indicate that the catalytic polymerization reaction involves well-defined molecular compounds. A second reason is that the proposed intermediates have been characterized by NMR-spectroscopy. A minor disadvantage is that not all parts of protocol can be tested for this reaction, since DLS measurements of the catalytic mixture cannot be performed as polymers are formed. However, this is compensated by all the previously performed studies, therefore, this reaction is highly suitable to validate the quantitative poisoning protocol using TMTU as a poison ligand.

Following the protocol, we first synthesized the TMTU poisoned analogue **2** (Scheme 4). The structure of the molecule was confirmed by X-ray crystallography (see the Supporting Information, SI1). NMR studies (see the Supporting Information, SI2) revealed that when complex **2** is placed under an atmosphere of CO at room temperature cationic species **4** (Scheme 4) is formed, whereas for standard catalyst **1** the cationic **3** species formed. That **3** is not formed by our poisoned analogue **2**, indicates that the TMTU ligand binds strongly and that CO does not replace it. It also shows that TMTU does not lead to decomposition of the original complex (**1**).



Scheme 4. Catalyst **1** used in CO/styrene copolymerization, its resting state **3**, its TMTU-poisoned analogue **2** and the TMTU resting state **4**.

As the coordination properties of TMTU were demonstrated to be suitable for the use as a poison ligand, we then proceeded with tests in catalytic reactions. First, we further validated the poison by applying the TMTU-poisoned analogue complex **2** as a precatalyst in the reaction. Only a negligible activity was obtained. From this we conclude that the poison binds strongly and that the putative poisoned complex (**2**) is not catalytically active itself (Figure 2). With these experiments we demonstrated that TMTU is an appropriate poison ligand, since it does not decompose the compound and binds strongly to the precatalyst.

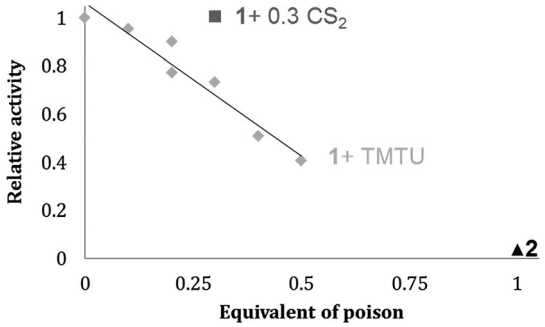


Figure 2. Quantitative partial poisoning studies of **1** and **2** showing the relative activity as a function of the amount of poison ligand.

Following the protocol we also performed DLS measurements on a solution of the catalyst itself and of the catalyst under CO atmosphere. In both cases no NPs were observed. This is a first indication that the process is catalyzed by a molecular catalyst.

After the validation experiments we performed a quantitative poisoning experiment by performing the CO/styrene copolymerization reaction applying 0 to 0.5 equivalents of TMTU with respect to the catalyst. We measured the total yield in polyketone after 24 h as a function of the added amount of TMTU (Figure 2).

The fact that the TMTU-poisoned analogue of the (pre)catalyst is virtually inactive in this reaction indicates that TMTU is a strong-binding poison, as was also observed in the NMR studies. When a strong-binding poison is applied to an efficiently activated molecular catalyst, a linear negative relationship between the activity and the amount of poison is expected.[63,68] Indeed, plotting the activity versus the poison fraction yields a straight line with a negative slope (Figure 2), indicating that the applied system behaves as expected for a molecular catalyst. The fraction of the metal that is active can then be derived by the determination of the slope of this line and calculating the intersection with the horizontal axis.[56,83] In this case the intercept is at 0.84 equivalents of TMTU per Pd-atom, which is strongly indicative of a molecular catalyst, which is in good agreement with all previous studies.

To place the performance of the TMTU poisoning ligand in context, we compared the efficiency of TMTU to that of the standard poison, CS_2. We applied 0.3 equivalent of CS_2 and compared the decrease in activity of the reaction caused by

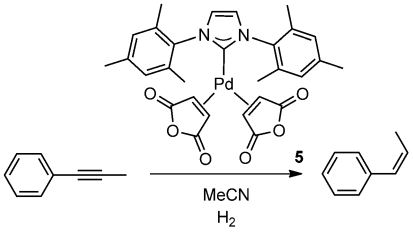
both poison ligands. TMTU reduced the catalyst activity of **1** by ~25% (Figure 2). However, addition of 0.3 equivalent of CS_2 to **1** did not influence the activity of the catalyst. Therefore, we conclude that CS_2 is a poor poison for this reaction. Probably, this is caused by a reversible binding of CS_2 to the catalyst, which in combination with the high volatility of CS_2 led to removal of the poison ligand from the reaction mixture.

From the experiments and validations described above we conclude that the quantitative TMTU poisoning protocol is successful. The protocol indicates that a molecular catalyst is active, which is in line with the previous studies of this reaction. In addition the quantitative partial poisoning tests show that TMTU is a superior poison compared to CS_2 for this reaction.

3. Pd^0-catalyzed Semihydrogenation of alkynes

3.1. Semihydrogenation of 1-phenyl-1-propyne to Z-1-phenyl-1-propene using molecular hydrogen

The semihydrogenation of alkynes that yields synthetic and pharmaceutically relevant *Z*-alkenes is an important catalytic synthetic reaction. An interesting feature of this reaction is that both molecular and particle catalyst systems are active.[45,50,51,84–89] Our group has previously reported a catalytic system that was proposed to proceed via an in situ generated molecular [Pd^0(IMes)] species as the active catalyst (IMes = 1,3-bis-mesityl-imidazol-2-ylidene) (Scheme 5).[46,90–92]



Scheme 5. The semihydrogenation of 1-phenyl-1-propyne to *Z*-1-phenyl-1-propene with [Pd^0(IMes)$(MA)_2$] **5**.

Sprengers et al. reported that the in situ generated catalyst is significantly more active than the isolated catalyst.[93] One explanation for this higher activity is that less maleic anhydride (MA) ligand is applied for the in situ generated species. Alternatively, this observation could also be an indication that NPs may actually be participating as active species. For this reason, we studied whether the isolated [Pd^0(IMes)$(MA)_2$] complex **5** is a precatalyst for a well-defined molecular species or a precursor for active (nano)particles. Using an isolated system instead of an in situ generated system is beneficial, because it circumvents issues that could arise from inefficient or incomplete formation of the active catalyst and generation of (active) NPs in that step.

Following the above described protocol we started with the validation of the catalyst and its precursors. First we evaluated whether the synthesis of **5** provides a precatalyst that is devoid of NPs. DLS and TEM-EDX demonstrated that in the reported preparation of **5** NPs are formed.[93,94] This is also the case for its precursors [Pd^0(*t*BuDAB)(MA)] (*t*BuDAB = 1,4-di-*tert*-butyl-diazobutadiene) **6**[95] and [Pd^0(NBD)(MA)] (NBD = norbornadiene) **7**.[96] The common technique of filtration over Celite was insufficient to remove these particles.[10,54] Column chromatography allowed the isolation of NP-free samples of **5** and **6**. However, we were unable to obtain **7** devoid of NPs. Presumably, this was due to the labile and volatile nature of the norbornadiene ligand.

To evaluate whether CS_2 and TMTU are appropriate poisoning ligands the respective proposed poisoned analogues of **5**, that is, complexes **8** and **9**, were synthesized (Figure 3). The X-ray structures of compounds **5**, **8**, and **9** were obtained (these

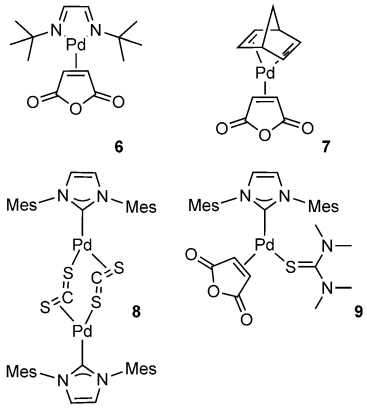


Figure 3. [Pd^0(*t*BuDAB)(MA)] **6**, [(Pd^0(NBD)(MA)] **7**, and the CS_2 (**8**) and TMTU (**9**) poisoned analogue of **5**.

are discussed in the Supporting Information, SI3). The CS_2 and TMTU-poisoned analogues of the proposed molecular catalyst, were tested as (pre)catalysts in the semihydrogenation reaction for poison validation. Both complexes did not display any activity, nor was the generation of NPs observed by DLS. Therefore, we concluded that both CS_2 and TMTU are appropriate poisons for the molecular catalysts (or NP catalyst precursors) in this reaction.

The next validation step in the protocol is determining whether the poison ligands are also effective for (preformed) NPs. Therefore, we tested the ability of the poison ligand to deactivate authentic particle-based precatalyst materials. We chose Pd on carbon to simulate poorly defined NPs and the BASF Nano-Cat on titanium silicate[50,97] as a control for well-defined small NPs. For the BASF Nano-Cat, it was already proven that the active species are authentic NPs.[50,97] For completeness, we first verified that Pd on carbon is also an authentic particle-based catalyst instead of a precursor for atomic substrate-ligated compounds. For this purpose, we performed a (Maitlis) "hot filtration" test.[6] When active soluble species are formed during a reaction, the filtrate should display activity. However, we did not observe any activity in the filtrate. Additionally, the amount of Pd that had leached from the support during the reaction was minimal (< 0.05%) according to inductively coupled plasma - atomic emission spectrometry (ICP-

AES) measurements (see the Supporting Information, SI4). Therefore, we concluded that for both materials, particles are the active catalysts.

Subsequently, we tested the ability of the poison ligand to deactivate these authentic particle-based precatalyst materials. The particle catalysts, without poison ligands, are quite active under the standard conditions (Figure 4). The Nano-Cat is

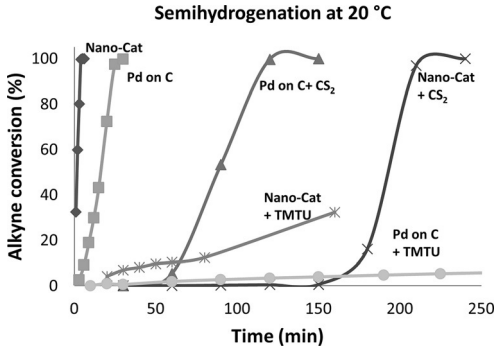


Figure 4. The semihydrogenation of 1-phenyl-1-propyne at 20 °C for Pd on carbon and the BASF Nano-Cat using either 0.25 equivalent of TMTU or CS_2.

faster than Pd on carbon, which is not surprising, because it has smaller particles and thus a larger part of the Pd is available for the reaction. We performed a partial poison test with TMTU and CS_2 to be able to compare the efficiency of both poisons. 0.25 equivalent of the appropriate poison with respect to the total amount of Pd was added to the reaction mixture and the reaction was followed in time (Figure 4). We evaluated the poisons at room temperature and at 70 °C (Figure 5), since

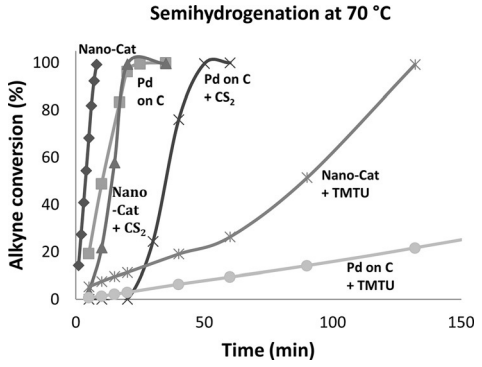


Figure 5. Activity of Pd on carbon and the BASF Nano-Cat in the semihydrogenation of 1-phenyl-1-propyne at 70 °C compared to the analogous reactions adding either 0.25 equivalent of TMTU or CS_2 as a poison.

poisons are generally less effective at higher temperature. Evaluation of the poison efficiency at elevated temperatures is therefore an important aspect in the evaluation of the effect of (new) poison ligands.

CS_2 (0.25 mol mol^{-1} Pd) did not deactivate the catalyst activity completely. Instead, an induction period was observed, after which catalytic activity starts. Possibly, this is the result of CS_2 escaping from the reaction mixture, since elevated temperatures shortened the induction period dramatically. Alternatively, the sigmoidal curve could also be caused by the "dissolution"[10] of the Pd-particles by CS_2. However, ICP-AES showed that CS_2 and TMTU did not increase the Pd leaching (see the Supporting Information, SI4), from which we concluded that the observed induction times are not caused by disassembly of the NPs by the poison ligands.

TMTU has an advantage over CS_2 as a poison ligand (Figure 4 and 5). Initially, TMTU (0.25 mol mol^{-1} Pd) reduces the catalytic activity somewhat less effectively than CS_2. Nonetheless, it still reduces the catalytic activity of the reaction by a respectible 96% or more. However, TMTU is a more reliable poison than CS_2, because it poisons the active catalyst for a much longer period. The advantages of TMTU as poison ligand are even more pronounced at 70 °C. Under these conditions the efficiency of both poisons decreases somewhat, but the inhibition of the catalytic activity by CS_2 lasts for a significantly shorter period of time than that of TMTU. This clearly shows that TMTU is the better poison for this reaction, especially at elevated temperatures.

Having demonstrated that TMTU and CS_2 are potent poisons under the applied reaction conditions, partial poisoning tests were performed with precatalyst **5** (Figure 6).[93] We first performed a partial poisoning analysis of the precatalyst that is

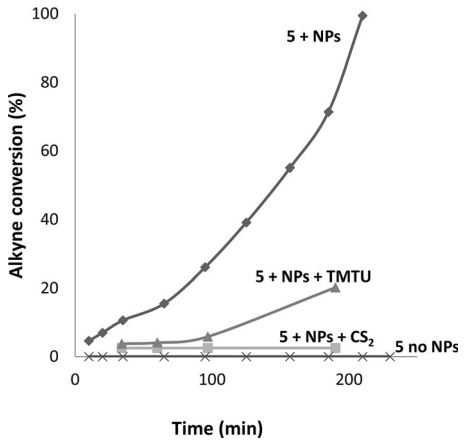


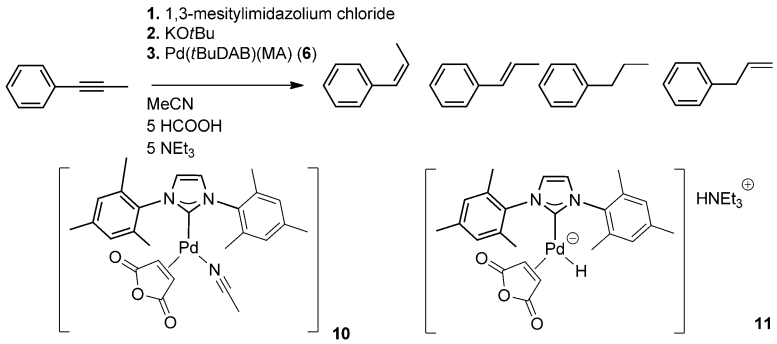
Figure 6. The partial poisoning test at standard reaction conditions using compound **5** with and without NPs. When poison was applied, 0.25 equivalent was used.

prepared according to the literature procedure, which in our hands contains NPs. In order not to hinder the generation of the active catalyst, the reaction was started by placing a solution containing the catalyst, the substrate and the internal standard in acetonitrile under an H_2 atmosphere. After 5 min 0.25 equivalent of the selected poison, with respect to the amount of precatalyst, was added, and the reaction was monitored in time. Both poisons decreased the activity significantly, and the activity drop is much larger than 25%, which strongly suggests that NPs are the active species.

Conclusive evidence that NPs are the true catalysts was provided by applying precatalyst **5** that is devoid of NPs. This species was catalytically inactive. Thus, the NPs that were generated in the complex synthesis are the active species

3.2. Transfer semihydrogenation of 1-phenyl-1-propyne to Z-1-phenyl-1-propene using an in situ generated [Pd^0(IMes)(MA)(MeCN)] catalyst

Other work in our group concerns a system for the transfer semihydrogenation of internal alkynes using an in situ generated catalyst **10** (Scheme 6), which applies a triethylamine-formic acid donor-pair (FA/NEt_3) as the hydrogen source. The use of this ionic hydrogen donor-pair circumvents the oxidative addition of hydrogen and formation of a [Pd^{II}(NHC)] dihydride species. Instead, the system is believed to involve an anionic [Pd^0(IMes)(MA)(H)] mono-hydride species **11**. Thus, it is proposed to proceed through a different mechanism than the previously discussed semihydrogenation reaction that uses molecular hydrogen. The system for the transfer semihydrogenation was intensively studied because it was the first system that did not show over-reduction and isomerization of the product *Z*-alkene at full conversion of the substrate.[49,94]



Scheme 6. The transfer semihydrogenation of 1-phenyl-1-propyne to *Z*-1-phenyl-1-propene and its side products produced by in situ generated catalyst **10** and proposed active species **11**.

Several kinetic studies were performed on this catalyst system, such as the determination of the order in the substrate of both the hydrogen donors and the transition metal. Two reasons were given for proposing a molecular catalyst. The first was the observed kinetic first-order dependence of the reaction rate on the precursor concentration. However, several NP-based hydrogenation catalysts were reported to also give a first order in transition metal.[10] A kinetic first-order in transition metal does not necessarily signify a molecular active catalyst; it only demonstrates a linear relationship between the activity and the concentration of the applied precatalyst. The second reason for proposing a molecular catalyst was the unprecedented selectivity. It was hypothesized that NPs would not possess the required chemoselectivity to differentiate between alkenes and alkynes. However, later studies demonstrated that NP catalysts can also give rise to such observed selectivities.[50,97] In this light, we felt that a thorough study to unravel the nature of the active catalyst in this system was needed; in particular because this catalyst system is a key element in our current research. Therefore, we also applied the aforementioned protocol to this reaction.

Validation of the poison ligands consists of their evaluation both with authentic NPs and poisoned analogues of the proposed catalyst. For the evaluation of the poison ligands with an authentic NP precatalyst, we first tested several particle-based (pre)catalysts in the transfer semihydrogenation of 1-phenyl-1-propyne with FA/NEt_3 (Figure 7). We found that not all types of NP (pre)catalysts are active. Most surprising was the inactivity of the BASF Nano-Cat, which is one of the most active catalysts for the hydrogenation of alkynes using molecular hydrogen. The commercially available Pd nanopowder <25 nm from Aldrich was also inactive. Lindlar's catalyst (Pd on $CaCO_3$ poisoned with lead acetate) and Pd on carbon, on the other hand, displayed reasonable activities. Subsequently, we evaluated whether these supported catalysts are genuinely particle catalysts by use of the Maitlis filtration test and subsequent ICP-AES analysis. The activity resided on the supported phase and only a small part of the Pd had leached into the solution (see the Supporting Information, SI5). We, therefore, concluded that the investigated materials are authentic NP catalysts.

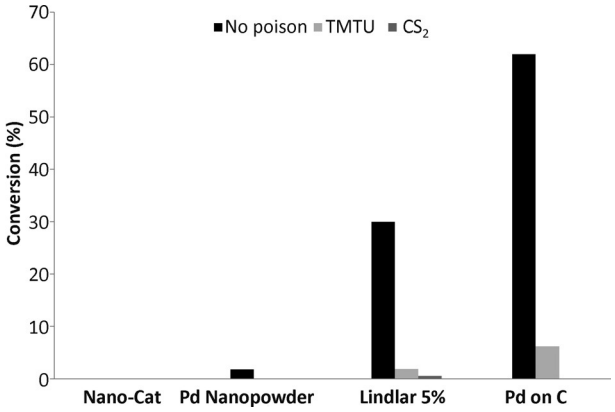


Figure 7. The transfer semihydrogenation of 1-phenyl-1-propyne using 3 mol% of several palladium NP catalysts with and without 0.25 equivalents of TMTU or CS_2, conversion after 24 h.

We continued with the validation of the poison ligands for particle catalysts. Both CS_2 and TMTU efficiently reduced the activity of the catalysts (>90%) (Figure 7). Especially CS_2 was highly efficient. However, when CS_2 was applied as a poison ligand ICP-AES determined that the Pd-leaching increased by more than one order of magnitude with respect to the standard reaction (see the Supporting Information, SI5). Consequently, even though CS_2 reduces the activity of the catalyst in an efficient manner, it also has an additional and unclear inter-

action with the (pre)catalyst, possibly making it a "non-innocent" poison.

Subsequently, we evaluated the poison ligands by testing the proposed CS_2 (**8**) and TMTU (**9**) poisoned molecular catalysts as precatalysts in the semihydrogenation reaction. The CS_2-poisoned compound (**8**) showed no activity in the semihydrogenation and NPs were not observed with DLS measurements. The TMTU-poisoned compound (**9**) showed some activity without NPs being observed with DLS. The activity of the TMTU-poisoned compound was reduced by 83% with respect to the catalyst without poison ligand.

In the validation experiments above, we found that TMTU and CS_2 both reduce the activity of authentic NPs and NHC-precatalysts. However, CS_2 caused an increase of leaching of the NP catalysts, therefore, TMTU is a more reliable poison ligand to apply for the DLS and quantitative poisoning measurements of the investigated catalyst system.

In the catalytic procedure for the transfer semihydrogenation reaction the NHC-species **10** is first generated from [Pd(*t*BuDAB)(MA)] (**6**), after which the reagents and substrate are added (Scheme 6). DLS measurements were performed after each addition, which showed that particles had already formed after the generation of the catalyst. Upon addition of formic acid, a white suspension formed, which is most likely triethylammonium formate. We filtered the suspension over a 0.4 μm filter, after which DLS measurements did not detect any NPs. The particles that were detected previously have probably been taken up in the macroscopic particles of the suspension. Half an hour after the start of the reaction another DLS measurement was performed, and particles of ~44 nm in size were observed. After an hour, Pd black formation was observed, and no further DLS measurements were performed.

Subsequently, we performed quantitative partial poisoning studies of the transfer semihydrogenation reaction with the in situ generated catalyst **10** ([Pd^0(IMes)(MA)(MeCN)], Scheme 6). We applied 0.25 equivalent of TMTU or CS_2 respectively, as poison ligands in the reaction. According to these experiments, TMTU and CS_2 caused an equal decrease in turnover frequency, which provides another indication that the poisons are neither inducing catalyst decomposition nor NP formation: it is highly unlikely that the two poison ligands decompose the proposed molecular catalyst at the same rate. Based on this observation and the previous validation experiments above we conclude that the poison ligands are behaving only as a poison and that the observed NP formation is inherent to the applied reaction conditions.

The quantitative poisoning study shows that only a fraction of the Pd is active (Figure 8). Drawing a tangent line for the initial decrease in activity gives an estimation that ~12% of the Pd is active in the reaction. Generally, such a value is indicative of catalytically active NPs.[63]

In the quantitative poisoning experiment the activity does not decrease to zero in a linear fashion. This behavior is typically observed when the binding of the poison to the active catalyst is not infinitely large with respect to the substrate. The substrate alkyne binds strongly to Pd, therefore, the alkyne (which is present in excess) may well be in competition with

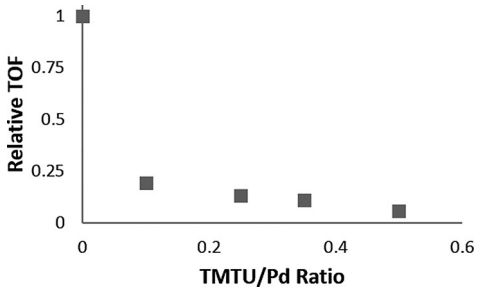


Figure 8. The quantitative partial poisoning of the proposed in situ generated catalyst **10**. The TOF was determined at 15% conversion.

the TMTU poison ligand. As a result of this competition, the degree of binding is concentration dependent, thus yielding a non-linear inhibition-concentration relationship. This phenomenon is common in literature.[64,83] A competition between alkyne and poison ligand is also consistent with the data from the poison validation with particle-based precatalysts, where the poison ligand does not fully deactivate the particle-based precatalysts as well. The estimated percentage of active Pd is the maximum. It is probably overestimated because there are few points in the "linear" area of the partial poisoning study.

Based on the separate outcomes of DLS and quantitative partial poisoning studies one would conclude that NPs are the true catalysts for this reaction. However, the evaluation step of the protocol (Scheme 2) that also includes all its validations and control experiments shows that the determination of the true catalyst is more complicated and requires more nuance. This illustrates the reliability of the protocol and how well DLS and quantitative partial poisoning complement echother. The evaluation of all the data from the protocol shows contradictory results. The data show that NPs of ≈44 nm are present. An estimative calculation shows that for these particles 3% of the Pd is at the surface (see the Supporting Information, SI6). Only a fraction of this may be active, since part of the surface is occupied by other coordinating species that solubilize the particles.[12,63,64] Hence, the observed NPs do not match well with the fraction of active metal that was observed. Such a mismatch is an indication that other species may be active. This is supported by the control experiment with the analogue of TMTU-poisoned catalyst. Complex **9** was active in the semihydrogenation, but no NPs were detected by DLS. Consequently, such species could also be active in this reaction. Further support comes from the fact that NPs of this size and type would not give the observed kinetic first-order in Pd as was described for this system.[49,94] Actually, for such particles a negative concentration dependence in Pd would be expected.[4]

The control DLS experiments showed that the results of the quantitative partial poisoning may not be accurate. NPs were formed in the generation of the catalyst and during the catalysis itself. If the observed NPs are not the true catalysts, a smaller fraction of Pd remains available for this active species. It was observed that a part of the initially applied Pd is removed from the reaction. However, we are unable to determine what part of the Pd is present in the form of these NPs. Consequent-

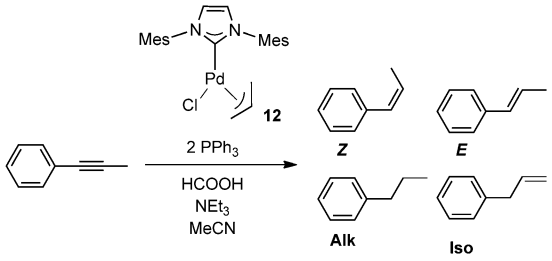
ly, the fraction of Pd in other forms is unknown as well and no activity relation can be made.

As prescribed by the protocol additional methods to determine the type of active catalyst were applied. We chose the mercury poisoning test[7,8,24,98–101] and the Crabtree test.[54] However, these often applied methods for the determination of the type of catalyst were not suitable for the investigated [Pd^0(NHC)] complexes. We found that mercury decomposes the precatalysts, which was previously also reported for several other transition metal complexes.[10,24,98] The Crabtree test required that the active catalyst is incubated with the dibenzo-[*a*,*e*]-cyclotetraene ligand, since the formation of the deactivated complexes is reported to be slow.[54] We were unable to perform this incubation as the catalyst is generated in situ.

Owing to the complexity of the reaction and the contradictory results of the validation and control experiments the type of the true catalyst cannot be reliably determined. The protocol has shown that only a small fraction of Pd is active, therefore, no matter the identity of the true catalyst, it provides new openings for improving this system.

3.3. Transfer semihydrogenation of 1-phenyl-1-propyne to Z-1-phenyl-1-propene using [Pd^{II}(IMes)(η^3-C_3H_5)(Cl)] with additional PPh_3 ligands as catalyst system

We reported another system for the transfer semihydrogenation of alkynes.[102] This system applies a precatalyst that is transformed in situ into a [Pd^0(IMes)] species by triethylammonium formate, which is stabilized by additional selectivity-enhancing PPh_3 ligands (Scheme 7).



Scheme 7. [Pd^{II}(IMes)(allyl)(Cl)] precatalyst (**12**) that is converted under reaction conditions to a PPh_3-stabilized Pd^0 catalyst system for the transfer semihydrogenation.

We performed several mechanistic studies on this system to determine the role of the additive and to find what mechanism lies behind the high selectivities that were observed. For this system first-order reaction kinetics were observed in catalyst concentration when the precatalyst was applied without any additives. As mentioned before, such kinetic behavior does not unequivocally prove that the reaction is catalyzed by a molecular catalyst, but at the time we nevertheless interpreted the data as such.[102] From mechanistic studies we concluded that the high selectivities that are induced by the additive are the result of the relative coordination strengths of the substrate, the phosphine and the products. The coordination of the phosphine ligand to the catalyst prevents the isomerization and over-reduction of the *Z*-alkene product. In the light of the results for the other transfer semihydrogenation catalyst system, determining the type of active catalyst is more relevant for this system. Additionally, determining the type of active catalyst for the Pd^{II}-precatalyst system may show the viability of additive methodologies to prevent the formation of active NPs and to stabilize molecular catalysts.

We validated the particle-based catalysts, the capabilities of the poison ligands to stop particle-based-catalysts and the reduction of the catalytic activity of the analogues of the poisoned molecular catalysts in the previous section. We performed DLS measurements of the reaction using two equivalents of PPh_3 and precatalyst **12** either without or with the addition of 0.25 equivalent of TMTU or CS_2, respectively. In all three cases NPs were observed. Therefore, DLS could not be used to prove that TMTU and CS_2 do not lead to decomposition of the catalyst. We found that CS_2 and TMTU reduced the activity of the reaction equally, thus indicating that the poisons are most likely "innocent". Based on all validation experiments we conclude that TMTU is an appropriate poison for the transfer semihydrogenation and has a similar efficiency as CS_2.

Subsequently, we performed a quantitative partial poisoning analysis by variation of the applied amount of TMTU, from which we estimated the percentage of the metal that is active (Figure 9). The plot of the relative activity as a function of the

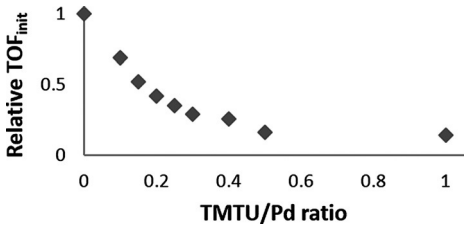


Figure 9. A quantitative poisoning analysis of the transfer semihydrogenation with **12** by variation of the TMTU over Pd-ratio and determining the initial TOF.

TMTU-Pd ratio for the transfer semihydrogenation seems to show a concentration-dependent relation just as for the previously described semihydrogenation catalyst system (Figure 8). The initial part of the plot shows a linear correlation between the applied poison and the activity, which is another indication of strong binding of the poison. Drawing a tangent line through the first five points gives an estimate that ~42% of the applied Pd atoms are active. This is a substantially higher amount than in the transfer semihydrogenation reactions in absence of stabilizing PPh_3, and suggests that molecular catalysts or small clusters are active rather than NPs.

Following the protocol, we performed DLS studies, in which NPs with average particle size of ~30 nm were observed after 40 min. For these NPs, about 4% of the Pd atoms are expected to be on the surface (see the Supporting Information, SI7). Such NPs do not correspond with the estimated 42% of the Pd that is active in the reaction according to the quantitative poisoning studies. The amounts of active Pd differ by more

than an order of magnitude between the two methods, therefore, we conclude that the observed NPs are not responsible for the bulk of the catalytic activity.

Hypothetically, three catalyst systems could give rise to the results that were obtained from the previous studies. 1) Nanocluster active catalysts, where also less active or inactive NPs are formed. 2) Dissolved substrate-ligated species that are in equilibrium with NPs/nanoclusters. 3) A well-defined, molecular species is active and at the same time less active, or inactive NPs are formed. To complicate matters, a combination of these catalyst systems may be operative as well. Determining which of these possibilities is real, is extremely difficult and sometimes impossible.[11,103] In such cases one may only indicate which case is more plausible,[10] therefore, a few remarks on each system are presented.

The percentage of Pd that is active is the best tool to assess whether nanoclusters may be active. The percentage of the metal that is active in nanoclusters has been scarcely studied.[63,83,104,105] If ~40% of all Pd is in an active state, this is a high but not unrealistic value for nanoclusters, for which a much larger amount of the Pd centers is exposed to the reaction medium at the surface of these particle as compared to NPs. The value is especially high considering that part of the metal is present in a NP form as well. Nanoclusters could also give rise to the observed kinetic first-order in palladium, if their structures are defined and their rate of formation does not depend too strongly on the Pd concentration.[4,109]

A molecular active species could also be obtained if an equilibrium exists between NPs and substrate ligated species. Such an equilibrium would explain the observed NPs and could also give rise to the estimated percentage of active Pd. A similar mechanism was derived for a [Pd^{II}NHC] catalyst system for Suzuki–Miyaura cross-coupling reaction proposed for catalysts.[107] In this publication the NHC ligand is still proposed to be part of the molecular active species that is in equilibrium with the NPs, however, the substrate to Pd ratios of such catalyst systems are generally orders of magnitude higher than for our system.[4,108]

Efficient well-defined molecular catalyst systems are expected to give values greater than 40% of active metal. However, if also inactive NPs are formed, a part of the added palladium is deactivated, thus leading to a lower percentage of active Pd atoms. Furthermore, we previously proposed that the phosphine coordination to the [Pd^0(NHC)] species leads to an inactive state,[102] which was also proposed for a Pd(NHC)PCy$_3$ system by Cazin et al.[41,109] The presence of an inactive species could also explain why a lower fraction of Pd that is active in the reaction is obtained for a molecular catalyst. The degree of Pd that is in a poison-independent inactive state depends on the binding strength of the phosphine ligand compared to that of the alkyne substrate. Unfortunately, we were unable to determine the binding constants for both species, therefore, we cannot quantify or estimate the amount of catalyst that is in a dormant state and correlate this to the observed active metal fraction. On a qualitative basis, we can derive that the binding of the phosphine ligand is strong. By application of 1.0 equivalent of PPh$_3$ the catalytic activity is reduced by 80%. Based on the observed strong binding of PPh$_3$, a significant fraction of the Pd may be in an inactive state.[102] In this case, the obtained percentage of active Pd fits well with a molecular active compound. The data obtained in the previous mechanistic studies are also circumstantial evidence of a molecular catalyst.[102] The proposed molecular catalyst would yield a kinetic first-order in catalyst concentration. The [Pd^0(IMes)(TMTU)(MA)] compound **9** shows some activity, but does not form NPs. An influence of the NHC ligand is observed. Based on these observations a molecular complex or small cluster derived thereof is the most likely catalyst.

To summarize, the type of catalyst for transfer semihydrogenation reaction using precatalyst **11** and PPh$_3$ additive ligands was investigated. The results obtained leave room for speculation, but combined with the known properties of the different types of suggested catalysts and indirect evidence provided by the mechanistic studies, the data point to a partially deactivated molecular catalyst system that dominates the catalytic reaction.

Conclusions

We have developed a protocol to determine the type of active catalyst for several Pd-catalyzed semihydrogenation reactions of alkynes to *Z*-alkenes. This protocol relies on DLS and quantitative partial poisoning, as well as various validation experiments. We developed a novel validation experiment involving the coordination of the poisons TMTU and CS$_2$ to relevant Pd^0 complexes, which revealed that TMTU is a good ligand for Pd. The X-ray crystal structures of **5**, **8**, and **9** have been obtained for reference.

Apart from the semihydrogenation reactions, we studied the Pd-catalyzed copolymerization of CO and styrene, which is an extensively studied, molecularly catalyzed reaction that is, therefore, ideally suited as an additional validation of the protocol. TMTU is a valid poison for this reaction as well. According to the protocol, the copolymerization reaction is indeed catalyzed by a molecular species. Hence, the additional validation of the protocol as well as the validation of TMTU as a poison ligand were successful. We also demonstrated that, for the copolymerization reaction, TMTU is a poison ligand superior to CS$_2$.

The protocol demonstrated that the semihydrogenation of alkynes with molecular hydrogen is not catalyzed by the previously proposed [Pd(NHC)]-catalyst **5**. Instead, it is catalyzed by NP-based species that were most likely generated during the synthesis of the NHC complexes.

Subsequently, the protocol was applied to two transfer semihydrogenation reactions. The first, employing an in situ generated [Pd^0(NHC)] system **10**, essentially does not operate as it was proposed, since only about 10% of the applied palladium is active in the reaction and NPs are observed. The results are indicative of NPs being the active catalysts, however, the control experiments do not warrant the conclusion that NPs catalyze the reaction. The second catalyst system that was investigated for this reaction originates from precatalyst **11** and PPh$_3$ as the additive. The results and previous mechanistic studies

indicate that the active catalyst for this system is probably a molecular species.

We found that TMTU is a superior poison ligand relative to the standard poison ligand CS_2 for the copolymerization and the semihydrogenation reaction. We propose, because of its versatility and coordination properties, to add TMTU to the range of available poison ligands and use it in future poisoning studies involving late transition metal (pre)catalysts.

Overall, this study has demonstrated the importance of determining the type of active catalyst. None of the semihydrogenation reactions appear to be as straightforward as they were originally presented. Critical evaluation of such systems, preferably in early stages of research, is essential. Protocols as the one presented here may facilitate such critical evaluations as a valuable tool for catalyst development, since it is straightforward, reliable and probably applicable to various other types of catalytic reactions.

Experimental Section

Complex synthesis and catalytic experiments were performed using Schlenk techniques under dry nitrogen. Solvents were dried according to standard procedures and distilled prior to use unless stated otherwise.[110] Maleic anhydride was crystalized from hot DCM. $[Pd(Cl(\eta^3\text{-}C_3H_5)]_2$, triethyl amine, formic acid, potassium *tert*-butoxide triphenylphosphine, Pd nano-powder, Pd on carbon (10 wt%), Pd on $BaSO_4$ (10 wt%) and Lindlar's catalyst (5 wt%) were purchased from Sigma-Aldrich. The BASF Nano-Cat was purchased from Strem chemicals. A Pd-DVTMS [1,3-divinyl-1,1,3,3-tetramethyl-disiloxane palladium(0)] solution was generously provided by Umicore. Compounds **5**[102] and **12**[111] were synthesized according to literature procedures. NMR spectra were recorded by using Bruker AV 400 MHz, Bruker DRX 300 MHz and Varian Mercury 300 MHz spectrometers. HR mass spectrometry was performed by using a Bruker MicrOTOF-Q machine using ESI. GC analysis were performed by using a Thermo Scientific Trace GC Ultra equipped with a R-Rxi 5 ms column (30 m, ID 0.25 mm) and quantified using the response factor corrected GC-areas in respect to the internal standard. ICP-AES analyses were performed by using a Mikroanalytisches Laboratorium Kolbe, Mülheim an der Ruhr, Germany. DLS data were obtained by using an ALV/LSE 5003 light scattering electronics and multiple Tau digital correlator. Complex synthesis is described in the Supporting Information, SI8.

The copolymerization of CO and styrene: A three-necked, thermostated 75 mL glass reactor equipped with a magnetic stirrer and connected to a temperature controller was heated to 30 °C. After establishment of the reaction temperature 20 mL 2,2,2-trifluoroethanol (TFE), 10 mL of styrene, 0.0127 mmol of the selected precatalyst and 0.0635 mmol of 1,4-benzoqinone were added, after which the solution was bubbled through with CO for 10 min. Subsequently, if required, the appropriate amount of poison was added, followed by addition of the appropriate amount of poison, if required. The solution was bubbled through with CO for 10 min and afterwards a previously filled, 4 L balloon was connected to the reactor. The system was stirred for 24 h, after which the reaction mixture was poured onto methanol (100 mL) and stirred for 1.5 h at room temperature. The obtained solid was filtered, washed thoroughly with methanol and dried under vacuum until a constant weight was obtained and analyzed by NMR spectroscopy.

Semihydrogenation of 1-phenyl-1-propyne with authentic particle-based precursors and molecular precursors: The appropriate catalyst precursor (0.008 mmol, 0.4 mol% based on Pd content) was added to a 2-necked Schlenk that was equipped with a hydrogen gas bag and a valve with a septum containing 10 mL of a previously prepared, degassed stock solution of MeCN with 0.83 M 1-phenyl-1-propyne and 8.3 M *p*-xylene. If required, 0.002 mmol of the appropriate poison was added as 0.5 mL of a stock solution of the poison. Then the mixture was placed under a hydrogen atmosphere by ten cycles of evacuation and subjecting to hydrogen atmosphere. Periodic sampling was performed by taking 0.05 mL of the mixture, filtering over a plug of silica with 1 mL of DCM which was analyzed by GC. DLS-measurements were performed by taking 1.5 mL of the solution, which was filtered over a 0.4 μm filter and transferred to a custom made cuvette that was adapted with a Schlenk connector that allowed inert handling.

A "hot" filtration test for the semihydrogenation of 1-phenyl-1-propyne with supported catalyst materials: The normal catalytic procedure was performed, only after 5 min a sample was taken and the reaction mixture was filtered over a column of Celite. The filtrate was transferred to another 2-necked Schlenk and exposed to hydrogen and the solution was allowed to react further and periodic samples were taken to determine the activity of the liquid phase.

Determination of the Pd leaching from the particle precatalyst materials in the semihydrogenation of 1-phenyl-1-propyne: Using ten times the standard amount of Pd on C and five times the standard volume of stock solution the reaction was run for twenty-one hours and filtered over Celite. The solution was concentrated on a rotatory evaporation device and dried under higher vacuum 3×10^{-2} mbar. The obtained oil was analyzed for Pd content using ICP-AES.

Transfer semihydrogenation of 1-phenyl-1-propyne using the proposed in situ generated [Pd^0IMes(MA)] catalyst: The procedure was performed according to the procedure as described by Hauwert et al., with minor adaptations in volumes and instead of Schlenk glassware a Radleys' twelve-place reaction station with integrated heating and cooling setup was used for these experiments.[49] In a typical experiment mesityl imidazolium chloride (12.5 mg, 0.037 mmol) was suspended in 20 mL MeCN and stirred overnight. KO*t*Bu (18 mg, 0.15 mmol) was added to generate the free carbene and the mixture was stirred for one hour. [Pd(*t*Bu-DAB)(MA)] (**6**) (12.4 mg, 0.033 mmol) was added and the reaction was stirred for another hour. Subsequently, determining the exact amounts by post-weighing, 1-phenyl-1-propyne (0.38 g, 3.3 mmol), *p*-xylene (0.35 g, 3.3 mmol), NEt_3 (1.69 g, 16.7 mmol), and formic acid (0.77 g, 16.7 mmol) were added in that order. After addition of the formic acid the reaction was heated to 70 °C. At this temperature the appropriate amount of poison was added. Samples for GC-analysis were taken at regular intervals by taking 0.05 mL of the reaction mixture, and filtering it over a plug of silica with 1 mL DCM. DLS samples were prepared by taking 1.5 mL of the reaction mixture, filtering it over a 0.4 μm filter and transferring it to a specially designed cuvette that was adapted with a Schlenk connection. The TOFs for the quantitative poisoning analysis were determined around 15% conversion.

Transfer semihydrogenation of 1-phenyl-1-propyne using preformed or Pd^{II}(IMes) precatalysts with PPh_3 additives: A stock solution was prepared, adding in their respective order: acetonitrile

(320 mL, 250.3 g), 1-phenyl-1-propyne (6.4 g, 55 mmol), *p*-xylene (internal standard, 5.68 g, 54 mmol), triethylamine (27.00 g, 267 mmol) and formic acid (11.48 g, 267 mmol), which was saturated with nitrogen gas by gently bubbling nitrogen through the solution for 20 min. From the stock solution 20 mL was taken, by a syringe, and added to one of the twelve reaction vessels. The exact amount of added stock solution was determined by weighing; for this reason, molar and weight percentages were applied to determine quantities and further calculations. The Radleys' station was heated to 70 °C, after which 0.03 mmol of the appropriate catalyst, and, if required, the PPh_3 additive was added. After 10 min the corresponding amount of the appropriate poison was added. Samples for GC analysis were taken at regular intervals by taking 0.05 mL of the reaction mixture and filtering it over a plug of silica with 1 mL DCM. DLS samples were taken by taking 1 mL of the reaction mixture, filtering it over a 0.4 μm filter and transferring it to a specially designed cuvette that was adapted with a Schlenk connection. The TOFs for the quantitative poisoning analysis were determined around 15% conversion.

Transfer semihydrogenation of 1-phenyl-1-propyne using particle-based precatalyst materials: The experiment was performed as described for the molecular catalysts. However, for Pd on C, Pd nano-powder and Lindlar's catalyst 3 mol% (0.09 mmol) of the precatalyst material was applied. For the poison validation 0.25 equivalent of the appropriate poison (with respect to the Pd) was applied (0.0023 mmol).

The "hot" filtration test for the semihydrogenation of 1-phenyl-1-propyne using particle-based precatalyst materials: A standard experiment, as described previously, was performed. After one hour the reaction mixture was filtered over Celite and the filtrate was allowed to react further, after which the activity was monitored by GC.

Determining the degree of leaching of Pd from the supported precatalyst material and the influence thereon for the transfer Semihydrogenation of 1-phenyl-1-propyne. The experiment was performed as the standard experiment, but on a two and a half time larger scale. The reaction was run for an hour and the mixture was filtered over Celite. Subsequently, the volatiles were removed with on a rotatory evaporation device and further drying was performed at lower pressures (3×10^{-2} mbar). The Pd content was determined by ICP-AES.

CCDC 1049599 (**2**), CCDC 1050449 (**5**), CCDC 1050450 (**8**), and CCDC 1050451 (**9**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via http://www.ccdc.cam.ac.uk/data_request/cif>.

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Keywords: alkynes · ligands · nanoparticles · poisoning · semihydrogenation

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