Transfer Hydrogenation of Azo Compounds with Ammonia Borane Using a Simple Acyclic Phosphite Precatalyst

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Abstract: Tris(quinolin-8-yl)phosphite, P(Oquin)₃, promotes the dehydrogenation of H₂N-BH₃ (AB) and the transfer hydrogenation of azoarenes using ammonia borane (AB) as H₂ source. The metal-free reduction of azoarenes proceeds under mild reaction conditions upon which several diphenylhydrazine derivatives are obtained in high yields. The reactivity of P(Oquin)₃ toward AB was evaluated through NMR in situ tests. The rate of the reaction, activation parameters, deuterium kinetic isotope effect (DKIE) and linear-free energy relationship were investigated. Such mechanistic and kinetic studies suggest that P(Oquin)₃ is a precatalyst and that AB is likely involved in more than one stage of the reaction pathway. Furthermore, the kinetic data indicate that the reaction proceeds through an ordered transition state, possibly associative.

Introduction

Hydrogenation is one of the most fundamental transformations in organic synthesis, and its industrial applications are broad, particularly in the production of fine chemicals to pharmaceuticals.[1] Considering that using H₂(g) requires special reaction (pressure) vessels and particular safety measures, researchers have dedicated substantial effort to develop simpler and safer alternatives for the reduction of unsaturated moieties. In this sense, transfer hydrogenation (TH) has become a practical and useful tool in reduction chemistry in the last decade.[2] TH-reactions using precious-metal catalysts have been intensively investigated.[3] However, for these, abundance, cost, and toxicity are significant issues. Furthermore, considering that for large-scale applications a catalyst for the release/transfer of hydrogen must be cheap and based on abundant materials, the use of platinum-group metals should be avoided. In this respect, organocatalytic-TH using main-group compounds is currently undergoing great development.[4]

Among the broad variety of potential hydrogen storage materials, ammonia borane (AB) has attracted particular interest due to its high weight percent of available hydrogen (19.6 %), high stability in air, high portability and the fact that its dehydrogenation is thermodynamically favorable (ΔH = −5.1 kcal/mol).[5] Although rapid H₂-release from AB has been widely demonstrated by metal-based catalysts,[6,7] latest focus on the hydrogen transfer from AB (or amine-boranes in general) has been directed to organocatalyzed dehydrogenation using, for example, p-block-based systems.[8a–c,9] We have addressed the use of pnictogen-based compounds for TH reactions from AB, e.g. a bismuth,[10] and several phosphorus-based catalysts.[11–19] DFT calculations have revealed an energetically feasible pathway for a concerted double hydrogen transfer (concerted metathesis) from AB, using a phosphorus catalyst.[11]

Studies by Radosevich and co-workers[12] have shown that the highly-strained T-shaped phosphorus(III) compound A (Scheme 1a) promotes the TH of azobenzene (2a) with yields up to 96 % of 1,2-diphenylhydrazine (3a). Reduction of 2a with quantitative yields was also achieved by Kinjo and co-workers[13,14] using diazaphospholene B (Scheme 1b).[15] In addition, these authors also investigated the potential of such compounds as transfer hydrogenation/hydroboration catalysts for the reduction of unsaturated bonds using AB and HB(pin) respectively, through a hydrophosphination/metathesis mechanism.[14] Similarly, Speed et al. described the reduction of imines and conjugated C=C bonds using HB(pin) and diazaphospholene C as precatalyst (Scheme 1c).[15,16] Treatment of C with HB(pin) (1 equiv.) resulted in the formation of B. The authors remarked that, after the hydrophosphination reaction, the initial metathesis occurred only at the exocyclic P-N or P-O bond (whichever the case). Prolonged exposure of B to AB or HB(pin) initiates further P-N bond cleavage, and the generation of PH₃ was observed.[17,18] Lately, reports by the groups of Radosevich,[17] Kinjo[18] and Speed[19] proved that it is possible to extend this application to challenging reduction reactions such as stereoselective reduction of imines and (α-unsaturated aldehydes, chemoselective reduction of C=C bonds in (α-unsaturated esters and hydroboration of pyridines. Additionally, diazaphospholene B catalyzes C-C coupling reactions,[14b] and an
analog of C has been used to promote reductive Claisen rearrangement in the presence of boranes.[20] These investigations suggest the possibility to further expand the scope of phosphorus compounds and their catalytic reactivity.

**Phosphorus-based catalysts used in transfer hydrogenation**

- **a) P–O catalyst**
  - Radosevich 2012

- **b) P–H activation / P–N hydrogenolysis catalyst**
  - Kinjo 2014

- **c) P–O precatalyst**
  - Speed 2017

This work: P–O precatalyst

*Acyclic phosphite precatalyst for the reduction of azocompounds*

Recently, some of us described the synthesis of the phosphorus(III) compound P(Oquin)₃ (1), as well as its coordination chemistry toward Pd⁰ and an application of such a complex as a catalyst for the solvent-free, mild oxidative coupling of primary amines to imines using air as an oxidant.[21] Unlike A–C, which require several synthetic steps, 1 is quickly prepared in a one-pot reaction from commercial products on a gram scale, rendering it convenient for catalytic applications. Furthermore, in the solid-state, 1 presents intramolecular interactions that restrain the structure and originate a distorted geometry around the P-atom (with an average O-P–O bond angle of 93.5 degrees)[21] which, being acyclic, could somehow be similar to the strained or cyclic PIII compounds previously mentioned.

Herein, we report that 1 promotes the reduction of azoarenes using AB as H₂ source, a reaction that has attracted considerable interest recently.[10,12–14] Furthermore, we describe the results of spectroscopic and kinetic investigations, which give insight into the mechanistic features of this reaction. To the best of our knowledge, there is no precedent on the use of an acyclic tricoordinate phosphorus(III) compound for the TH of aromatic azo compounds into arylhydrazines.

### Results and Discussion

In a recent report,[21] the preparation of P(Oquin)₃ (1) was described. According to the reported protocol, the phosphite can be obtained by treating phosphorus trichloride with 8-hydroxyquinoline (HOquin) in the presence of a base (NEt₃ or nBuLi). Following this reported procedure, 1 is sufficiently pure to perform coordination chemistry toward Pd⁰, but not appropriate for organocatalytic applications. The problem lies in the difficulties to eliminate the formed NEt₃·HCl or LiCl in an efficient way. For this reason, an alternative preparation of 1, depicted in Scheme 2, has been now developed in our group. The new methodology consists in the in situ preparation of the 8-quinolinol sodium salt followed by its reaction with PCl₃ (for further details see the supporting information). The NaCl can be separated more easily than NET₃·HCl or LiCl. An analytically pure batch of phosphite was obtained in 90% yield after recrystallization from dichloromethane and diethyl ether.

**Scheme 1.** Cyclic phosphorus compounds and the acyclic phosphite P(Oquin)₃ used in catalytic transfer hydrogenation (TH) from different H₂ sources to unsaturated bonds.

**Scheme 2.** Alternative synthesis of P(Oquin)₃ (1).

Considering the studies by Radosevich,[17] Kinjo[18] and Speed,[19] our group became interested in exploring the poten-
tial of the p-block compound P(Oquin)$_3$ (1) as an organocatalyst in similar transformations. Thus, initially, it was important to study the reactivity of 1 toward AB. To this end, a test using a twenty-fold excess of AB was carried out. The quantitative formation of PH$_3$ ($^{31}$P = $\delta = -242$ ppm, $^{1}$J$_{PH} = 180$ Hz), along with dehydrogenated ammonia borane species, such as borazine and polyborazylene$^{[7]}$ was observed by $^{31}$P and $^{11}$B NMR spectroscopy (Figures S8 and S9, supporting information). These findings evidence the dehydrogenation of ammonia borane along with a chemical transformation of 1. To evaluate the effect of the amount of AB complex on the reaction with 1, the ratio 1/AB was reduced to 1:5 and 1:1 (pseudostoichiometric or stoichiometric reaction, respectively) in independent tests. Although in such cases the reaction is less selective, producing several phosphorus- and boron-containing species (identified by $^{31}$P or $^{11}$B NMR, respectively), it was possible to observe products of the interaction of 1 with AB and to confirm that 1 is a hydrogen acceptor, which is transformed into other compounds. In particular, the presence of quinoline-based boron compounds, such as the corresponding borinate ester BH$_2$(Oquin) (11B=AB), was determined (Figure S14, supporting information). Also, another (major) signal at 14 ppm in $^{11}$B NMR, attributed to the in situ formation of B(Oquin)$_3$ (Figure S3), was identified, along with the common AB dehydrogenation product polyborazylene.$^{[7]}$

Regardless of such lack of selectivity, after determining the reactivity of 1 as hydrogen acceptor from AB, it was important than to study its potential to promote transfer hydrogenation reactions or, more specifically, to determine whether the phosphate or its products after dehydrogenation of AB could engage in the transfer of hydrogen to an unsaturated substrate. Thus, the hydrogenation of azobenzene (2a) in the presence of the ratio 1:1 to yield 1,2-diphenylhydrazine (3a), was tested as a model reaction (Table 1). For the sake of comparison, other analogous phosphate compounds were also tested as catalyst precursors.

The reduction of 2a in THF at 60 °C produces 3a in high yields (>95 % after 16 h, entry 1). By using stoichiometric amounts of AB (1.1 equiv. relative to azobenzene) at the highest catalyst loading studied (i.e. 30 mol-%), the reaction proceeded without significant loss in yield, but a longer reaction time was required (>95 % after 24 h, entry 2). However, when stoichiometric amounts of AB were used at catalyst loadings between 20 mol-% and 5 mol-%, the catalytic activity dropped significantly (entries 4, 6, 9 and 11 compared to entries 3, 5, 8 and 10, respectively). The observed effect is more pronounced for lower catalyst loadings. Good conversion was achieved using 10 mol-% of 1 and a four-fold excess of AB (80 % after 24 h, entry 8). Moderate activity was observed for loadings below 5 mol-% of P(Oquin)$_3$ (57 %, entry 10). Lowering the (pre)catalyst loading to 12.5 mol-% still gave high conversions of 2a when compared to higher catalyst loadings (ca. 90 %, entries 3 or 5 vs. entry 7). Compounds similar to 1, e.g. (R)-binaphthol-P(8-Oquin) [(R)-binaphthol-P(8-Oquin) = 8-(dinaphtho-[2,1-d:1’2’-f][1,3,2]dioxaphosphepin-4-yl oxy)quinoline$^{[22]}$ and P(1-O-Naphthyl)$_3$,$^{[23]}$ or the aromatic phosphate P(OPh)$_3$ were inefficient catalyst precursors under the studied conditions, yielding 3a in only 63 %, 17 % or 40 %, respectively (entries 13 and 14). In the absence of a catalyst precursor, a very poor conversion was observed, thus highlighting the catalytic nature of the transformation (entry 15). In a screening of solvents (see the supporting information), high activity was also obtained in acetonitrile, benzene, and toluene. In particular, the latter two apolar hydrocarbons gave a quantitative reduction of 2a after 24 h. However, THF was selected as the solvent for the rest of the studies to avoid interference with aromatic signals at quantifying steps on the $^{1}$H NMR spectra.

Considering the spectroscopic evidence obtained from the reactivity tests (i.e. the formation of PH$_3$, BH$_2$(Oquin), BH(Oquin)$_3$ and HOquin) it was important then to determine the influence of such compounds on the model reaction (Table S2, Section D, Supporting Information) and, thus, to shed some light into the possible mechanism and/or catalytic species involved in the transformation. In this sense, initially, the catalytic activity of 8-quinolinol (HOquin) was tested. 70 % conversion was achieved with 30 mol-% of 8-quinolinol after 24 h. Longer reaction time (64 h) did not increase the conversion in this case. Also, NaPH$_2$ was independently examined as a PH$_3$ source. No conversion of 2a to 3a was observed, using either

### Table 1. Metal-free transfer hydrogenation of 2a using phosphate 1 as precatalyst. Screening of catalyst precursors.$^{[4]}$

| Entry | Catalyst precursor | Time (h) | Catalyst loading (mol%) | Conversion (%$^{[d]}$) |
|-------|--------------------|----------|--------------------------|-----------------------|
| 1     | 1[1]               | 16       | 30                       | >95                   |
| 2     | 1[1]               | 24       | 30                       | >95                   |
| 3     | 1[1]               | 24       | 20                       | >95                   |
| 4     | 1[1]               | 24       | 20                       | 78                    |
| 5     | 1[1]               | 24       | 15                       | 94 ± 1f (91)[6]       |
| 6     | 1[1]               | 24       | 15                       | 73 ± 3                |
| 7     | 1[1]               | 24       | 12.5                     | 87 ± 3                |
| 8     | 1[1]               | 24       | 10                       | 80 ± 2                |
| 9     | 1[1]               | 24       | 10                       | 57 ± 2                |
| 10    | 1[1]               | 24       | 5                        | 57 ± 2                |
| 11    | 1[1]               | 24       | 5                        | 20 ± 1                |
| 12    | None               | 64       | 30                       | 40                    |
| 13    | None               | 64       | 30                       | 63                    |
| 14    | None               | 64       | 30                       | 17                    |
| 15    | None               | 64       | 0                        | <5                    |

[a] 2a (54.7 mg, 0.300 mmol), AB (37.0 mg, 1.200 mmol, 4 equivalents), 1,3,5-trimethoxybenzene (16.7 mg, 0.099 mmol, internal standard), THF (1.25 mL), argon atmosphere, 60 °C, 24 h. [b] AB (10.2 mg, 0.330 mmol, 1.1 equivalents). [c] Conversions determined by $^{1}$H NMR using the internal standard. Values with errors are the result of at least two independent experiments. Triplicates were performed when the deviation of two experiments was larger than ±5. [d] Values in parenthesis correspond to isolated yield.
NaPH₂ or combining NaPH₂ with HCl (10 mol-%, 1.0 m in Et₂O) to produce PH₃ in situ. Subsequently, the catalytic performance of a 1:3 mixture of NaPH₂ and 8-quinolinol was investigated. This mixture yielded a conversion to 3a of >95 % after 24 h, thus reproducing the performance (in terms of product yield) achieved by 1. The substrate to AB ratio could be lowered to 2:1 and the reduction of 2a still occurred effectively (>95 %).

Finally, to investigate the possible role of the boron-containing species generated in situ from the system 1 + AB, separate TH reactions were performed using some of the boron-esters observed in the reactivity tests. In fact, BH₂Oquin and BH(Oquin)₂ were among such boron compounds detected on the NMR scale experiments. These were also independently synthesized[24] to be used on the catalytic tests (see the Supporting Information), yielding 70 % and >95 % conversion of 2a to 3a, respectively. The use of BH₂(Oquin) as catalyst[24] in the reaction led to a yield of the diphenylhydrazine product 3a lower than with the system 1 + AB. This seems to indicate that BH₂(Oquin) is not the (sole) species responsible for the catalysis in this case. Unfortunately, it was impossible to assess the role of B(Oquin)₃ on the reaction. Attempts to isolate pure B(Oquin)₃ (which was assigned to a signal at 14 ppm in the ¹¹B NMR spectra, vide supra) yielded a mixture of BHₓ(Oquin)₃₋ₓ (x = 0,1,2) that could not be separated. Steric crowding on the boron atom, due to the presence of the three “Oquin” moieties, could be responsible for the impossibility to isolate such compound.

The findings from the reactivity tests strongly suggest that 1 is indeed a catalyst precursor, which serves as an appropriate source of the actual catalyst(s). While the identity of the true catalyst(s) presently remains unknown, both the phosphorus source and the “Oquin” moiety are required for the catalytic TH of 2a from AB. Furthermore, although NaPH₂/8-quinolinol and

Table 2. Metal-free transfer hydrogenation of azo compounds using phosphite 1 as precatalyst. Screening of substrates.\[a\]

| Symmetrical  | Unsymmetrical |
|--------------|--------------|
| 2b–n (0.300 mmol), 1 (13.9 mg, 0.030 mmol), AB (37.0 mg, 1.200 mmol), 1,3,5-trimethoxybenzene (16.7 mg, 0.099 mmol, internal standard) THF (1.25 mL), Argon atmosphere, 60 °C, 24 h. \[b\] 16 h. \[c\] 12 h. Given conversions (%) determined by ¹H NMR spectroscopy. Values in parentheses (%) correspond to isolated yields. |

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BH(Oquin)$_2$ also worked effectively in converting 2a into 3a in the presence of AB, the use of these catalytic systems would be more inconvenient. NaPH$_2$ is hard to prepare, difficult to handle and pyrophoric.$^{[25]}$ BH(Oquin)$_2$ (as well as BH$_2$(Oquin)$^{[24]}$) is thermally unstable and needs to be stored cold under inert atmosphere. For all the above, 1 was chosen as catalyst precur-
sor for the rest of the study.

The following were selected as optimized conditions to ex-
amine the scope of the catalytic system with a series of sym-
metrical and unsymmetrical (E)-diazenes (Table 2): 10 mol-%
of catalyst precursor 1, 4 equivalents of AB, 60 °C, 24 h (unless otherwise stated). Although the best conversion for substrate 2a was achieved using 15 mol-% of phosphite 1 as catalyst, for the rest of the azoarenes studied the use of catalytic loadings of 10 mol-%, 12.5 mol-% or 15 mol-% did not significantly affect the conversion obtained. Thus, the catalyst loading was kept to the lowest possible to achieve the observed yields (Table 2). Symmetrical azoarenes bearing electron-donating groups (EDG) such as methyl in different relative positions (p-, m- and/or o-, 2b-d, k), were converted into the corresponding phenyl-
hydrazine compounds with good yields. The bulky compound 2d is the only exception, for which 35 % of the corresponding product was achieved after 24 h. Steric hindrance around the N=N bond might explain the low yield for such a compound. In the case of p-dimethylaniline derivatives (2j and 2l, symmetri-
cal and unsymmetrical, respectively) a quantitative conversion was achieved. For p-methoxy (2i) a moderate conversion was obtained. Additionally, symmetrical and unsymmetrical azo-
arenes bearing electron-withdrawing groups (EWG) in the para-
position, such as fluoro (2e), chloro (2f), and bromo (2g) deriva-
tives, were reduced with good to excellent yields. In addition, a derivative substituted with trifluoromethyl groups (2h) in the m-position was tested, and a conversion of 90 % was achieved. (E)-diazenes bearing a p-NH$_2$ (2m) or p-COOH (2m) gave very poor yields of the corresponding hydrazine after 24 h. Increasing the reaction time up to 64 h in these cases did not improve the conversion, suggesting that the system does not tolerate groups that have acidic protons.

The kinetics for the catalytic TH of 2a to yield 3a were exam-
ined. The progress of the reaction as a function of time was monitored by $^{1}H$ NMR spectroscopy (Figure S15, supporting in-
formation). Plotting ln ([$AB$]/[AZB]$_{0}$) vs. time (h) produced a straight line (Figure S16, supporting information). Here, [AZB] is the molar concentration of azobenzene at each given time and [AZB]$_{0}$ is the initial molar concentration of azobenzene. This simple experiment suggested a pseudo-first-order rate equa-
tion with respect to the azobenzene concentration in the pres-
ence of an excess of AB. Additionally, an induction period was observed, which needed to be considered for the analysis of the kinetic data. This period might be related to the time re-
quired for the activation of the precatalyst 1, thus forming the actual active species, as evidenced by the reactivity (mechanis-
tic) tests (vide supra).

The evaluation of the reaction order with respect to the other individual components of the system was also carried out. A generic rate law for the TH of azobenzene is shown in (Equa-
tion (1)). From this, the values $\alpha$, $\beta$, and $\gamma$ were determined by measuring the influence of the concentration for each respective component on the reaction rate.

$$r = k_{app}[AB]^{\alpha} [cat]^{\beta} [AB]^{\gamma}$$ (1)

The rate of the reaction was measured as a function of the concentration of azobenzene, ranging between 0.044 M and 0.220 M, while the concentration of precatalyst and AB, tempera-
ture and time were kept constant. The representation of ln r vs. ln [AB] (Figure S17, supporting information) returned a straight line with a slope of 1.02, indicating a first-order de-
pendence on the concentration of azobenzene. This confirmed the result from the monitoring of the reaction as a function of time (vide supra). Likewise, the rate of reaction was measured depending on the catalyst concentration, ranging from 0.004 M to 0.025 M, while the concentration of azobenzene, concentra-
tion of AB, temperature and reaction time were kept constant. A fractional order (1/2) dependence on catalyst concentration can be observed from the plot of ln r vs. ln [cat] with a slope value of 0.48 (Figure S18, supporting information). The kinetic data were also analyzed using the graphical method described by Burés,$^{[26]}$ thus confirming our findings for catalyst loadings higher than 10 mol-% (see supporting information). This result suggests that there is a complex relationship between the cata-
lyst concentration and the reaction rate and confirms that 1 acts as a precatalyst. The fractional order could be a conse-
quence of the induction time required to form the actual cata-
lyst or could also be related to the fact that more than one catalytically active species is involved. Given the fact that an excess of AB (4 equivalents respect AZB, formally up to 8 eq. H$_2$) has been used, its concentration is higher than needed at any time and, thus, it can be considered constant. Conse-
quently, AB concentration disappears from the rate law equa-
tion (Equation 1) and it is integrated into the rate constant k, leading to an apparent rate constant $k_{app} = k[AB]^\gamma$. Once the order of reaction with respect [AZB] and [1] were determined, the magnitude of $k_{app}$ could be calculated (0.029 ± 0.005 s$^{-1}$, L$^{0.5}$-mol$^{-0.5}$). These kinetic experiments indicate that the rate law can be represented as in (Equation (2)) at constant tempera-
ture (60 °C) and using a four-fold excess of AB (formally 8 equivalents of H$_2$).

$$r = k_{app}[AB]^{\gamma}[1]^{1/2}$$ (2)

The temperature dependence on the rate of reaction was evaluated using temperature ranges between 40 °C and 80 °C, at 10 °C intervals. The representation of the ln [AZB] vs. time gave a straight line (Figure S19, supporting information). An induction time caused by precatalyst activation was observed, which was inversely proportional to the temperature and the substrate concentration. Points representing the induction time were discarded from the graph, to obtain a better fit on linear-
ity.

After determination of the temperature influence on the re-
action rate, an Eyring and Arrhenius analysis was performed (see Figure 1). The ln (r/T) was plotted against the inverse of the temperature (1/T) (Figure 1a) yielding a straight line. From the slope and the intercept, values of $\Delta H^*$ = 17.1 ± 2.6 kcal/mol, $\Delta S^*$ = −31 ± 7 e.u and $\Delta G^*$ = 26.4 ± 5.7 kcal/mol were calcu-
lated. The sign and magnitude of the entropy of activation are consistent with a reaction step involving a transition structure typical of a bimolecular reaction. This might be in agreement with an associative mechanism, in which at least two reaction partners form a single activated complex.\(^{[8b,8c,17,27]}\) The In \(r\) was plotted against 1/T (Figure 1b) and from the Arrhenius analysis, an activation energy of 17.8 ± 4.1 kcal/mol was obtained.

Figure 1. Eyring (a) and Arrhenius (b) plot for TH of azobenzene catalyzed by P(Quin). Based on respective equations, activation thermodynamic parameters and activation energy were determined.

To the best of our knowledge, only two examples of kinetic experiments have been reported for the TH of azobenzene involving AB as the hydrogen source. Kinjo and co-workers studied the kinetics for the TH of azobenzene using the diazaphosphene catalyst B.\(^{[13,14]}\) Their results also suggest a first-order rate equation with respect to the substrate. Radosevich and co-workers\(^{[12]}\) carried out kinetic experiments for the TH of azobenzene catalyzed by species A. Also, in this case, in the presence of an excess of azobenzene, the reaction follows a pseudo-first-order kinetics. Furthermore, Eyring analyses were performed obtaining the following activation thermodynamics parameters: \(\Delta H^\ddagger = 21.8\) kcal/mol, \(\Delta S^\ddagger = -11.6\) e.u and \(\Delta G^\ddagger(298.15) = 25.2\) kcal/mol, for Kinjo’s system; \(\Delta H^\ddagger = 12.4\) kcal/mol, \(\Delta S^\ddagger = -36\) e.u and \(\Delta G^\ddagger(298.15) = 23.13\) kcal/mol, for Radosevich’s system. The sign of the enthalpy of activation (+\(\Delta H^\ddagger\)) and the sign and magnitude of the entropy of activation (−\(\Delta S^\ddagger\)) in the present work agree with the results cited before. Moreover, the magnitudes of the free-energy of activation (+\(\Delta G^\ddagger\)) are very similar in all cases. This might suggest that the nature of the transition state of the rate-determining step is related in these cases.

Further kinetic analysis using deuterated ammonia boranes was carried out to examine deuterium kinetic isotope effects (DKIEs, Figure 2). The DKIEs values were determined based on the ratio of the reaction constants \(k_{AB}/k_{AB(D)}\), where \(k_{AB}\) corresponds to the reaction constant with the protiated ammonia borane and \(k_{AB(D)}\) is the reaction constant of each of the respective deuterated ammonia boranes.

Normal DKIEs values of 1.45 and 1.50 were observed for the reaction of azobenzene with \(D_2N\cdot BH_3\) and \(H_2N\cdot BD_3\), respectively, and a DKIE of 2.14 in the case of the fully-deuterated compound. The group of Kinjo reported a trend similar to the one found in this investigation for the kinetic isotope effect (KIE) in their system, i.e. \(k_{AB} > k_{AB(D)} > k_{AB(DD)}\) \((AB(D) = H_2N\cdot BD_3; A(D)B = D_2N\cdot BH_3; A(D)B(D) = D_2N\cdot BD_3)\), determined by experimental and theoretical means. The overall KIE was associated with the cleavage of both B–H and N–H bonds in the rate-determining step of the reaction, in a double-hydrogen-transfer concerted mechanism.\(^{[13,14]}\) For the TH of azobenzene catalyzed by 1, as expected, the DKIE obtained with perdeuterated AB \((D_2N\cdot BD_3, k_{AB}/k_{AB(DD)} = 2.14)\), corresponds to the product of the individual KIEs (within the experimental error, \(k_{AB}/k_{AB(D)} = 1.45, k_{AB(D)}/k_{AB(DD)} = 1.50, k_{AB(D)}/k_{AB(DD)} \times k_{AB(D)/k_{AB(DD)}} = 2.18\)). This suggests that B–H and N–H bonds are simultaneously broken and are probably relevant to the rate-determining step (RDS). Similar observations have been previously made for other homogeneous catalytic systems of AB dehydrogenation.\(^{[10,28]}\) In the literature,\(^{[6d,10,13,14,27–29]}\) \(k_{AB}/k_{AB(D)}\) values ranging from 1.39\(^{[27]}\) to 7.05\(^{[10]}\) have been considered as significant and a clear indication of both B–H/N–H bond breaking as the rate-determining step.

Finally, a Hammett study was performed to investigate the effect of different substituents in \(p\)-position on the aryl ring. THF solutions (0.132 M) of different \(p\)-substituted azobenzene compounds were chosen as follows: two of them bearing electron-donating groups (Me and OMe), and two with electron-withdrawing groups (Cl and F). The reaction rate \((r)\) for each substrate \((2a–b, e–f, i)\) was obtained from the slope of the plot.
of the natural logarithm of the substrate concentration \( \ln(\text{p-\text{FG-AZB}}) \) against time. Once the reaction rate for the \( p \)-substituted azobenzene series was known, a Hammett analysis was carried out. Log \( k \) was plotted against the substituted constant (\( \sigma \)) as depicted in Figure 3.

The Hammett plot returns a straight line and reveals a linear free-energy relationship (\( \Delta G^\ddagger \)) between the \( p \)-substituted azobenzene compounds. In other words, \( \Delta H^\ddagger \) is constant for the series whereas \( \Delta S^\ddagger \) is proportional to the substituent constant \( \sigma \). The azocompound series studied followed the linear-free energy relationship (LFER) equation with a reaction constant (\( \rho \)) of 1.294. The sign of the reaction constant indicates that the transition state of the rate-determining step presumably carries a negative charge, while the magnitude means that this system is less sensitive to functional groups around the aryl ring than related systems.\(^{13,14}\)

The experimental evidence and results obtained, along with the kinetic data (rate of reaction, activation thermodynamics parameters, DKIE, and LFER) confirm that \( \text{AB} \) suffers dehydrogenation initiated by the acyclic phosphite \( \text{P(Oquin)}_3 \) (1), thus generating catalytically active species which perform the transfer hydrogenation of azobenzenes. The system is very efficient, and a variety of substituted phenylhydrazines were obtained. However, it is not possible to make a mechanistic outline or to propose a catalytic cycle for the system since the identity of the active species (catalyst) could not be unequivocally determined. Regardless of that, it becomes clear that: 1) \( \text{P(Oquin)}_3 \) is a pre-catalyst, and its use is more convenient than the generation of the catalytic system in situ since it can be more easily handled, 2) the mechanism is probably associative, as reflected in the \( \Delta S^\ddagger \) which indicates a more ordered (concerted TH) transition state, and 3) deuteration of \( \text{AB} \) significantly affects the reaction rate and suggests a simultaneous N-H and B–H bond cleavage that (directly or indirectly) influences the rate-determining step.

**Conclusions**

The phosphorus(III) compound 1 reacts with \( \text{AB} \) generating a catalytically active system which was exploited to perform the transfer hydrogenation of apolar N=N bonds in azaarenes. The corresponding hydrazines were obtained in high yields. The reaction conditions were studied for a model reaction (azo-benzene as substrate) and the hydrazine formation proceeds under mild conditions: 10 mol-% 1 as catalyst precursor, 60 °C, 24 h and 4 equivalents of \( \text{AB} \). Kinetic measurements indicate that the best approximation for the rate law is \( r = 0.029 \pm 0.005 \times 1^{-1} \times \text{L}^{-0.5} \times \text{mol}^{-0.5} \times \text{[AZB]}_1 \times [1]^{1/2} \) at a constant concentration of \( \text{AB} \) and temperature (60 °C). The analysis of KIEs indicated that the cleavage of B–H and N-H bonds of \( \text{AB} \) is either part of the rate-determining step or at least has a significant indirect effect in the reaction rate. Activation thermodynamic parameters were obtained from both Eyring and Arrhenius analysis, and suggest that the reaction proceeds through an organized transition state, consistent with an associative mechanism. A Hammett plot showed a linear free-energy relationship (\( \Delta G^\ddagger \)) among the \( p \)-substituted azobenzene compounds studied. The kinetic and mechanistic investigations do not provide enough evidence on the identity of the catalytically active species, formed from 1, but suggest that \( \text{AB} \) is involved in more than one reaction step (at least in the reaction with phosphite 1 and in the hydrogen transfer to the substrates). The potential of 1 to promote novel transformations via bond activation in small molecules will certainly be an ongoing area of interest in our group. Additional efforts are also being directed to the synthesis of alternative \( \sigma^3\text{P} \) compounds for the reduction of even less reactive, nonpolar covalent bonds.

**Experimental Section**

**General Information:** A full description of the general experimental methods, including preparation and purification of starting materials for the catalytic and kinetic studies can be found in the Supporting Information. The synthesis of \( \text{P(Oquin)}_3 \) follows an alternative method to the one reported in the literature.\(^{221}\) is described in the electronic supplementary information (ESI) file.

**Catalytic TH of azo compounds.** Compound 1 (13.9 mg, 0.030 mmol), the corresponding azocompound 2a-n (0.300 mmol), ammonia borane (37.0 mg, 1.20 mmol), the internal standard 1,3,5-trimethoxybenzene (16.7 mg, 0.099 mmol) and THF (1.25 mL) were loaded in a Schlenk tube under argon atmosphere. The Schlenk tube was sealed, placed in an oil bath, and heated at 60 °C. The reaction was monitored by \(^1\text{H} \) NMR spectroscopy. Products 3a–n were purified by flash column chromatography on silica gel (9:1 = petroleum ether/ethyl acetate) or simply extracted from the reaction mixture with \( n \)-hexane when quantitative conversion was achieved.

**Kinetic study.** In a dry 25 mL Schlenk tube with a silicone septum screw cap and under argon atmosphere a THF solution of azobenzene (0.500 mmol, 0.132 M), 1 (23.2 mg, 0.050 mmol), ammonia borane (72.1 mg, 2.00 mmol), and 1,3,5-trimethoxybenzene (28.0 mg, 0.165 mmol) was loaded and heated at 60 °C. Aliquots (0.2 mL) for NMR sample were transferred with a syringe and the NMR tubes were filled with dry THF and a \( \text{CaCl}_2 \) capillary. Reaction progress was monitored as consumption of azobenzene, by \(^1\text{H} \) NMR, every 30 minutes for 14 h.

Rate of reaction as a function of substrate or precatalyst concentration. **Dependence on the Concentration of Substrate:** The general procedure was applied using the following concentration (mol.L\(^{-1}\)) of azo-
benzene: 0.044, 0.088, 0.132, 0.176 and 0.220. The concentration of precatalyst and AB, as well as temperature and time, were kept constant during such experiments. Dependence on the Concentration of Precatalyst: The general procedure was applied using the following concentration (mol·L⁻¹) of 1: 0.004, 0.007, 0.013, 0.019 and 0.025. The concentration of substrate and AB, as well as temperature and time, were kept constant during such experiments. Rate of reaction as a function of temperature (Eyring and Arhenius study): The general procedure was followed for the range of temperatures 40–80 °C, rising the temperature in 10 °C intervals. The concentration of substrate, 1 and AB, as well as time, were kept constant during such experiments. The Eyring plot was obtained based on the representation of ln(k/T) against the inverse of temperature (1/T). With this, activation thermodynamic parameters were calculated. The Arheniuss plot was obtained from ln(k) vs. inverse of temperature (1/T), which returned the activation energy. Hammett study: The general procedure was applied using different p-substituted azobenzenes, bearing either electron-donating or electron-withdrawing groups (OMe, Me, F and Cl). The Hammett study.

Deuterium kinetic isotope effect (DKIE’s): A [D₈]THF solution of azobenzene (27.3 mg, 0.150 mmol, 0.220 m), 1 (7.0 mg, 0.015 mmol), ammonia borane · H₂BH₃ (18.5 mg, 0.600 mmol), and 1,3,5-trimethoxybenzene (8.3 mg, 0.049 mmol) were loaded in a dry J-Young-Tube, under argon atmosphere. The tube was sealed and heated at 60 °C. The reaction process, as consumption of azobenzene, was monitored by ¹H NMR spectroscopy in-situ at 20-minute intervals for 6 h. This procedure was repeated for different deuterated ammonia borane adducts (D₅N-BH₃, D₅N-BD₂, and D₅N-BD₃, 0.600 mmol). The DKIE values were determined based on the ratio of reaction rates (kₐₖ/kₑ₄₅₈₆).

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Keywords: Ammonia borane · Hydrogen transfer · Hydrogenation · Organocatalysis · Phosphite

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