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Mechanism for enolate transfer between Si and Cu

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Abstract: Exchange of X (F, Cl and OMe) and a substituted enolate chain between SiMe₃ and various Cu(I) complexes has been examined. Reaction mechanisms go through a cyclic transition state in which the reaction coordinate is associated to the rotation of the SiMe₃ moiety. The dependence of the thermodynamic and kinetic features to the nature of the active and ancillary ligand was examined. Formation of copper enolate is shown to be favoured when stabilized enolates are used. Replacement of F by Cl reverses the preference of the reaction. This was associated to the small difference between the Cu-Cl and Si-Cl bond energies, in contrast to other Si-X bonds which are systematically stronger than their Cu-X analogues.

Introduction

Silvlated enolate are used as latent nucleophiles in many reactions, their activation being induced through Lewis acids or bases.^[1] In the case of basic activation, Si-O bond breaking leading to transfer of the enolate toward a copper (or more generally to a metal) complex is proposed. $\ensuremath{^{[2-20]}}$ This can be formally described as a chain transfer between Si to Cu, enolate exchanging with an X group whose nature depends on the exact reaction at stake. For instance, in the case of the copper catalysed asymmetric vinylogous Mukaiyama-aldol (Cu-CAVM) reaction,^[21] which has been at the origin of our study, a dienolate transfer from a trimethylsilyl (TMS) moiety toward a Cu(I) complex is proposed in order to form a Cubonded nucleophile (Scheme 1). This can be carried out either with X = F (initiation step) or with X = alcoholate (regeneration step), as this X is the product of the condensation. Beyond this peculiar reaction which has attracted our attention,^{[22],[23]} Cu(I)-Si chain transfers are extensively encountered in organic synthesis. The Cu-F/Si-OMe exchange has been observed by NMR and is proposed in the initiation steps of Cu-catalyzed allylation. $\ensuremath{^{[24]}}$ In the opposite, the Cu-enolate / Si-Cl exchange has been used to trap and characterized the stereochemical outcome in cuprate chemistry.^[25]

Transfers of OR chains between Cu and $SiMe_3$ thus exhibit a versatility which allowed using trimethylsilyl as a protecting group or a trapping agent. Understanding of this reversibility nevertheless remains quite poor considering the extensive use made for these reactions. Rationalization through Si-X bond energies is often proposed, especially in association to the significantly larger strength of the Si-F bond (565 kJ/mol)

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Scheme 1. Proposed mechanism for Cu-CAVM evidencing two Cu-Si chain transfers in the initiation and regeneration steps.

when compared to the Si-O (452 kJ/mol) or Si-Cl (371 kJ/mol).^[26] Such a rationale should only holds for exchange of free anions. For exchange between Si and Cu, the bond energies to Cu should also be taken into account,^{[27],[28],[29]} and additional effects should be encountered.

We thus undertook a combined computational and experimental study of the exchange reaction between SiMe₃ and a Cu(I) complex (Scheme 2, X = OMe, F and Cl; OR = OMe and various conjugated enolates). The mechanism for the ligand transfer is first described in the case of the identity reaction,^[30] that is for exchange of two identical ligands (X = OR = OMe) between Cu and Si. The effects of the exchanged ligand on the various features of the mechanism are then computationally quantified and the trends obtained are confirmed experimentally. Finally, the role of the ancillary ligand at copper, and thus of the exact nature of the [Cu] center, is discussed.





Results

Study of the identity reaction

In order to streamline each effect separately, we consider at first an "identity" reaction, which is the exchange of two identical ligands (OMe) and thus a symmetric system. In this case, the copper center is taken as $Cu(PH_3)_2$. A concerted cyclic pathway without assistance of the reaction medium is proposed, which can be paralleled to the proposal of the literature for the transmetallation steps in cross-coupling mechanisms.^[31]

It starts (Figure 1) with the pre-coordination of the silylated compound to the copper center through the O atom (formation of AR). The TS for this step was not searched, as such an associative mechanism is expected to be strongly driven by entropic effects which are only poorly reproduced within a static approach. The second step is a cyclization through the formation of a bond between the methoxy ligand at Cu and the Si center. The obtained intermediate, named RI, exhibits a five-coordinated Si center^[32] and a fourmembered Cu-O-Si-O ring. Two short and two long metal-O bonds are obtained, thus keeping the track of the initial metal the OMe group is bonded to. An alternative reaction path from separated reactant to RI was found which was going through precoordination of the OMe of the copper to the silvl moiety (thus increasing the coordination number at Si prior to increasing that at copper). But the associated TS was found more than 25 kcal mol⁻¹ above TS' so that this path was discarded. Continuing the path in Figure 1, the long and short Si-O (or Cu-O) bonds are exchanged in the next step, so that the two Cu-O (resp. Si-O) are identical and equal to 2.04 Å (resp. 1.91 Å) in the corresponding transition state, named TS. The most evident feature of the reaction coordinate along this step is nevertheless not the bond lengthening / shortening but it is the substituent permutation of the SiMe₃ moiety. It corresponds to the exchange of the OMe group between apical and equatorial positions at the Si center. The Si center thus goes from a trigonal bipyramid in RI to a square based pyramid in TS, undergoing a global rotation of the SiMe₃ moiety.^[33] A similar feature has been reported for "front-side $S_N2"$ on $\text{SiH}_3\text{Cl.}^{[34]}$ The end of the mechanism is then the mirror image of the first two steps (as the exchanged ligands are identical): the longest Si-O bond is broken and then dissociation occurs.

This reaction is athermal as it exchanges identical ligands. The structures of TS' and RI have close energies with differences of about 0.7 kcal/mol so that TS' is slightly below RI when Gibbs free energies are considered. This step is thus better described as an inflection point on the potential energy surface rather than a true minimum and the localization of RI and TS' does not affect the conclusion on the mechanism. In addition, considering the entropic cost for formation of the adduct, this structure is found to be higher in Gibbs free energy than the separated reactant.



5.8

2.0

(16.1)

C : black ; O : red ; Si : blue : P : violet ; Cu : orange).

(0)

-1.3

(12.1)

1.3

(17.5)

As a conclusion, the activation barrier has to be evaluated between the separated reactants and TS. For all the calculations that follows, we will thus focus on the localization of TS with respect to the separated species, the adducts being given for the sake of completeness.

Modulation of OR ligands

We next examine the exchange between two different ligands (Scheme 2), using Cu(PH₃)₂ all along this part as a model for the copper center [Cu]. The X ligand is kept equal to OMe. For the OR one, a variety of enolates is examined (Table 1, O-CH=CH₂ (entry 2), O-C(OMe)=CH₂ (entry 3) and O-C(OMe)=CH-CH=CH₂ (entry 4)). For the latest, we are modelling the regeneration step of the Cu-CAVM (Scheme 1). The thermodynamic data of the reactions are summarized in Table 1. Gibbs free energies have been evaluated for all extrema located with respect to the sum of the Gibbs free energies of the separated reactants (ΔG_{prod} refers to separated products).

This leads to an overall stabilization of the reaction path with increasing conjugation, as ΔG values decrease along the series $\Delta G(OMe) > \Delta G(O-CH=CH_2) > \Delta G(O-C(OMe)=CH_2) > \Delta G(O-C(OMe)=CH-CH=CH_2)$. Nevertheless, this stabilization is much more important for the separated products (as evidenced by the ΔG_{prod} values, which varies from 0.0 to -5.6, -9.9 and -14.2 kcal mol⁻¹, entries 2, 3 and 4 respectively, thus a maximum stabilization by 14.2 kcal mol⁻¹) than for the transition state (ΔG_{TS} ranging from 23.6 to 22.6, 19.6 and 18.1 kcal mol⁻¹ respectively, thus a maximum stabilization by 5.5 kcal mol⁻¹).

2.0

(16.1)

-1.3

(12.1)

1.3

(17.5)

Table 1. Thermodynamic data (Gibbs free energies in kcal mol⁻¹ with respect to separated X-Cu(PH₃)₂ and RO-SiMe₃) as a function of OR and X for the reaction depicted in Scheme 2.

	OR	х	$\Delta {\rm G}_{\rm AR}$	$\Delta {\rm G}_{\rm TS}$	ΔG_{AP}	$\Delta {\rm G}_{\rm prod}$
1	OMe	OMe	12.2	23.6	12.2	0
2	O-CH=CH ₂	OMe	11.7	22.6	4.5	-5.6
3	O-COMe=CH ₂	OMe	11.6	19.6	-0.4	-9.9
4	O-COMe=CH-CH=CH ₂	OMe	9.5	18.1	-2.6	-14.2
5	OMe	F	9.1	18.5	7.2	-0.5
6	OMe	Cl	10.9	39.7	33.9	23.4
7	O-COMe=CH-CH=CH ₂	Cl	9.6	36.5	20.2	9.2

Consequently, the conjugation in OR chains has a strong stabilizing role for products, and to a lesser extend for the TS. The regeneration step of the Mukaiyama reaction is thus reversible for shorter chains, whereas it becomes highly favoured thermodynamically and thus irreversible for longer and more conjugate chains

Whereas experimental results can be found for the reactivity of a variety of enolates,^[35] no direct comparison to our computational data could be made. We thus decided to confirm these results experimentally through Si-OR/Cu-OMe chain transfer followed by in situ trapping by benzaldehyde, which is considered as fast compared to the chain transfer step (Scheme 3). As a consequence, this experimental procedure allows evaluating the kinetic of the chain transfer step, and thus probing $\Delta G_{TS}.$ First, a 1:1 TMS-OR : Cu(OMe)(BINAP) mixture is considered to be formed through stoichiometric addition of CuCl, sodium methanolate and the BINAP (bis(diphenylphosphine)binaphtyle) ligand, used to promote the double coordination of the phosphine to copper and keep as close as possible to the computational bisphosphine model. Transfer of the O-C(OEt)=CH₂ moiety takes place with 85% conversion in 16h at room temperature. This is fully in line with the 19.6 kcal mol⁻¹ value found for ΔG_{TS} in Table 1 (entry 3). In a second experience carried out with TMS-OC(OEt)=CH-CH=CH₂, in line with Cu-CAVM published results, cyclic (B) and linear (C) products are obtained, both resulting of the trapping of the copper enolate by benzaldehyde. Both B and C come from terminal addition of the dienolate to benzaldehyde, leading to Z and E alcoholates. The former arrangement allows an additional lactonisation step resulting in B. Considering that the differenciation between B and C occurs at or after the trapping by benzaldehyde, the evaluation of the chain transfer step can be obtained from the addition of the B and C contents. A global 80% conversion into B and C within the time and temperature of experience is obtained, showing a similar advancement of the reaction in the first and second experiments. This reaction time can thus be considered as an "end of reaction" in both cases.



Scheme 3. Competition reaction between enolates with benzaldehyde in the presence of 1 equiv. of CuCl, MeONa and BINAP (For further experimental details see the supporting information).

Evaluation of their relative kinetics will thus be carried out using a competitive reactivity protocol: TMS-OC(OEt)=CH₂ and TMS-OC(OEt)=CH-CH=CH₂ are added with benzaldehyde in 1:1:1 ratio. In these condition, the majority ($\mathbf{B} + \mathbf{C} = 27+46$ = 73%) of the reaction products (77% conversion) comes from addition of the most conjugate species.

Considering the reaction condition (kinetic control on the chain transfer step), the ratio between **A** (product of the transfer of TMS-OC(OEt)=CH₂) and (**B** + **C**) should be equal to:

$$\frac{[A]}{[B]+[C]} = \exp\left(-\frac{\Delta G_{TS}(A) - \Delta G_{TS}(B/C)}{RT}\right) < 1$$

Thus the larger amount of **B** + **C** is in line with a larger value for $\Delta G_{TS}(A)$ compared to $\Delta G_{TS}(B/C)$. Let us note that the A/(B+C) experimental ratio (27/73) is associated with a $\Delta (\Delta G_{TS})$ value of 0.3 kcal mol⁻¹, in line with the small value obtained computationally.

Modulation of X ligands

We next examine the role of X by replacing the OMe group by a halogen, namely F or Cl. Highly different behaviors are obtained for the two halogens, as illustrated by the Gibbs free energies reported in Table 1. When X = F or OMe, similar mechanisms and G values are obtained (compare entries 1 and 5, Table 1). The energy differences between the two systems ranging from 3 kcal/mol (for AR) to 5 kcal/mol (for AP). A slight stabilization is thus obtained for the whole reaction path for fluorine compared to methoxy but, to a first approach, OMe and F can be proposed to behave similarly. This conclusion, within the perspective of the Cu-CAVM, allows proposing that initiation and regeneration steps of catalytic cycle have similar properties.

A totally different picture, reported in Figure 2 in the case of OR = OMe, is obtained for X = Cl as a significantly different



and $Cu(PH_3)_2$. The energies E (in black) and the enthalpies of Gibbs free energies G (in parenthesis and in blue) are calculated with respect to the energies of separate reactant species. Distances are given in Å. Color code : H : white ; C : black ; O : red ; Si : blue : P : violet ; Cu : orange).

reaction path was obtained. In addition, the overall transformation is highly endergonic for X = Cl (ΔG_{prod} = +23.4 kcal mol⁻¹, Table 1, entry 6), instead of neutral for X = F or OMe.

After formation of the adduct through a Cu...O bond, the cyclic structure exhibiting a pentacoordinated Si center cannot be formed for the OMe and Cl pair. In fact, no pentacoordinated Si is thus obtained in this mechanism, neither with Cl in axial (reactant side) nor in equatorial (product side) position. This observation is consistent with a disfavored reaction involving hypervalent Si for X = I reported in the literature.^[32] First row X groups (OMe and F) seems to favor the formation of hypervalent Si intermediates, in contrast to Cl. Moreover, the nature of the equatorial substituents has been shown to modulate the stability of the pentacoordinated Si structures from stable transition complex to transition state^[36], as well as solvation,^[34] or the apical substituents in the case of pentacoordinated P.^[37]

Both coordination of the chlorine atom, rotation of the SiMe₃ unit and breaking of the Si-O bond are already completed before reaching the TS. The high endergonicity of the reaction is associated to a late TS, much higher in energy than the one obtained before. As a conclusion, the opposite reaction, that is transfer from Si to Cu resulting in the formation of a silvlated enolate is highly favorable and exhibit a small activation. This corresponds to the direction of electrophilic quench or protection of the alcoholate chain.





Scheme 4. Reaction of silylated dienolate with benzaldehyde in the presence of 1 equiv. of CuCl and BINAP (*For further experimental details see the supporting information*).

We next wondered what happens when the most stabilizing conjugate chain is associated to the destabilizing Cl (Table 1, entry 7). When looking only at the separated species, the effects of the chain and of Cl are purely additive, as no species contained both X and OR at the same time. As a consequence, Cl effects the same destabilization (by nearly 24 kcal mol⁻¹) for O-COMe=CH-CH=CH₂ than for OMe. The reaction is thus endergonic by 9.21 kcal mol⁻¹ and is thus not possible. This was confirmed experimentally as no conversion is observed in absence of NaOMe using the same conditions as already used (Scheme 4).

On the opposite, nearly no effect of the nature of OR is observed on the TS, which remains more than 35 kcal mol⁻¹ above the reactant, and thus more than 25 kcal mol⁻¹ above the products. As a consequence, protection of a conjugated enolate chain by $SiMe_3$ through reaction with TMSCl, despite favorable, is most probably difficult as a 27.3 kcal mol⁻¹ activation Gibbs free energy is obtained.

To conclude this first part dealing with the effect of the transferred ligands, it appears that the reaction thermodynamic is driven by both the nature of X and OR, whereas the kinetic of the reaction is mostly governed by the nature of X, with a smaller influence of OR (Scheme 2).

Modulation of the [Cu] center

In the previous paragraph, a neutral electron rich copper complex was used as it was coordinated to two phosphines. In this part we aim at examining the role played by the nature, charge and number of ligands in the Cu/Si transmetallation. The Gibbs free energy values are reported in Table 2 and energetic and geometrical data in ESI.

First, changing from two to one phosphine gives rise to a slight destabilization of TS (+2.2 kcal/mol in TS when going from bis to mono-phosphine compound) but to no significant effect on the products stability. In contrast, using a "naked" copper (no ligand) leads to a major evolution of the reaction profile. The adducts become very stable (-32.5 kcal/mol for AR and -21.8 kcal/mol for AP) whereas the energy of the TS with respect to separated reactant remains unchanged. This can be easily understood as, the passage from two to zero phosphine leads to an electron poor cooper which will tend to interact strongly with any potential ligand.





Scheme 5. Reaction of silylated dienolate with benzaldehyde in the presence of 1 equiv. of CuCl and NaOMe (For further experimental details see the supporting information).

Table 2. Gibbs free energies (in kcal mol-1 with respect to separated F-[Cu] and MeO-SiMe3) as a function of the nature of [Cu] for the reaction depicted in Scheme 2 in the case X = F and OR = OMe.

	[Cu]	ΔG_{AR}	$\Delta {\rm G}_{\rm TS}$	ΔG_{AP}	ΔG_{prod}	
1	Cu(PH ₃) ₂	9.1	18.5	7.1	-0.5	
2	Cu(PH₃)	8.1	20.7	6.7	-0.7	
3	Cu	-21.5	18.0	-12.8	-6.8	
4	Cu(OMe ₂)	8.0	22.8	5.7	-1.5	
5	Cu(CO)	3.7	18.2	4.9	-3.9	

In this configuration, the reaction seems to be impossible as the adducts become the most stable point on the reaction path: the coordination to copper in this species is so strong that it is impossible to exchange OMe and F.

This computational result was confronted to experiment following a similar procedure to that described above, but in absence of BINAP (Scheme 5). The product obtained results from Cu-CAVM reaction on the α position of the copperenolate intermediate, and corresponds to a different regiochemistry for quenching but a similar Si to Cu chain transfer. Let us mention that formation of the branched product is consistent with previous studies^[38] that have shown that the regiochemistry is strongly ligand dependent. A significantly lower conversion (comparing Scheme 3 and 5) is also observed. To put this experimental result in perspective with our computational one, it is necessary to discuss the limit of our computational model. Considering an uncoordinated copper when working in THF is an unrealistic model as, in ethereal solvent, the coordination of at least one solvent molecule on the copper center (explicit solvation) should be taken into account. A model using OMe₂ as an ethereal solvent was thus used. It yields a pathway similar to that obtained for the system with two phosphine ligands, with a TS about 4 kcal mol⁻¹ higher in energy. The lower conversion, when compared to the BINAP containing experiments, is consistent with a slower but still possible chain transfer. We have not been able to confirm this analysis experimentally. Indeed, when trying to carry out the reaction in non-coordinating solvent (toluene), the low solubility of the reactants led to no reaction both in presence and absence of BINAP.

Finally, we computationally examined the replacement of PH_3 by a π -acceptor ligand, namely CO. The same mechanism is obtained with energies close to those of the system with two phosphines are obtained. A slight stabilization, of AR, AP and products (by less than 2 kcal/mol) is obtained.

As a conclusion, effects of the number and nature of the ligand on the reaction energy or kinetic could be observed but remain quite small, except for the stability of the adduct. In absence of procedure allowing comparison of the reactivity of the various Cu center in similar conditions, it is not possible to confirm these tendencies experimentally.

Discussion

We have thus shown that the thermodynamic of the reaction of Scheme 2 is strongly influenced by the nature of X, OR and, to a lesser extent, by the copper ancillary ligands. Indeed, as shown above, the reaction can range from strongly exothermic (X = OMe, OR = O-C(OMe)=CH-CH=CH₂) to athermic (X= F, OR = OMe) and even strongly endothermic (X = Cl, OR = OMe). With these results in hand, we decided to revisit the commonly used interpretative schemes in silylation chemistry, which resort only on the Si-Y bond strength, and try to adapt them in case of coordination of Y to copper complexes.

The thermodynamic of the reaction was found to be determined by the Gibbs free energy difference between separated reactants and products, which is very close to the energy difference as the reaction does not modify the number of free molecules between reactant and products. We also remind that the [Cu]-F values reported below are systematically overestimated (see Computational Details) so that only trends with the bond energy differences can be considered. The reaction results in breaking of Cu-X and Si-OR bonds, and formation of Si-X and Cu-OR bonds. Quantitative values for various transferred ligands are gathered in Table 3 for $[Cu] = Cu(PH_3)_2$. Si-Y bonds are stronger than the [Cu]-Y analogues by values close to 20 kcal mol⁻¹, except for Cl. In this case, bondings to Cu or Si centers are similar. This enables understanding the specific behaviour of Cl when considering the reaction to Scheme 2 for OR = OMe. A Cu-Cl bond is broken and replaced by a Si-Cl bond of similar energy. In contrast, the formed Cu-O bond is much weaker than the initial Si-O one, so that the reaction is thus endothermic. In contrast, for F, the formed Si-F is stronger than the broken Cu-F by a value similar to the difference between the formed Cu-O and the broken Si-O: these two effects thus compensate and the reaction is quasi athermic.

Let us now examine the effect of the OR group: when increasing the length of the chains and thus their conjugation, their bond energies with Cu and Si decrease. This can be understood when implying the π -acceptor character of [M]: the more conjugate the lone pair at O is, the less available to π -donate toward [M], and the weakest is the [M]-O bond. The smaller decrease of the [M]-O bond energy in the case of Cu can be associated to a lesser π -acceptor character of the copper compared to SiMe₃.

Table 3. Bond energies (E([M]-Y) in kcal mol⁻¹) for [M] = SiMe₃ and Cu(PH₃)₂ as a function of the examined ligand computed according to the procedure reported in Computational Details. $\Delta E_{Cu/Si} = E(Y-Cu(PH_3)_2) - E(Y-SiMe_3)$.

Y \ [M]	SiMe₃	Cu(PH ₃) ₂	$\Delta E_{Cu/Si}$
F	155.8	128.7	-27.1
Cl	112.9	108.9	-4.0
OMe	109.3	82.9	-26.4
OCHCH₂	95.3	72.7	-22.6
OCOMe=CH ₂	87.7	65.0	-22.7
OCOMe=CH-CH=CH ₂	77.4	56.3	-21.1

Conclusions

Anionic ligands transfer between SiMe₃ and Cu(I) complexes with various substitution has been examined. Reaction mechanisms are determined, and go through the formation of a cyclic transition state in most cases. The reaction coordinate is associated to the rotation of the SiMe₃ moiety. The thermodynamic and kinetic features dependence on the nature of the transferred ligand was detailed, whereas no major effect of the nature of the copper complex could be evidenced. On one side, variously conjugated alcoholates have been examined. The greater the conjugation of the chain, the most thermodynamically favored the formation of the Copper-enolate, since the Si-O bond is much more sensitive to delocalization than the Cu-O one. No such effect could be found on the kinetic of the reaction: the activation energy is decreased with exothermicity in line with the Hammond postulate. This effect is found to be moderate, as shown by the relatively moderate selectivity observed in the case of the enolate / dienolate competition. On the other side, the exchanged (F, Cl or OMe) were shown to play a major role as they define both the kinetic and the thermodynamic of the reaction. F or OMe are found to favor formation of copper-enolate and to increase the kinetic of the reaction, whereas CI favors the formation of the silylenolate. As evidenced from the following description, rationalization of the obtained values was systematically carried out, in order to develop simple reasoning model to the prediction of further reactivity. We now have in hand a deeper understanding of the initiation and regeneration steps of Cu-CAVM and we can now complete the reaction mechanism by examining the C-C bond formation step of this reaction, especially in order to better understand the regioand enantioselectivity. These results will be published in due time.

Experimental Section

Computational Details. The calculations were carried out with the Gaussian 09 package of programs^[39] using the PW91 functional.^[40] Copper was represented with the effective core potential SDDall from the Stuttgart group and the associated basis set.^{[41],[42]} The 6-31++G^{**} basis

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set was used for all the other atoms (Si, F, Cl, O, C, P, H). The validity of this computational level, in absence of dispersion correction, was confirmed through energetic and geometric comparison to MP2 (See Supporting Information). As a conclusion, no dispersion correction was added. Full geometry optimizations were carried out followed by analytical frequency calculations within the harmonic approximation to confirm the nature of the stationary points obtained. The transition states were given a small displacement along the imaginary frequency and full geometry optimization was then carried out to ensure the connection between transition states and the intermediates. Thermal corrections to obtain the Gibbs free energies were calculated at 298 K and 1 atm using unscaled frequencies computed in the harmonic approximation. Simple models of copper complexes have been used which can be viewed as prototype of various classes of copper or cuprate complexes, in order to search for general features of the mechanism. In particular, two PH₃ ligands have been used to model the tol-Binap ancillary ligands used in the Mukaiyama reaction. Considering the simplicity of these models, no implicit solvation was added. Explicit solvation has been taken into account when needed by including OMe2 molecule as a model of ethereal solvents. The bond energies E([M]-Y), where [M] is a metal center and Y a transferred group, are computed using the radical electronic structure of [M] and Y, taken in the geometry of the optimized [M]-Y molecule, as the energy difference between the separated fragment and the complex, in order to get positive values of E. The value obtained for Si-O is very close to that reported in standard textbooks (109.3 kcal mol⁻¹ vs 108.1 kcal mol⁻¹) whereas a significantly larger value is obtained for Si-Cl and Si-F (155.8 and 112.0 kcal mol-1 respectively, compared to 135.2 or 88.8 kcal mol-1 in ref [26]. This overestimation is associated to the computational procedure, which resorts on a monodeterminental approach to the evaluation of the energy of F and Cl. This approach overestimates the energy of the atoms, and thus the associated bond energy. However, the difference between F and Cl is well reproduced (43.8 kcal mol⁻¹ vs 46.4 kcal mol⁻¹), and this overestimation is independent of the metal center the atoms are bonded to. As a consequence, our theoretical values can be used only to compare the difference between bond energies with different metal but identical Y.

Experimental Details. Unless otherwise specified (see paragraph below), all commercial products and reagents were used as purchased, without further purification. Reactions were carried out in round-bottom flasks equipped with a magnetic stirring bar under argon atmosphere. NMR spectra were recorded with a Bruker Ultra Shield 400 Plus. ¹H chemical shifts are reported in delta (δ) units in parts per million (ppm) relative to the singlet at 7.26 ppm for d-chloroform (residual CHCl₃). chemical shifts are reported in ppm relative to the central line of the triplet at 77.0 ppm for d-chloroform. Splitting patterns are designated as s, singlet: d. doublet: t. triplet: g. guartet: guint, guintet: m. multiplet: and br. broad and combinations thereof. All coupling constants (J values) are reported in Hertz (Hz). Data are reported as follows: chemical shift (δ in ppm), multiplicity, coupling constants (Hz), integration and attribution. THF was dried by distillation over sodium metal and benzophenone under argon. Dichloromethane and diethylether were dried by distillation over CaH₂ under argon. CuCl and MeONa were purchased from Aldrich, kept under argon atmosphere, and dried over P2O5 before use.

Enolate synthesis: *N*,*N*-diisopropylamine (DIPA) (6.2 mL, 44.2 mmol, 1.20 equiv) and freshly distilled THF (70 mL) were added to a flame-dried flask at 0 °C. Then, n-BuLi (27.6 mL, 44.2 mmol, 1.20 equiv, 1.6 M in Et₂O) was added dropwise over a period of 30 min. The pale yellow solution obtained was stirred for an additional 15 min and then cooled at -78 °C, freshly distilled ethyl acetate was added (3.4 mL, 36.8 mmol, 1.00 equiv), and the color turned yellow. The resulting mixture was stirred at the same temperature for another hour. Thus, freshly distilled chlorotrimethylsilane (TMSCI) (5.5 mL, 58.9 mmol, 1.60 equiv) was added dropwise over a period of 10 min. The milky solution obtained was stirred for 30 min at -78 °C and then allowed to reach room temperature. The suspension was filtered through oven dried anhydrous Na₂SO₄, and the solvent was removed under reduced pressure. The crude product obtained was diluted with pentane (150 mL), filtered off, and the solvent

was removed under vacuum; this step was performed twice. Purification of the residue was performed by distillation (60 °C, 50 mbar), yielding a colorless oil (2.3 g, 14.3 mmol, 39 %) corresponding at the desired product which contains a trace amount of C–TMS. ¹H NMR (400 MHz, CDCl3): δ 3.73 (q, J = 7.1 Hz, 2H), 3.18 (d, J = 2.7 Hz, 1H), 3.04 (d, J = 2.6 Hz, 1 H), 1.28 (t, J = 7.1 Hz, 3 H), 0.21 (s, 9 H) ppm. ¹³C NMR (100 MHz, CDCl₃): δ 160.9, 63.3, 60.1, 14.2, 0.0 (3C) ppm. These data are in accordance with that previously described. ^[43]

Dienolate synthesis: N,N-Diisopropylamine (DIPA) (6.2 mL, 44.2 mmol, 1.20 equiv) and freshly distilled THF (70 mL) were added to a flame-dried flask at 0 °C. Then, n-BuLi (27.6 mL, 44.2 mmol, 1.20 equiv, 1.6 M in Et₂O) was added dropwise over a period of 30 min. The pale yellow solution obtained was stirred for an additional 15 min and then cooled at °C. -78 Freshlv distilled 1,3-dimethyl-3,4,5,6-tetrahydro-2(1H)pyrimidinone (DMPU) (6.0 mL, 44.2 mmol, 1.20 equiv) was added dropwise to the reaction mixture, giving rise to a milky solution. After 30 min, freshly distilled ester was added (4.6 mL, 36.8 mmol, 1.00 equiv), and the color turned yellow. The resulting mixture was stirred at the same temperature for another hour. Thus, freshly distilled chlorotrimethylsilane (TMSCI) (5.5 mL, 58.9 mmol, 1.60 equiv) was added dropwise over a period of 10 min. The milky solution obtained was stirred for 30 min at -78 °C and then allowed to reach room temperature. The formation of a white suspension in an orange solution was observed. The suspension was filtered through oven dried anhydrous Na₂SO₄, and the solvent was removed under reduced pressure. The crude product obtained was diluted with pentane (150 mL), filtered off, and the solvent was removed under vacuum; this step was performed twice. The crude product so obtained was diluted with pentane and washed with a saturated aqueous solution of NaHCO $_3$ and brine. The organic layer was dried over anhydrous Na₂SO₄, and the solvent was removed under reduced pressure. Purification of the residue was performed by distillation (100 °C, 0.7 mbar), yielding a colorless oil (5.7 g, 30.5 mmol, 83%) corresponding to a mixture of the two inseparable Z/E isomers with a ratio of 8:2 in favor of the Z isomer (¹H NMR determination). Z isomer: ¹H NMR (400 MHz CDCl₃): ō 6.46-6.58 (m, J = 10.4 and 17.2 Hz, 1H), 4.80 (dd, J = 1.8 and 17.2 Hz, 1H), 4.58 (dd, J = 1.8 and 10.4 Hz, 1H), 4.43 (d, J = 10.4 Hz, 1H), 3.78 (q, *J* = 7.0 Hz, 2H), 1.28 (t, *J* = 7.0 Hz, 3H), 0.21 (s, 9H) ppm. ¹³C NMR (100 MHz, CDCl₃): ō 157.6, 132.5, 106.4, 80.8, 63.3, 14.3, 0.3, ppm. E isomer: ¹H NMR (400 MHz, CDCl₃) δ 6.46–6.58 (m, J = 10.4 and 17.2 Hz, 1H), 4.80 (dd, J = 1.8 and 17.2 Hz, 1H), 4.58 (dd, J = 1.8 and 10.4 Hz, 1H), 4.51 (d, J = 10.4 Hz, 1H), 3.89 (q, J = 7.0 Hz, 2H), 1.22 (t, J = 7.0 Hz, 3H), 0.24 (s, 9H) ppm.¹³C NMR (100 MHz, CDCl₃) δ 154.6, 132.1, 107.3, 88.4, 62.8, 14.8, -0.2 ppm. These data are in accordance with that previously described.^[23]

Reaction between enolate and benzaldehyde: CuCl (74 mg, 0.74 mmol, 1.0 equiv.) and MeONa (40 mg, 0.74 mmol, 1.0 equiv.) were added in a flame dried round bottom flask, dissolved in freshly distilled THF (60 mL), and stirred at 50 °C for 2 h. The light brown suspension obtained was cooled at room temperature and cannulated in a separately flame dried round bottom flask containing BINAP (463 mg, 0.74 mmol, 1.0 equiv.), 2x5 mL of freshly distilled THF were used to rinsed the flask. After being stirred for 1 h at room temperature, freshly distilled benzaldehyde (76 µL, 0.74 mmol, 1.0 equiv) was added, followed by freshly distilled enolate (145 μ L, 0.74 mmol, 1.0 equiv). After being stirred at room temperature for an additional 16 h, the mixture was treated with HCl 1M (20 mL) and MeOH (10 mL), an extraction of the aqueous phase was performed with diethylether (50 mL). The organic layer was washed with an ammonia solution (3x30 mL) and brine (1x30 mL), the solvent was removed under vacuum and the crude was analyzed by ¹H NMR (conversion: 85 %). Characteristic peaks: Benzaldehyde: ¹H NMR (400 MHz, CDCl₃): δ 9.92 (s, 1 H) ppm. Product A: ¹H NMR (400 MHz, CDCl₃): δ 5.02 (dd, J = 8.8 and 4.2 Hz, 1H) ppm. These data are in accordance with that previously described.^[44]

Reaction between dienolate and benzaldehyde: CuCl (74 mg, 0.74 mmol, 1.0 equiv.) and MeONa (40 mg, 0.74 mmol, 1.0 equiv.) were added in a flame dried round bottom flask, dissolved in freshly distilled THF (60 mL), and stirred at 50 °C for 2 h. The light brown suspension obtained was cooled at room temperature and cannulated in a separately flame dried round bottom flask containing BINAP (463 mg, 0.74 mmol, 1.0 equiv.), 2x5 mL of freshly distilled THF were used to rinsed the flask. After being stirred for 1 h at room temperature, freshly distilled benzaldehyde (76 μ L, 0.74 mmol, 1.0 equiv) was added, followed by freshly distilled dienolate (160 μ L, 0.74 mmol, 1.0 equiv). After being

stirred at room temperature for an additional 16 h, the mixture was treated with HCI 1M (20 mL) and MeOH (10 mL), an extraction of the aqueous phase was performed with Diethylether (50 mL). The organic layer was washed with an ammonia solution (3x30 mL) and brine (1x30 mL), the solvent was removed under vacuum and the crude was analyzed by ¹H NMR (conversion: 80 %). Characteristic peaks: Benzaldehyde: ¹H NMR (400 MHz, CDCl₃): ō 9.92 (s, 1 H) ppm. Product B: ¹H NMR (400 MHz, CDCl₃): δ 6.15 (ddd, J = 9.6, 2.4 and 1.2 Hz, 1H), 5.46 (dd, J = 11.0 and 4.9 Hz, 1H) ppm. Product C: ¹H NMR (400 MHz, CDCl₃): δ 5.81 (dt, J = 15.7 and 1.6 Hz, 1H), 4.72 (dd, J = 7.7 and 5.2 Hz, 1H) ppm. These data are in accordance with that previously described.^[38] Competition between enolate and dienolate with benzaldehyde: CuCl (74 mg, 0.74 mmol, 1.0 equiv.) and MeONa (40 mg, 0.74 mmol, 1.0 equiv.) were added in a flame dried round bottom flask, dissolved in freshly distilled THF (60 mL), and stirred at 50 °C for 2 h. The light brown suspension obtained was cooled at room temperature and cannulated in a separately flame dried round bottom flask containing BINAP (463 mg, 0.74 mmol, 1.0 equiv.), 2x5 mL of freshly distilled THF were used to rinsed the flask. After being stirred for 1 h at room temperature, freshly distilled benzaldehyde (76 µL, 0.74 mmol, 1.0 equiv) was added, followed by a freshly prepared mix of dienolate and enolate (1:1 (verified by ¹H NMR), 305 µL, 0.74 mmol of each, 1.0 equiv. of each). After being stirred at room temperature for an additional 16 h, the mixture was treated with HCl 1M (20 mL) and MeOH (10 mL), an extraction of the aqueous phase was performed with Diethylether (50 mL). The organic layer was washed with an ammonia solution (3x30 mL) and brine (1x30 mL), the solvent was removed under vacuum and the crude was analyzed by ¹H NMR (conversion: 77 %). Characteristic peaks: Benzaldehyde: ¹H NMR (400 MHz, CDCl_3): δ 9.92 (s, 1 H) ppm. Product A: ^{1}H NMR (400 MHz, CDCl₃): δ 5.02 (dd, J = 8.8 and 4.2 Hz, 1H) ppm. Product B: ¹H NMR (400 MHz, CDCl₃): δ 6.15 (ddd, J = 9.6, 2.4 and 1.2 Hz, 1H), 5.46 (dd, J = 11.0 and 4.9 Hz, 1H) ppm. Product C: ¹H NMR (400 MHz, CDCl₃): δ 5.81 (dt, J = 15.7 and 1.6 Hz, 1H), 4.72 (dd, J = 7.7 and 5.2 Hz, 1H) ppm. These data are in accordance with that previously described. [38, 44]

Reaction with CuCI:

CuCl (74 mg, 0.74 mmol, 1.0 equiv.) and BINAP (463 mg, 0.74 mmol, 1.0 equiv.) were added in a flame dried round bottom flask, dissolved in freshly distilled THF (60 mL). After being stirred for 2 h at room temperature, freshly distilled benzaldehyde (76 μ L, 0.74 mmol, 1.0 equiv) was added, followed by freshly distilled dienolate (160 μ L, 0.74 mmol, 1.0 equiv). After being stirred at room temperature for an additional 16 h, the mixture was treated with HCl 1M (20 mL) and MeOH (10 mL), an extraction of the aqueous phase was performed with Diethylether (50 mL). The organic layer was washed with an ammonia solution (3x30 mL) and brine (1x30 mL), the solvent was removed under vacuum and the crude was analyzed by ¹H NMR (conversion: 0 %).

Reaction without ligand: CuCl (74 mg, 0.74 mmol, 1.0 equiv.) and MeONa (40 mg, 0.74 mmol, 1.0 equiv.) were added in a flame dried round bottom flask, dissolved in freshly distilled THF (60 mL). After being stirred for 2 h at room temperature, freshly distilled benzaldehyde (76 µL, 0.74 mmol, 1.0 equiv) was added, followed by freshly distilled dienolate (160 µL, 0.74 mmol, 1.0 equiv). After being stirred at room temperature for an additional 16 h, the mixture was treated with HCl 1M (20 mL) and MeOH (10 mL), an extraction of the aqueous phase was performed with Diethylether (50 mL). The organic layer was washed with an ammonia solution (3x30 mL) and brine (1x30 mL), the solvent was removed under vacuum and the crude was analyzed by 1H NMR (conversion: 40 %). Characteristic peaks: Benzaldehyde: 1H NMR (400 MHz, CDCl3): ō 9.92 (s, 1 H) ppm. Products D: Dia 1: 1H NMR (400 MHz, CDCl3): δ 5.90 (ddd, J = 17.2, 10.3 and 8.5 Hz, 1H) ppm. Dia 2: 1H NMR (400 MHz, CDCl3): δ 5.62 (ddd, J = 17.2, 10.3 and 8.9 Hz, 1H) ppm. These data are in accordance with that previously described.^[38]

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