

 Very Important Publication

Dual Photoredox Catalysis with Vanadium Complexes in Low Oxidation State: Diastereoselective Pinacol Coupling

Emanuele Pinosa,^{a, b} Yuri Gelato,^{a, c} Francesco Calogero,^{a, b}
Matteo Maria Mosconi,^a Andrea Gualandi,^{a, b,*} Andrea Fermi,^{a, b}
Paola Ceroni,^{a, b} and Pier Giorgio Cozzi^{a, b,*}

^a Dipartimento di Chimica “Giacomo Ciamician”, Alma Mater Studiorum – Università di Bologna, Via Gobetti 85, 40129 Bologna, Italy

E-mail: andrea.gualandi10@unibo.it; piergiorgio.cozzi@unibo.it

^b Center for Chemical Catalysis – C3, Alma Mater Studiorum – Università di Bologna, Via Selmi 2, 40126 Bologna, Italy

^c Department of Pharmacy – Drug Sciences, University of Bari “A. Moro”, Via E. Orabona 4, 70125 Bari, Italy

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Abstract: Dual photoredox catalysis is modifying the approach to sustainable metal catalysis based on metals in low oxidation state, as the use of stoichiometric metal as reductants are avoided. In this study, we showcase the potential use of vanadium in a dual photoredox process, allowing us to effectively control the formation of V(II) and its corresponding chemical reactions. A diastereoselective pinacol coupling with aromatic aldehydes is described. The process shows broad scope, and interestingly, unprotected salicylic aldehydes are compatible with the reaction protocol. Additionally, among all the ligands investigated we found that inexpensive bipyridines control the diastereoselection of the reaction favoring the *d,l* chiral compound (*dr* > 20:1 for most of the aldehydes investigated). To promote the reaction and avoid an unproductive and not stereoselective radical coupling of the generated ketyl radical, the use of [DMQA]⁺, a stable organic dye, was found crucial. Furthermore, this dye possesses the remarkable capability of efficiently capturing light in the red segment of the visible spectrum, effectively raising efficiency of the protocol. The utilization of red light carries notable advantages in terms of penetration and safety, making it particularly significant. Moreover, careful photophysical investigations were able to give indications about the mechanism of the reaction.

Keywords: Metallaphotoredox catalysis; Vanadium catalysis; Aldehydes; Pinacol coupling; Diastereoselectivity; Red light

Introduction

Photoredox catalysis^[1] has recently encountered an exponential growth to become an accessible, practical, and broadly investigated powerful methodology in synthesis and catalysis.^[2] Interesting and completely new challenging chemical transformations are often introduced,^[3] expanding the synthetic repertoire and pushing the boundaries of these new approaches. Single electron transfer (SET) promoted reactions in the presence of metal^[4] and/or organic^[5] photocatalysts were employed in these new transformations. The combination of metals and photoredox catalysis, named dual photoredox catalysis, offers opportunity to the interplay of two catalytic cycles that act in synergy

for new transformations.^[6] In particular, ketyl radicals,^[7] approached by SET reduction, could serve as means of inverting the reactivity of the starting carbonyl compound, allowing different reactivity with non-nucleophilic partners (i.e. alkenes). The major limitation in the approach is the high reduction potential of aldehydes ($E_{p/2}$ (PhCHO/PhCHO^{•-}) = -1.93 V vs. SCE in MeCN) and ketones ($E_{p/2}$ (acetophenone/acetophenone^{•-}) = -2.11 V vs. SCE in MeCN).^[8] The high barrier to the reduction was passed by metal or metal complexes in low oxidation state such as K,^[9] Zn,^[10] Mn,^[11] Ti,^[12] and SmI₂.^[13] In these methodologies unavoidable metal waste is formed. New photochemical methods for obtaining ketyl radicals have been described with the introduction of

photoredox catalysis.^[14] Rueping first reported the direct access to symmetrical pinacol and diamine products using photoredox catalysis, which showed good tolerance towards functional groups. This was achieved by using a catalytic amount of $[\text{Ir}(\text{dF}(\text{CF}_3)\text{ppy})_2(\text{dtbbpy})](\text{PF}_6)$ as the photocatalyst.^[15] The pinacol coupling is facilitated by the Brønsted acid activation of the carbonyl, occurring in the reaction mixture, that lowers the reduction potential for the formation of ketyl radical. Other contributions have then reported about pinacol coupling by activating the carbonyl with a Brønsted acid in the reaction mixture with different photocatalysts and conditions.^[16] These methods do not require the use of stoichiometric reducing metals and instead employ stoichiometric reductants such as amines or Hantzsch's esters to complete the catalytic cycle of the photocatalyst. As the reported methods are dealing with the dimerization of the ketyl radical generated in the photoredox conditions, generally the diastereoselectivity is poor and pinacols are obtained as inseparable mixture of *d,l* and *meso* diastereoisomers in 1:1 ratio. Recently, Gansäuer,^[17] our group,^[18] Shi,^[19] and Kanai^[20] have reported the chemistry of $[\text{Ti}(\text{III})]^{2+}$ generated under photoredox conditions, and we applied titanium photoredox chemistry for a diastereoselective ($\text{dr} > 20:1$) and enantioselective (ee up to 92%) pinacol coupling^[22] of aromatic aldehydes. We utilized the red-absorbing dye *N,N'*-dipropyl-1,13-dimethoxyquinacridinium tetrafluoroborate $([\text{nPr-DMQA}]^+[\text{BF}_4]^-) \mathbf{1}^+$,^[23] as the photocatalyst for the reaction. This helical carbenium ion is capable of minimizing unselective radical-radical coupling and facilitates the formation of $\text{Ti}(\text{III})$. The reduction potentials of $\mathbf{1}^+$ have been reported as: $E^0(\mathbf{1}^+/\mathbf{1}^*) = -0.82 \text{ V vs. SCE}$, and $E^0(\mathbf{1}^{2+}/\mathbf{1}^+) = +1.44 \text{ V vs. SCE}$ in CH_2Cl_2 .^[23a] The reduction potential of $[\text{DMQA}]^+$ was well suited for reduce the titanium complex, but not sufficient to promote the formation of ketyl radicals directly by the reduction of aldehydes even in the presence of *in situ* generated Brønsted acids. Furthermore, employment of the low-energy portion of the visible spectrum (orange and red) with selected dyes is an important topic in modern photoredox catalysis, as evidenced by Rovis.^[24] We wondered if the selective conditions found for titanium complex were compatible with other metals for enhancing the scope of dual metal photoredox catalysis in the presence of organic dyes.^[25] The low reduction potential reported for the couple $\text{V}^{\text{III}}/\text{V}^{\text{II}}$ ($E(\text{V}^{\text{III}}/\text{V}^{\text{II}}) = -0.255 \text{ V vs. SCE}$)^[26] and the low toxicity of vanadium^[27] attracted our interest. Additionally, although interesting, oxidative photoredox chemistry of vanadium complexes was recently reported,^[28] to the best of our knowledge, investigation in photoredox chemistry of vanadium in low oxidation state is still missing in literature. Pedersen^[29] introduced in organic synthesis the vanadium complex

$[\text{V}_2\text{Cl}_3(\text{THF})_6][\text{Zn}_2\text{Cl}_6]^{30}$ obtained from reduction of $\text{VCl}_3 \cdot \text{THF}_3$ with Zn metal, for selective cross pinacol couplings.^[31] On the basis of our precedent study for the reduction of $[\text{Ti}(\text{IV})]$ complexes we decided to use $([\text{nPr-DMQA}]^+[\text{BF}_4]^-)$ in photocatalytic vanadium mediated pinacol coupling processes, and herein, we illustrate the implementation of our findings in a highly diastereoselective ($\text{dr} > 20:1$ *d,l:meso*) pinacol coupling promoted by 3 mol% of a commercially available $\text{VCl}_3 \cdot \text{THF}_3$ solution in DCM, in the presence of 6,6'-dimethylbipyridine as the effective ligand.

Results and Discussion

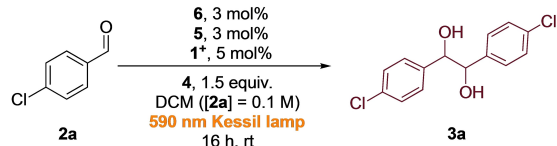
To study all the parameters for the reaction, we chose *p*-chlorobenzaldehyde (**2a**) as the model substrate. The reaction was optimized by varying conditions and in Table 1 we report some important features regarding the optimization process.

Taking into account the previous studies performed by Pedersen^[29] and others^[31] the pinacol coupling reactions were investigated in DCM. A difficulty in setting up the reaction was related to the sensitivity of $\text{VCl}_3 \cdot \text{THF}_3$ to oxygen. To obtain reproducible results, we found suitable the use of commercially available solution of $\text{VCl}_3 \cdot \text{THF}_3$ in DCM. While vanadium was able to promote the reaction, differently from the results reported,^[29,31] the diastereoselection was quite poor (Table 1, entry 8). Ligands able to coordinate vanadium were investigated to improve the outcome of the reaction. While bis-phosphine, TMEDA,^[32] and achiral Salen (*N,N'*-ethylenebis(salicylaldiminato) dianion)^[33] shut down the reactivity of vanadium, monodentate Schiff bases were not improving the diastereoselection (see SI for details).

Positive results were obtained when bipyridine ligands^[34] were employed for the reaction. The addition of 6,6'-dimethylbipyridine ligands to $\text{VCl}_3 \cdot \text{THF}_3$ resulted in the formation of a complex that produced **3a** with a diastereoisomeric ratio of $> 20:1$ in favor of the desired *d,l* diastereoisomer (see Table 1, entry 1). For the reaction, the presence of light, $\text{VCl}_3 \cdot \text{THF}_3$, $\mathbf{1}^+$ and Hantzsch's ester were found crucial (Table 1, entries 2–5). As the vanadium complex absorbs light in the visible region, increasing of the concentration of VCl_3 the reaction was completely inhibited (Table 1, entry 6).

As many cross and pinacol couplings performed with vanadium(II) are realized in DCM,^[31] we have just investigated the use of THF as the alternative solvent for the reactions (Table 1, entry 9), and we found a quite reduced reactivity. The use of two different photocatalyst in the reaction was also evaluated (entries 13 and 14). Both the photocatalysts are absorbing in the blue light region of visible spectra. The reaction went to completion affording the product with a good *dr* ratio, contrary to the case of

Table 1. Optimization details.



Entry ^[a]	Deviations from standard conditions	Conversion %	dr 3a ^[c]
1	None	99(94)	> 20:1
2	0.2 mmol scale	99(99)	> 20:1
3	1 mmol scale	99(99)	> 20:1
4	No light	NR	—
5	No 4	NR	—
6	No 1 ⁺	NR	—
7	No 6	NR	—
8	10 mol% 6	NR	—
9	THF instead of DCM	28	2:1
10	No 5	96	2.8:1
11	bpy instead of 5	90	6:1
12	dtbbpy instead of 5	92	6:1
13	3DPAFIPN, 456 nm instead of [ⁿ Pr-DMQA]	99	15:1
14	1% mol of [Ir(dF(CF ₃)ppy) ₂ (dtbbpy)]PF ₆ , 427 nm, instead of [ⁿ Pr-DMQA]	99	13:1
15	4,4'-diMeObpy instead of 5	NR	—
16	4,4'-diPhbpy instead of 5	NR	—
17	TMEDA instead of 5	NR	—
18	dppe instead of 5	NR	—
19 ^[d]	ClV(Salen) instead of 6 and 5	NR	—

^[a] Reaction performed on a 0.1 mmol scale.

^[b] Conversion determined by ¹H NMR analysis of the reaction crude. Isolated yield after chromatographic purification is reported in brackets.

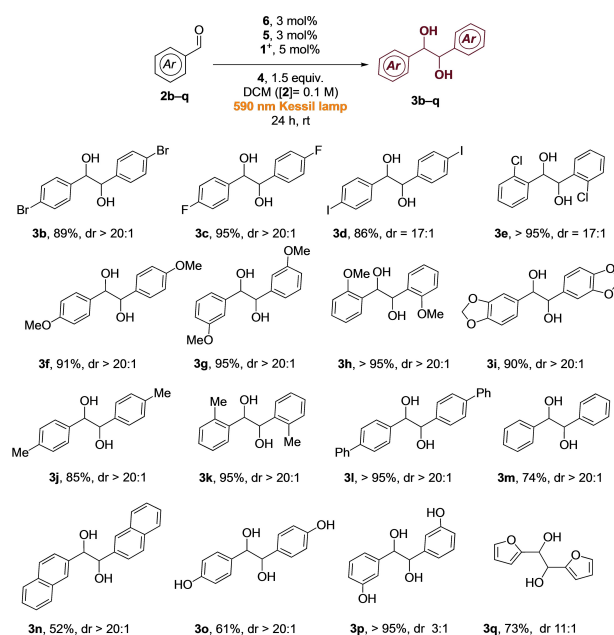
^[c] Determined by ¹H NMR analysis of the reaction crude and it is reported as *d/l*:*meso* ratio.

^[d] Achiral unsubstituted Salen ligands was used. The ClV(Salen) complex was obtained by the addition of 2 equiv. of Et₃N in the reaction mixture. NR=no reaction; bpy=2,2'-bipyridyl; dtbbpy=4,4'-di-*tert*-butyl-2,2'-dipyridyl; 4,4'-diMeObpy=4,4'-dimethoxy-2,2'-bipyridine; 4,4'-diPhbpy=4,4'-diphenyl-2,2'-bipyridine; TMEDA=tetramethylethylenediamine; dppe=1,2-bis(diphenylphosphino)ethane; Salen=N,N'-ethylenebis(salicylaldiminato) dianion; 3DPAFIPN=2,4,6-tris(diphenylamino)-5-fluoroisophthalonitrile.

titanium.^[23a] However the dr ratio was inferior respect to [ⁿPr-DMQA], probably due to some amount of background reaction.^[23a]

The optimal reaction conditions were investigated with a series of aromatic aldehydes, while aliphatic aldehydes were found unreactive (Scheme 1). Unfortunately, the pinacol coupling of aliphatic aldehydes is still an unsolved problem in photoredox catalysis, although Nagib published an interesting solution for obtaining a masked ketyl radical.^[35] With the aromatic aldehydes tested we found a general high reactivity and a high diastereoselectivity as it is possible to evince by Scheme 1, that reports the salient results obtained in our investigation.

In general, for almost all the investigated examples, the dr was >20:1, except for 3-hydroxybenzaldehyde who gave a low diastereoselectivity, probably caused by strong complexation with the vanadium complexes. When the hydroxy groups were protected, as in *o*-methoxy benzaldehyde, the high diastereoselective ratio was completely restored. Contrary to the photoredox reaction mediated by titanium complex,^[22] the presence of *ortho* substituent in the aromatic ring is well tolerated in the reaction with vanadium. The superiority of vanadium to respect the titanium mediated photoredox pinacol coupling was also noted in the cases of the substrates 2e and 2o, that gave with titanium a poor diastereoselection (dr=3:1 in both cases). Furthermore, comparing this vanadium-mediated protocol with the same reaction mediated by Cp₂TiCl₂, the reaction rate was increased. In the case of titanium, the reaction required 72 hours to reach



Scheme 1. Scope of the diastereoselective photoredox vanadium pinacol coupling.

completeness in an expensive solvent, PhCF_3 . In the case of vanadium DCM was the optimal reaction solvent and higher reactivity was observed, as 24 hours were required to achieve the complete conversion with most of the aromatic aldehydes tested. The reaction was scaled up over 1 mmol without observing a decrease in isolated yields. Interestingly, also heterocyclic compounds such as aldehyde **2q**, that was not reactive with titanium, posed no problems with the vanadium coupling.

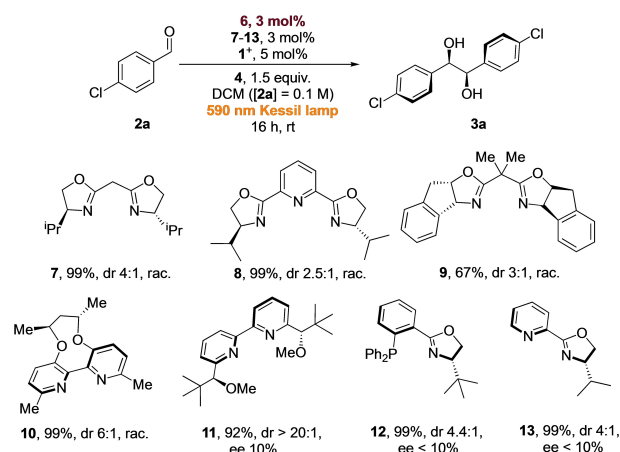
We have briefly investigated the possibility to perform intramolecular vanadium-mediated reactions by a model substrate (see SI for details).^[36] The reaction was observed for a biphenyl aldehyde derivative, and the desired pinacol product was isolated in low yields but with high diastereoselectivity. As aliphatic aldehydes were completely unreactive to our conditions, we have tried to perform cross pinacol coupling, using *o*-methoxybenzaldehyde (to favor chelation with vanadium complex) and hydrocinnamic aldehyde (4 equiv.). Unfortunately, only the pinacol coupling of the aromatic aldehyde was present after the quenching (for a further example see SI).

We decided to explore the use of chiral ligands to promote a stereoselective coupling reaction, motivated by the good reactivity and high diastereoisomeric ratio achieved. Examples of titanium^[37] and vanadium^[38] enantioselective catalytic pinacol coupling of aldehydes were reported in the literature promoted with chiral Salen complexes, by the use of the Fürstner/Gansäuer catalytic protocol^[22b,39] (in the presence of a stoichiometric metal reductant, and a scavenger to liberate and restore the metal catalytic cycle).

Recently, using a simple prepared chiral Ti(Salen)Cl₂ complex previously reported by Joshi,^[37b] we described the photoredox enantioselective titanium promoted pinacol coupling reaction.^[22] Although Salen-mediated vanadium pinacol coupling were described in literature,^[38] we surprisingly found that the vanadium Salen complexes were completely unreactive. We evaluated as possible chiral *N,N*-ligands the commercially available **7** and **8**, or simply prepared^[40] **9** chiral bis-oxazoline in combination with $\text{VCl}_3 \cdot \text{THF}_3$, but only the racemic compound was isolated, in low diastereoisomeric ratio (Scheme 2). Finally, two chiral bipyridine ligands **10**^[41] and **11**^[42] were tested for the model reaction. In the case of **11** a high diastereoselectivity was obtained, but, unfortunately, with only a 10% of enantiomeric excess as the result of the stereoselective reaction. Other modifications of the ligand **11** are in progress to find a suitable chiral ligand for the reaction.

Photophysical studies

To elucidate the importance and contributions of each reaction partner, as well as to comprehensively unveil



Scheme 2. Attempt to perform an enantioselective photoredox vanadium mediated reaction. Reaction performed on a 0.1 mmol scale. Conversion determined and dr determined by ¹H NMR analysis of the reaction crude and reported as *d/l:meso* ratio. ees determined by chiral HPLC (ID, *n*-hexane: *i*-PrOH = 90:10, 0.75 mL/min, 40 °C, 214 nm. t_R (*R,R*-enantiomer) = 9.878 min, t_R (*meso*-diastereoisomer) = 13.839 min, t_R (*S,S*-enantiomer) = 15.205 min).

the mechanism of the proposed protocol, an extensive investigation of the photophysical properties was conducted. Building upon the optimized reaction conditions and on previous evidence reported in the literature,^[23] CH_2Cl_2 was selected as the solvent for the photophysical characterization of **1⁺**.

In agreement with published results, compound **1⁺** shows a low energy-lying absorption band with maximum at 614 nm ($\epsilon_{614 \text{ nm}} = 10300 \text{ M}^{-1} \text{ cm}^{-1}$ in CH_2Cl_2 , $\lambda_{\text{onset}} \sim 680 \text{ nm}$; see Figure 1) allowing the absorption of orange light for its excitation (LED source at $\lambda_{\text{max}} = 590 \text{ nm}$). The emission band of **1⁺** is peaked at 648 nm – with a lifetime of 12.3 ns in air-equilibrated conditions and a quantum yield of 0.21 in air-equilibrated CH_2Cl_2 solution – corresponding to a spectroscopic energy E_{0-0} of 1.96 eV. As depicted in Figure 1, the presence of molecular oxygen has a negligible impact on the emission lifetime ($\tau_{\text{degas.}} = 12.6 \text{ ns}$). The photocatalyst is employed as a racemic mixture, therefore no investigations on electronic circular dichroism nor circular polarized luminescence have been carried out.

Given the photophysical data presented above, the effects of each of the reaction partners on the luminescence of **1⁺** were evaluated. Consistently with what was observed in our previous report,^[22a] **2a** is not able to markedly quench the luminescence of the excited state of **1⁺**, even at high concentrations ($k_{q1} < 1.0 \cdot 10^7 \text{ M}^{-1} \text{ s}^{-1}$, Figure 2 and Figure S3).

The modest reduction potentials of **1⁺** at the excited state ($E_0(\mathbf{1}^{2+}/\mathbf{1}^+) = -0.52 \text{ V vs. SCE}$) and in the ground state ($E_0(\mathbf{1}^+/\mathbf{1}^\bullet) = -0.82 \text{ V vs. SCE}$ in CH_2Cl_2)

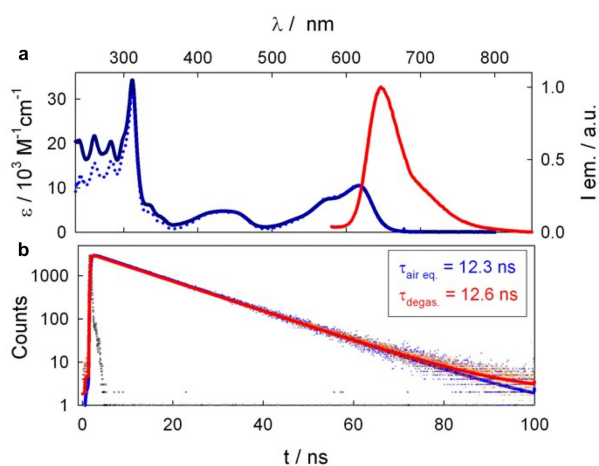


Figure 1. Photophysical investigation of the vanadium mediated pinacol coupling. **a.** Absorption (blue line) and emission spectra (red line) of air equilibrated CH_2Cl_2 solution of $\mathbf{1}^+$ at r.t. ($\lambda_{\text{ex}} = 575 \text{ nm}$). The excitation spectrum (dotted blue line; $\lambda_{\text{em}} = 690 \text{ nm}$) is also shown. **b.** Comparison between fluorescence decays of air-equilibrated (blue dots) and N_2 -saturated (red dots) CH_2Cl_2 solutions of $\mathbf{1}^+$ at r.t. The corresponding monoexponential fitting functions are shown as solid lines. The instrument response function (IRF) is also reported (grey dots).

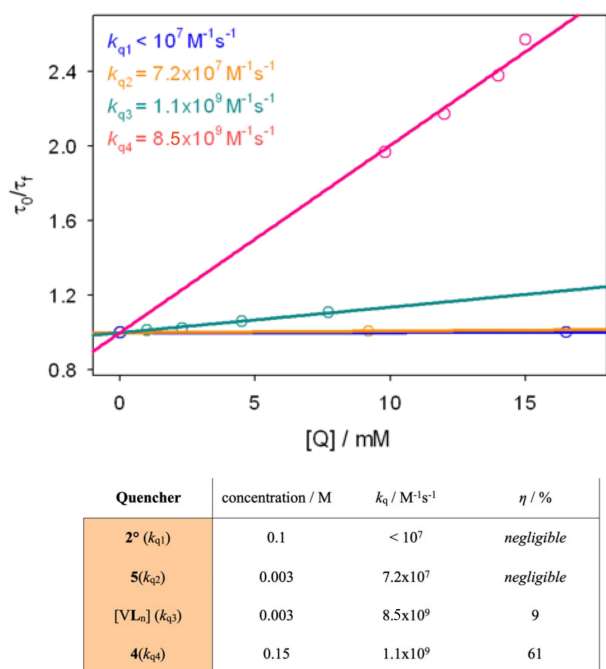


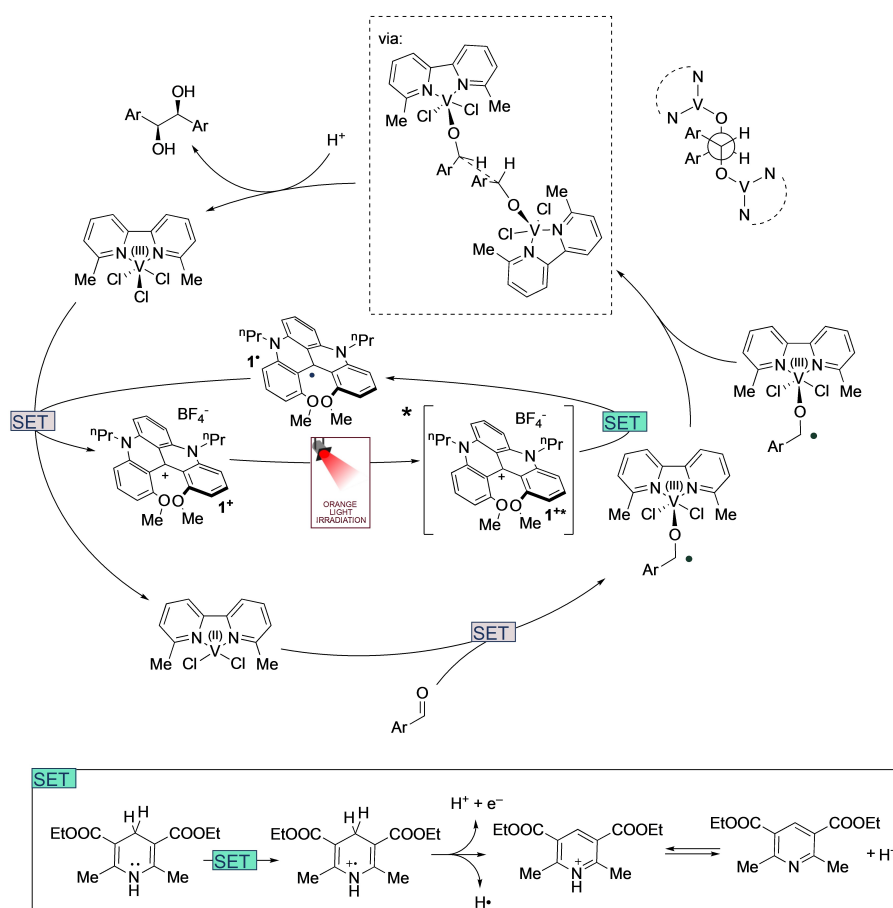
Figure 2. Comparison of measured quenching constants for different reaction partners and quenching efficiencies weighted on concentrations at the optimized reaction conditions. k_{qn} = quenching constant associated with each of the reaction partners obtained by Stern – Volmer analysis.

do not allow direct reduction of the model substrate preventing its non-diastereoselective metal-free dimeri-

zation. At the same time no relevant quenching mechanism has been observed upon additions of free ligand $\mathbf{5}$ (up to *ca.* 9.2 mM, $k_{q2} = 7.2 \cdot 10^7 \text{ M}^{-1}\text{s}^{-1}$, Figure 2 and Figure S4). On the other hand, quenching processes have been observed both for $\text{VCl}_3 \cdot \text{THF}_3$ $\mathbf{6}$ ($k_q = 8.0 \cdot 10^9 \text{ M}^{-1}\text{s}^{-1}$, see Supporting Information Figure S7), for the corresponding complex formed after equimolar addition of ligands $\mathbf{5}$ to $\mathbf{6}$ ($k_{q3} = 8.5 \cdot 10^9 \text{ M}^{-1}\text{s}^{-1}$, Figure 2 and Figure S6), and for the Hantzsch's ester $\mathbf{4}$ ($k_{q4} = 1.1 \cdot 10^9 \text{ M}^{-1} \text{S}^{-1}$, Figure 2 and Figure S5). Noteworthy, the dynamic quenching observed in the case of $\mathbf{6}$ further emphasizes the crucial role of ligand $\mathbf{5}$ for the diastereoselective outcome. Quencher $\mathbf{4}$, although showing a lower quenching constant compared to that determined for the vanadium complex ($k_q = 1.1 \cdot 10^9 \text{ M}^{-1}\text{s}^{-1}$ vs. $8.5 \cdot 10^9 \text{ M}^{-1}\text{s}^{-1}$, respectively), results the most efficient quencher with an efficiency of *ca.* 61%, due to the higher concentration present in the reaction conditions.

With these results in hand, we were able to propose a mechanistic picture of the dual photoredox and vanadium catalyzed dimerization of aromatic aldehydes (Scheme 3). Upon orange light irradiation, in accordance with the reported photoredox potentials of $\mathbf{1}^+$ ($E_0(\mathbf{1}^+/\mathbf{1}^{\bullet}) = 1.14 \text{ V vs. SCE}$), the excited state $\mathbf{1}^+$ is reductively quenched by $\mathbf{4}$ ($E_0(\mathbf{4}^{\bullet+}/\mathbf{4}) = 1.0 \text{ V vs. SCE}$)^[43] leading to the formation of radical $\mathbf{1}^{\bullet}$, which is reasonably able, in a second stage, to reduce the vanadium (III) complex that triggers the redox activity towards aldehydes (Scheme 3). Analogous to our recent report, the generated vanadium complex in low oxidation state can undergo a single electron transfer in the presence of $\mathbf{2a}$, leading to the formation of the corresponding ketyl radical. In Scheme 3 we have depicted the diastereoselective step suggesting the encounter of two ketyl radicals. Due to sterical hindrance, the most favorable approach is that showing the oxygen and a phenyl substituent in *anti*-position, but this hypothesis was not considered since it would lead to the *meso* product. Formation of *d/l* products might be generated through a transition state in which the two aryl groups are in a *gauche* relationship, while the vanadium complexes are in *anti*-position.^[44] In our case a crucial role is played by ligand $\mathbf{5}$, surrounding the metal center. The presence of a decorated bipyridyl ligand produces a defined transition state in the dimerization step, forcing the *gauche* relationship of the two aryl moieties. After the pinacolization, the release of the final product and the restoration of the transition metal catalyst in its pristine state is probably attributable to the scavenging action by the

Hantzsch's ester oxidation pathway that leads to the formation of the corresponding pyridine with the formal release of two protons.



Scheme 3. Proposed mechanism for the photoredox mediated pinacol coupling.

Conclusion

In conclusion, we have described a highly diastereoselective pinacol coupling promoted by V(II) complexes obtained via photoredox conditions. The reaction shows a broad scope, generality, and gives high yields with aromatic and heterocyclic aldehydes. The presence of substituents on the aldehyde is well-tolerated and *ortho* substituted aldehydes were found reactive without loss in the diastereoselection. The possibility of using vanadium complexes for diastereoselective cross-pinacol coupling reactions offers avenues to be explored for new reactions under photoredox conditions. Furthermore, cyclopentadienyl vanadium(II) complexes were reported active in pinacol coupling reactions of aliphatic aldehydes and moves towards these directions will be pursued in our laboratory.

Experimental Section

General Procedure for the Diastereoselective Photoredox Pinacol Coupling Promoted by a Vanadium Complex in Low Oxidation State

All the reactions were performed on 0.2 mmol of aldehyde in a flame dried 10 mL Schlenk tube, equipped with a Rotaflo stopcock, magnetic stirring bar, and an argon supply tube. Under vigorous argon flux, 6,6'-dimethyl-2,2'-dipyridyl **5** (1.1 mg, 0.006 mmol, 3 mol%) was dissolved in anhydrous dichloromethane (0.6 mL), then $\text{VCl}_3 \cdot \text{THF}_3$ (**6**; 0.5 M in DCM, 12 μL , 0.006 mmol, 3 mol%) was added. The reaction mixture turned instantly into green color. The mixture was let stirring at room temperature for one hour, then the aldehyde **2 a–q** (0.2 mmol), the photocatalyst **1⁺** (0.01 mmol, 5.0 mg, 5 mol%) and the diethyl 1,4-dihydro-2,6-dimethyl-3,5-pyridinedicarboxylate **4** (0.3 mmol, 76 mg, 1.5 equiv.) were added in the Schlenk tube. Anhydrous dichloromethane (1.4 mL) was then added, and the reaction mixture was further subjected to a freeze-pump-thaw procedure (three cycles), and the vessel was then refilled with argon. The reaction was irradiated under vigorous stirring for 24 h at room temperature. The crude reaction was filtered over a pad of silica, the solvent was evaporated under reduced pressure and the reaction crude was analyzed by ^1H NMR to evaluate the diastereoisomeric ratio of the products. The crude was subject to

flash column chromatography (SiO₂, *n*-hexane/AcOEt) to afford products **3a–q** in the stated yields.

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RESEARCH ARTICLE

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