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# Electron-Rich Phenoxyl Mediators Improve Thermodynamic Performance of Electrocatalytic Alcohol Oxidation with an Iridium Pincer Complex

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**ABSTRACT:** Electron-rich phenols, including *α-rac*-tocopherol **Ar**<sup>1</sup>**OH**, 2,4,6,-tri-*tert*-butylphenol **Ar**<sup>3</sup>**OH**, and butylated hydroxytoluene **Ar**<sup>4</sup>**OH**, are effective electrochemical mediators for the electrocatalytic oxidation of alcohols by an iridium amido dihyride c o m plex (PNP)Ir(H)<sub>2</sub> (IrN 1, PNP = bis[2diisopropylphosphino)ethyl]amide). Addition of phenol mediators leads to a decrease in the onset potential of catalysis from -0.65 V vs Fc<sup>+/0</sup> under unmediated conditions to -1.07 V vs Fc<sup>+/0</sup> in the presence of phenols. Mechanistic analysis suggests that oxidative turnover of the iridium amino trihydride (PNHP)Ir(H)<sub>3</sub> (IrH 2, PNHP = bis[2-diisopropylphosphino)ethyl]amine) to IrN 1 proceeds through two successive hydrogen atom transfers (HAT)



to 2 equiv of phenoxyl that are generated transiently at the anode. Isotope studies and comparison to known systems are consistent with initial homolysis of an Ir–H bond being rate-determining. Turnover frequencies up to 14.6 s<sup>-1</sup> and an average Faradaic efficiency of 93% are observed. The mediated system shows excellent chemoselectivity in bulk oxidations of 2-propanol and 1,2-benzenedimethanol in THF and is also viable in neat 2-propanol.

## INTRODUCTION

Electrocatalytic oxidations are important for energy conversion and selective chemical synthesis.<sup>1-3</sup> Alcohol electrooxidation strategies enable the direct utilization of biofeedstock polyols as fuels<sup>1,4-7</sup> and can also provide an alternative to stoichiometric and unselective chemical oxidants.<sup>1,8,9</sup> Although heterogeneous electrocatalysts<sup>1,10</sup> have been explored extensively, homogeneous molecular electrocatalysts provide opportunities to interrogate the key chemical or electrochemical steps that influence the rate, selectivity, and thermodynamics of key intermediates and to tune these properties through rational synthetic design. Ideal catalysts should not only exhibit high rates but should optimally operate with 100% Faradaic efficiency (FE) at or near the thermodynamically reversible potential of alcohol and carbonyl interconversion. The difference between the reversible potential and the catalyst operating potential is the overpotential and is a measure of the reaction's thermodynamic efficiency. The overpotential is principally dictated by the electrochemical properties  $(pK_a)$ and  $E^0$ ) of the catalyst (or electrode composition for heterogeneous electrocatalysts<sup>1,10</sup>).

One of the major challenges in the design of new electrocatalysts is that both the electrochemical properties and chemical properties of the catalysts (and intermediates) need to be optimized to simultaneously achieve fast rates at the appropriate electrochemical potential and pH. Electrochemical mediators can be employed to mediate critical electron and/or proton transfer steps. The use of mediators in electrochemical reactions has a long history in electrosynthesis,<sup>11–14</sup> including bioinspired mediators such as quinones<sup>15–17</sup> and NAD+,<sup>13</sup> as well as nitroxyls.<sup>14</sup> Nitroxyls can function both as alcohol oxidation electrocatalysts<sup>18–20</sup> and mediators that operate by hydrogen atom abstraction (e.g., Cu-coordinated alcohols).<sup>14,21–23</sup> Ferrocene, flavins, and polypyridyl complexes of ruthenium and osmium mediate the transfer of electrons from glucose oxidases to anodes in glucose-detection technologies and fuel cells.<sup>6,24,25</sup> Typically, mediators are two-electron/two-proton shuttles or agents that mediate electron transfer.

Our studies with Ru<sup>26,27</sup> and Fe pincer<sup>28</sup> compounds revealed that complexes active for transfer hydrogenation or acceptorless alcohol oxidation are good candidates for alcohol electrooxidation catalysts. As these and many other electrocatalytic processes involve metal hydrides as key intermediates,<sup>26,28–30</sup> strategies to improve both the rate and efficiency

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of electro-oxidation of metal hydrides are critical. The electrooxidation of transition metal hydrides typically involves stepwise electron transfer (ET) and proton transfer (PT) steps (Figure 1, red steps). As discrete ET and PT pathways can be



Figure 1. Unmediated (red) and mediated (blue) approaches to electrocatalytic alcohol oxidation with bifunctional metal hydride catalysts.

associated with high kinetic barriers,<sup>31,32</sup> we targeted mediators that can intercept metal hydrides to bypass thermodynamically costly ET and PT steps.<sup>27</sup> Many metal hydrides have relatively low bond dissociation free energies (BDFEs),<sup>33,34</sup> and this makes them susceptible to interception by hydrogen atom transfer (HAT),<sup>35–37</sup> a subclass of proton-coupled electron transfer (PCET) reactions.<sup>38–40</sup> If the hydrogen atom acceptor were electrochemically regenerable, a transition from unmediated to mediated electrocatalytic alcohol oxidation could be envisioned (Figure 1, blue steps).

There are specific thermochemical criteria that are necessary for this class of electrochemical mediators. First, the mediator must be a strong enough hydrogen atom acceptor to remove a hydrogen atom from the metal hydride; the resulting A-Hbond in the mediator must therefore have a BDFE similar to or greater than the M-H BDFE (Figure 1).

To afford a thermodynamic improvement over direct electrocatalysis with the metal hydride catalyst, the mediator must be electrochemically regenerable at potentials cathodic of the direct electrocatalysis onset potential. Lastly, the mediator should be sufficiently acidic to be deprotonated by bases used in the unmediated process so that a reliable comparison of overpotentials can be made between the mediated and unmediated systems.

With these considerations in mind, we investigated phenoxyl radicals as mediators for electrocatalytic alcohol oxidation. Due to their importance as antioxidants and their roles as hydrogen atom acceptors in enzyme catalysis, electron-rich phenoxyl radicals and their thermochemistry have been studied extensively.<sup>38,41–46</sup> Phenoxyls can be readily generated through deprotonation of the parent phenol with base and subsequent one-electron oxidation of the resulting phenoxide at the anode (Figure 2).<sup>38</sup> The thermochemical parameters of the phenol/ phenoxide/phenoxyl cycle are tunable by varying the aryl substituents. Phenol  $pK_a$  increases and phenoxide oxidation



Figure 2. Phenol thermochemical cycle.

potential decreases as electron-donating groups are added. Generally, the phenol BDFE increases as electron-withdrawing groups are added, but even the most electron-rich phenols (excluding hydroquinones and catechols) have BDFEs in excess of 73 kcal/mol in organic solvents.<sup>38</sup>

Phenoxyl-mediated alcohol electrooxidation also requires a catalyst that rapidly dehydrogenates alcohols, tolerates electrochemical conditions, and is susceptible to oxidation by HAT. These requirements directed us to the Ir(III) amido pincer complex IrN 1, which was first reported as an active bifunctional catalyst for the fast transfer hydrogenation of ketones with 2-propanol (Figure 3).<sup>47</sup> The mechanism of



Figure 3. Transfer hydrogenation of ketones with an iridium pincer catalyst.

transfer hydrogenation was proposed to proceed through the reversible dehydrogenation of secondary alcohols by 1 to generate the Ir(III) trihydride IrH 2.47 This isolable intermediate is the quantitative product when 1 is treated with 2-propanol.<sup>47</sup> There is precedent for electrocatalytic activity in this class of PNP pincer catalysts, as a related iron complex catalyzes alcohol electrooxidation, and IrH 2 itself performs CO<sub>2</sub> electroreduction.<sup>28,48</sup> Two additional properties of 2 make it an attractive target for interception by HAT in an electrochemical setting. First, both 1 and 2 tolerate strong bases because transfer hydrogenation is still viable in the presence of a 10-fold excess of KO<sup>t</sup>Bu.<sup>47</sup> Second, we expected the Ir-H bonds of 2 to be weak because similar octahedral bis(phosphine) Ir(III) hydrides have low bond dissociation enthalpies (BDEs) (58-64 kcal/mol).<sup>33,34,49</sup> This iridium system is therefore an excellent candidate for phenoxylmediated alcohol electrooxidation because it rapidly dehydrogenates alcohols, tolerates strong bases, and has weak Ir-H bonds that are likely susceptible to HAT to phenoxyl radicals.

Herein we demonstrate that electron-rich phenoxyl radicals are competent mediators for the electrocatalytic oxidation of alcohols to carbonyls by IrH **2**. The addition of phenoxyl mediators affords a substantial thermodynamic benefit by lowering the onset potential of catalysis from -0.65 V vs Fc<sup>+/0</sup> under unmediated conditions to -1.07 V vs Fc<sup>+/0</sup> in the presence of the phenol and a base.

### RESULTS AND DISCUSSION

On the basis of prior studies with Ru<sup>26,27</sup> and Fe<sup>28</sup> transfer hydrogenation catalysts, we anticipated that IrH **2** might be a viable candidate as an alcohol electrooxidation catalyst. To test this hypothesis, we investigated the electrochemistry of IrH **2** by cyclic voltammetry and carried out a bulk electrolysis of 2propanol with **2** as a soluble electrocatalyst. Cyclic voltammetry (CV) of IrH **2** in THF shows two irreversible oxidative features with onsets at -0.65 V vs Fc<sup>+/0</sup> and 0.04 V vs Fc<sup>+/0</sup> (Figure S2). These features are unchanged upon addition of 350 mM 2-propanol. However, upon addition of the phosphazene base 1-ethyl-2,2,4,4,4-pentakis(dimethylamino)- $2\lambda^5$ , $4\lambda^5$ -catenadi(phosphazene) (P<sub>2</sub>-Et) (pK<sub>a</sub>(THF) = 25.3, pK<sub>a</sub>(MeCN) = 32.9) to this solution, the current at -0.65 V vs Fc<sup>+/0</sup> increases significantly, consistent with electrocatalytic turnover (Figure 4).<sup>50</sup> To confirm this, bulk oxidations of 2-



Figure 4. Titration of IrH 2 with P<sub>2</sub>-Et in the presence of excess 2-propanol in THF (0.4 mM IrH 2, 350 mM 2-propanol, 100 mM NBu<sub>4</sub>BF<sub>4</sub>,  $\nu$  = 25 mV/s).

propanol with 2 and P<sub>2</sub>-Et were carried out at -0.355 V vs Fc<sup>+/0</sup> in a divided H-cell (Figure S3) for 6.5 h. Analysis of the reaction mixture revealed acetone as the product with an average Faradaic efficiency of 78% based on the ratio of acetone generated to the current passed (Figures S4 and S5). Although the catalytic wave is close in potential to the background oxidation of P<sub>2</sub>-Et (Figure S1), the reasonably high Faradaic efficiency with respect to acetone rules out 2-catalyzed oxidation of P<sub>2</sub>-Et and background P<sub>2</sub>-Et oxidation as possible causes of the increase in current observed in Figure 4.

These observations are consistent with an electrocatalytic alcohol oxidation (ECAT) mediated by IrN 1 and IrH 2 (Figure 5). Stoichiometric NMR experiments indicate that IrN



Figure 5. Direct electrocatalytic alcohol oxidation with IrH 2.

1 readily generates IrH 2 in the presence of excess 2-propanol (Figures 6A, S10). That the electrocatalytic peak occurs at a



**Figure 6.** Speciation of the iridium catalyst in the presence of excess alcohol (A) and base (B).

similar potential to that of oxidation of IrH 2 suggests that oxidation of 2 is a key step. Stoichiometric studies reveal that IrH 2 does not react with excess base  $P_2$ -Et (Figures 6B, S11–S13), consistent with electron transfer as the initial step in the oxidation of 2 to 1, as proposed for the analogous Fe pincer complex.<sup>28</sup>

To assess the role of the phenoxide on electrocatalytic alcohol oxidation, we investigated changes in the cyclic voltammetry of  $\alpha$ -rac-tocopherol Ar<sup>1</sup>OH (pK<sub>a</sub>(MeCN) = 30, BDFE(MeCN) = 75.2 kcal/mol)<sup>38,42,51</sup> upon addition of IrH 2 in THF in the presence of excess P<sub>2</sub>-Et and 2-propanol. In the absence of IrH 2 (Figure 7, green trace), the quasi-reversible



**Figure** 7. Comparison of  $Ar^1O^-/Ar^1O^-$  quasi-reversible oxidation (green, 0.8 mM  $Ar^1OH + 23$  mM  $P_2$ -Et), unmediated ECAT (orange, 0.4 mM IrH 2 + 7 mM  $P_2$ -Et), and mediated ECHAT (blue, 0.4 mM IrH 2 + 0.8 mM  $Ar^1OH + 23$  mM  $P_2$ -Et) in THF with 100 mM NBu<sub>4</sub>BF<sub>4</sub> and 400 mM 2-propanol ( $\nu = 25$  mV/s).

peak-shaped wave of the phenoxide/phenoxyl  $Ar^1O^-/Ar^1O^$ couple is apparent. When IrH 2 is added, this feature is replaced by an irreversible, plateau-shaped wave of greater maximum current at the same onset potential (Figure 7, blue trace). These characteristics are consistent with the electrocatalytic turnover of  $Ar^1OH$ , presumably through net HAT from IrH 2 to the phenoxyl  $Ar^1O^{.52-54}$  Most importantly, this new electrocatalytic process, which we refer to as electrocatalytic hydrogen atom transfer (ECHAT), occurs with  $E_{onset}$ = -1.07 V vs Fc<sup>+/0</sup>, whereas unmediated ECAT (Figure 7, orange trace) has  $E_{onset} = -0.65$  V vs Fc<sup>+/0</sup>. The operating potential of electrocatalysis decreased by 420 mV simply by adding the  $Ar^1OH$  mediator.

We screened several other electron-rich phenoxyls (Figure 8) for their performance as electrochemically regenerable HAT



mediators by cyclic voltammetry. The screening process identified 2,2,5,7,8-pentamethylchromanol Ar<sup>2</sup>OH, 2,4,6-tri*tert*-butylphenol **Ar**<sup>3</sup>**OH**, and butylated hydroxytoluene **Ar**<sup>4</sup>**OH** as effective mediators, as in each of these cases, titration with IrH 2 was concomitant with marked increases in the peak current of the  $Ar^{x}O^{-}/Ar^{x}O^{\cdot}$  wave and a transformation from reversible or quasi-reversible peak-shaped signals to irreversible catalytic plateau-shaped ones (Figures S24-S26) in the range of -0.95 V to -1.1 V vs Fc<sup>+/0</sup>. Hydroquinone Ar<sup>5</sup>OH and 4aminophenol Ar<sup>6</sup>OH did not appear to be effective in these screens and the CVs exhibited multielectron/multiproton behavior (Figures S27 and S28). 2,6-Dimethoxyphenol Ar<sup>7</sup>OH and 3,5-dimethoxyphenol Ar<sup>8</sup>OH were also ineffective, as the  $Ar^{x}O^{-}/Ar^{x}O^{-}$  couples were insufficiently cathodic (Figures S29 and S30) and overlapped with the oxidation of IrH 2. We used Ar<sup>1</sup>OH for all subsequent electrochemical experiments because it had the lowest onset potential and the greatest increase in plateau current in response to IrH 2 titration (Figures S31-S33).

Having established that electron-rich phenoxyl mediators can substantially reduce the potential of electrocatalytic alcohol oxidation with IrH **2**, we conducted additional electrochemical experiments, scan rate studies, CV titrations, and isotope effect studies to provide further insights on the mechanism of this tandem electrocatalytic process. To assess if hydrogen atom transfer by a phenoxyl radical is a plausible step in the electrocatalytic oxidation of 2-propanol with IrH **2**, we investigated the catalytic oxidation of 2-propanol with a stable phenoxyl radical as the terminal oxidant (Figure 9A).

When a stirred solution of the persistent and isolable phenoxyl 2,4,6-tri-*tert*-butylphenoxyl  $Ar^3O$  (BDFE (MeCN) = 77.1 kcal/mol)<sup>38</sup> in deuterated toluene was treated with 0.37% IrH 2 and a slight excess of 2-propanol, the vibrant deep blue color of the phenoxyl radical disappeared within 15 s to afford a light yellow solution. Subsequent <sup>1</sup>H NMR analysis showed a 2:1 ratio of the corresponding phenol  $Ar^3OH$  and acetone in 76% yield (Figure 9A). This result demonstrates that phenoxyl radicals are competent terminal oxidants for the oxidation of 2propanol by IrH 2 and suggests that the oxidation of IrH 2 to give IrN 1 can be mediated by the consecutive homolyses of the Ir–H and the N–H bonds of IrH 2 by 2 equiv of phenoxyl.

To provide further evidence that hydrogen atom transfer is a viable oxidative process, the stoichiometric reaction of IrH 2 with a weaker hydrogen atom acceptor was investigated. When treated with 2 equiv of the persistent nitroxyl radical TEMPO ((2,2,6,6-tetramethylpiperidin-1-yl)oxyl) (BDFE(MeCN) = 66.5 kcal/mol),<sup>38</sup> IrH 2 is slowly oxidized to IrN 1, reaching 29% conversion over 16 h (Figure 9B). This observation provides further evidence that IrN 1 can be generated through successive HATs from IrH 2. An analogous stoichiometric experiment was carried out with 2 equiv of Ar<sup>3</sup>O, but the results were less conclusive (Figures S19 and S20). Although the blue color of the  $Ar^{3}O$  was quenched almost immediately upon addition to a solution of IrH 2 in toluene- $d_{81}$  only partial conversion of IrH 2 to IrN 1 was observed. Several new and unidentified metal hydride signals were detected by <sup>1</sup>H NMR. Treatment of IrN 1 with 1.8 equiv of Ar<sup>3</sup>O· results in the formation of Ar<sup>3</sup>OH (Figures S21 and S22), which suggests that poor mixing in combination with overoxidation of IrN 1 may be the causes of the complex product mixture and incomplete conversion observed in the stoichiometric reaction of IrH 2 and Ar<sup>3</sup>O.

Under the conditions of kinetically limited (Zone KS) electrocatalysis,<sup>53</sup> the plateau current, and therefore the turnover frequency, are limited only by the rate of homogeneous chemical reactions and not by the mass transport of chemical species.<sup>52</sup> The plateau-shaped wave of Figure 7 and experiments demonstrating that the plateau current of  $Ar^1OH$ -mediated electrocatalytic 2-propanol oxidation with 2 remains constant between scan rates of 25 and 1600 mV/s (Figures S34 and S35) indicate that under these experimental conditions, the reaction is in the kinetically



Figure 9. Catalytic (A) and stoichiometric (B) HAT from IrH 2 to persistent radicals.



Figure 10.  $k_{obs}$  vs iridium concentration (0.75 mM Ar<sup>1</sup>OH, 23 mM P<sub>2</sub>-Et, 400 mM 2-propanol, 100 mM NBu<sub>4</sub>BF<sub>4</sub> in THF,  $\nu = 25$  mV/s).



Figure 11. Plateau current vs  $Ar^1OH$  concentration (1.1 mM 1, 45 mM P<sub>2</sub>-Et, 400 mM 2-propanol, 100 mM NBu<sub>4</sub>BF<sub>4</sub> in THF,  $\nu = 25$  mV/s).



Figure 12. Plateau current squared vs 2-propanol concentration (1.1 mM IrH 1, 0.4 mM  $Ar^1OH$ , 42 mM  $P_2$ -Et, 100 mM  $NBu_4BF_4$  in THF,  $\nu = 25$  mV/s).

limited regime where the magnitude of the plateau current depends only on the rates of homogeneous chemical reactions.

Under the assumption that the phenol is the key electrocatalytic intermediate, the formula for plateau current for the kinetically limited catalytic wave can be written as

$$i_{\text{plateau}} = FA[\text{Ar}^{1}\text{OH}]_{\text{total}}\sqrt{2Dk_{\text{obs}}}$$
(1)

where *F* is the Faraday constant, *A* is the electrode surface area,  $[\mathbf{Ar^{1}OH}]_{\text{total}}$  and *D* are the total concentration and diffusion coefficient of the  $\mathbf{Ar^{1}OH}$ , and  $k_{\text{obs}}$  is the catalytic turnover frequency.<sup>52,54</sup> A complete derivation of eq 1 is presented in Supporting Information. In the absence of IrH 2, the maximum current of the noncatalytic peak-shaped  $\mathbf{Ar^{1}O^{-}/Ar^{1}O^{-}}$  wave is governed by the Randles–Sevcik equation:

$$i_{\text{peak}} = 0.4463FA[\text{Ar}^{1}\text{OH}]_{\text{total}}\sqrt{\frac{F\nu D}{RT}}$$
 (2)

Here v is the voltammetric scan rate, R is the gas constant, and T is the temperature. Division of eq 1 by eq 2 and subsequent rearrangement enables the tabulation of  $k_{obs}$  by comparing the catalytic plateau currents in the presence of substrate to the noncatalytic peak current in the absence of substrate:

$$k_{\rm obs} = \frac{1}{2} \left( 0.4463 \frac{i_{\rm plateau}}{i_{\rm peak}} \right)^2 \frac{F\nu}{RT}$$
(3)

Titration of IrH **2** into a cell containing  $Ar^1OH$ , P<sub>2</sub>-Et, and 2propanol and analysis of the corresponding plateau currents (eqs 1-3) by cyclic voltammetry reveals that  $k_{obs}$  shows a linear dependence on Ir concentration (Figure 10), indicating a first-order dependence on Ir. Turnover frequencies up to 14.6 s<sup>-1</sup> were observed. When this experiment is repeated with 2-propanol- $d_8$  in place of protiated 2-propanol, the plot of  $k_{obs}$ vs [Ir] also shows a linear dependence but with a slope that decreases by a factor of 4.2, corresponding to a primary kinetic

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Figure 13. Plateau current squared vs P<sub>2</sub>-Et concentration (1.1 mM IrH 1, 0.4 mM  $Ar^{1}OH$ , 420 mM 2-propanol, 100 mM  $NBu_{4}BF_{4}$  in THF,  $\nu = 25 \text{ mV/s}$ ).

isotope effect (KIE) of 4.2 (Figures S37 and S38). Foot-of-thewave analysis<sup>52,55</sup> of the same voltammograms in Figure 10 affords a value of  $k_{obs}/[Ir]$  that is within 10% of that calculated from the catalytic plateau analysis (Figures S39 and S40).

Analysis of the plateau current vs  $[Ar^1OH]$  reveals the linear relationship (Figure 11) predicted by eq 2, which indicates that  $k_{obs}$  is independent of phenol concentration.

Analysis of the square of the plateau current as a function of 2-propanol concentration (eq 1) reveals that  $i_{\text{plateau}}^2$  increases as the concentration of 2-propanol is increased up to about 200 mM but does not change at concentrations above 200 mM 2-propanol (Figure 12). These data indicate that the  $k_{\text{obs}}$  is independent of 2-propanol concentration for [iPrOH]<sub>0</sub> > 200 mM, concentrations at which the other titrations and the bulk electrolyses were performed.

Analogous studies carried out as a function of  $[P_2-Et]$  reveal that  $i_{plateau}^2$  is independent of the concentration of  $P_2$ -Et, but the catalytic wave is plateau-shaped only for concentrations greater than 5 mM (Figure 13). Below this limit, the wave is peak-shaped. This behavior is consistent with a transition from mass-transport limited catalysis (zone K) at low base concentrations to kinetically limited catalysis (zone KS) at high base concentrations.<sup>52,53</sup> Foot-of-the-wave analysis of these same voltammograms reveals that the rate of catalysis remains independent of base concentration even when the waves are peak-shaped due to mass-transport limitation (Figures S41 and S42). Thus, the experimental data are consistent with eq 4:

$$k_{\rm obs(exp)} = k[\rm{IrH}]_0 \tag{4}$$

where  $k_{obs}$  is first-order with respect to iridium and zero-order with respect to  $Ar^1OH$ , P<sub>2</sub>-Et, and 2-propanol.

On the basis of this mechanistic investigation and the known reactivities of phenols and the iridium complex 2, a mechanism consisting of the elementary steps of Figure 14 can be proposed. Step 1 is the first net HAT from IrH 2 to  $Ar^1O$ , which generates  $Ar^1OH$  and an iridium radical species 3. Step 2 is the second net HAT event from 3 to  $Ar^1O$ , which regenerates IrN 1. Step 3 is the acid—base reaction of P<sub>2</sub>-Et and  $Ar^1OH$ , step 4 is heterogeneous electron transfer from  $Ar^1O^-$  to the anode, and step 5 is the dehydrogenation of 2-propanol by IrN 1 to yield acetone and IrH 2.

If hydrogen atom transfer from IrH 2 to the phenoxyl  $Ar^1O$  is assumed to be turnover limiting, this mechanism would predict that the rate should conform to eq 5 with  $k_{obs}$  defined as in eq 6:

$$2 + Ar^{1}O^{\bullet} \xrightarrow{k_{1}} 3 + Ar^{1}OH$$

$$3 + Ar^{1}O^{\bullet} \xrightarrow{k_{2}} 1 + Ar^{1}OH$$

$$Ar^{1}OH + P_{2}-Et \xrightarrow{k_{3}} Ar^{1}O^{\bullet} + HP_{2}-Et^{\oplus}$$

$$Ar^{1}O^{\oplus} \xrightarrow{k_{4}} Ar^{1}O^{\bullet} + e^{\oplus}$$

$$1 + R-OH \xrightarrow{k_{5}} 2 + R=O$$

Figure 14. Proposed elementary steps of electrocatalytic hydrogen atom transfer (ECHAT).

$$d[acetone]/_{dt} = k_{obs}[Ar^{1}O\cdot]_{0}$$
(5)

$$k_{\rm obs} = k_1 [\rm{IrH}]_0 \tag{6}$$

where  $[\mathbf{Ar}^{I}\mathbf{O}\cdot]_{0}$  and  $[\mathrm{IrH}]_{0}$  are the concentrations of  $\mathbf{Ar}^{I}\mathbf{O}\cdot$ and  $\mathrm{IrH}$  at the anode surface. The plateau shape of the ECHAT waves dictates that the substrate concentration at the anode surface  $[\mathrm{IrH}]_{0}$  is essentially the same as that in the bulk solution, so  $[\mathrm{IrH}]_{0} = [\mathrm{IrH}]_{\mathrm{total}}$ .<sup>52</sup> If the net hydrogen atom transfer (HAT) of step 1 is assumed to be slow relative to deprotonation and heterogeneous electron transfer, the phenoxyl  $\mathbf{Ar}^{I}\mathbf{O}\cdot$  is the predominant resting state of the phenol mediator at the anode and  $[\mathbf{Ar}^{I}\mathbf{O}\cdot]_{0} \approx [\mathbf{Ar}^{I}\mathbf{OH}]_{\mathrm{total}}$ . Steadystate assumptions on the concentrations of 3,  $\mathbf{Ar}^{I}\mathbf{OH}$ , and  $\mathbf{Ar}^{I}\mathbf{O}^{-}$  leads to a predicted rate law for the mechanism of Figure 14 in terms of the known total bulk concentrations of phenol and iridium:

$$d[acetone]/_{dt} = k_{obs}[Ar^{1}OH]_{total}$$
<sup>(7)</sup>

$$k_{\rm obs} = k_{\rm l} [\rm{IrH}]_{\rm total} \tag{8}$$

This rate law is in agreement with that determined experimentally (eq 4). Substituting the slope of the plot of  $k_{obs}$  vs [IrH]<sub>total</sub> concentration (Figure 10) for  $k_{obs}/[IrH]_{total}$  in eq 8 gives a value of  $k_1 = 4650 \text{ M}^{-1} \text{ s}^{-1}$  for protated 2-propanol and  $k_{1-d} = 1100 \text{ M}^{-1} \text{ s}^{-1}$  for 2-propanol- $d_8$ . According to the proposed mechanism of Figure 14, this corresponds to the second-order rate constant for the reaction of  $\text{Ar}^1\text{O}$  with IrH(D) 2.

The kinetics and mechanistic studies (Figure 9) suggest that the reaction of  $Ar^1O$  with the IrH 2 is the key turnover-

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Figure 15. Proposed mechanism for the tandem electrocatalytic oxidation of 2-propanol with phenols as electrocatalytic hydrogen atom transfer (ECHAT) mediators.

limiting step in the tandem catalytic cycle ([iPrOH] > 200 mM). The mechanism of this net hydrogen atom transfer could proceed by a concerted hydrogen atom transfer, or by stepwise electron and proton transfers. Although it is difficult to experimentally discriminate between concerted HAT and ET-PT or PT-ET,<sup>38,56</sup> several lines of evidence argue against the stepwise processes. A putative ET-PT pathway would involve an endergonic (+9.7 kcal/mol) electron transfer from IrH 2 to  $Ar^1O$  followed by deprotonation of the resulting iridium cation by  $Ar^1O^-$  or  $P_2$ -Et (Figure S43). A significant primary KIE of 4.2 is observed experimentally, which is consistent with Ir-H bond breaking in the rate-determining step. Large KIEs and unfavorable electron transfers have been used previously to rule out discrete ET-PT pathways in the oxidation of toluenes by permanganate, the comproportionation of ruthenium oxo and aquo complexes, 57,58 and the oxidation of ascorbate by Ar<sup>1</sup>O, where initial ET was calculated to be endergonic by +12.2 kcal/mol.<sup>59</sup> The observation that the rate of the electrocatalytic oxidation is independent of P<sub>2</sub>-Et concentration (Figure 13) argues against a rapid ET preequilibrium followed by proton transfer. $^{60-62}$ 

A stepwise PT-ET mechanism is also unlikely, as this would occur via initial deprotonation of IrH 2 by  $P_2$ -Et, which we have shown is unfavorable (Figures 6 B, S36). Therefore, the rapid oxidation of IrH 2 by  $Ar^3O$  in Figure 8A, which occurs in the absence of a base, is unlikely to proceed by an initial PT, and the oxidation of IrH 2 by phenoxyl mediators under ECHAT conditions is most likely a concerted, rather than stepwise, HAT event. Similar logic applies to the slow oxidation of IrH 2 by TEMPO (Figure 8B).

The primary KIE of 4.2 observed for the electrocatalytic reaction in the presence of phenol is also consistent with metal hydride homolysis, as this value is similar to the maximum KIE of 4.4 estimated from the previously reported IR spectrum of IrH **2** (see Supporting Information).<sup>47</sup> Similar reasoning was used by Norton and co-workers in their studies of the

oxidation of the metal hydrides  $HMn(CO)_5$  and  $H_2Os(CO)_4$  by tris(p-*tert*-butylphenyl)methyl radical 4.<sup>63</sup>

Shown in Figure 15 is a proposed mechanism that is consistent with the experimental evidence to date. Following the rapid dehydrogenation of 2-propanol by IrN 1, oxidation of IrH 2 back to IrN 1 proceeds through two successive hydrogen atom transfer events to 2 equiv of  $Ar^1O$ . The kinetic data suggest that the first hydrogen atom transfer from IrH 2 to  $Ar^{1}O$  is turnover-limiting  $(k_{1} = 4650 \text{ M}^{-1} \text{ s}^{-1})$ . Subsequent hydrogen atom abstraction of the intermediate 3 by Ar<sup>1</sup>O· generates IrN 1. The 2 equiv of Ar<sup>1</sup>OH are then turned over through fast deprotonation by P2-Et and heterogeneous single electron transfer. Significantly, as the oxidation of the phenoxide  $Ar^1O^-$  occurs with  $E_{onset} = -1.07$  V vs Fc<sup>+/0</sup>, 420 mV cathodic of  $E_{\text{onset}}$  for IrH 2, the addition of the phenol mediator results in a significant decrease in the operating potential of the tandem electrocatalytic process relative to that for the electroxidation with IrH 2 alone.

The observations that (1) the stable phenoxyl radical  $Ar^{3}O$ . is a competent terminal oxidant for the oxidation of 2-propanol with IrH 2 (Figure 9) and (2) that the reaction of IrH 2 with the nitroxyl radical TEMPO affords the amido complex IrN 1 support this proposed mechanism. We have no direct evidence for the intermediacy of the Ir(II) dihydride 3 nor information regarding its redox potential and/or  $pK_a$ ; thus, the data to date do not allow us to rule out that the proposed interconversion of 3 to IrN 1 occurs by stepwise proton and electron (ET-PT or PT-ET) processes. Furthermore, while the kinetic isotope effect observed is consistent with the initial abstraction of a hydride from IrH 2, we cannot rule out that the N-H bond of IrH 2 is homolyzed first. Stable rhodium aminyl complexes have been synthesized through the deprotonation and oxidation of the corresponding rhodium secondary amino complex with N-H homolytic BDEs as low as 76 kcal/ mol.<sup>64-66</sup> Related iridium aminyl species have been detected in situ and invoked as key intermediates in catalytic alcohol dehydrogenation.<sup>67,68</sup> Nevertheless, the rate constant of  $k_1 =$ 



Figure 16. Bulk electrocatalytic alcohol oxidations. FE for A and B are the averages of two runs, and C and D were each performed once. The error for FE is  $\pm 10\%$  for any one experiment.

4650  $M^{-1} s^{-1}$  calculated for the turnover-limiting step involving the reaction of IrH 2 with  $Ar^1O$  is similar to previously reported rate constants for bimolecular HAT from Rh(III) (1170  $M^{-1} s^{-1}$ ), Co(I) (1600  $M^{-1} s^{-1}$ ), and Fe(II) (12000  $M^{-1} s^{-1}$ ) hydrides to the trityl radical 4 (BDE (4) = 74 kcal/mol, BDE ( $Ar^1OH$ ) = 80.4 kcal/mol).<sup>36,37</sup>

To corroborate the results obtained by CV, controlledpotential electrocatalytic alcohol oxidations with IrH 2 were carried out under both unmediated and phenol-mediated conditions in a divided glass H-cell with a disposable reticulated vitreous carbon (RVC) working electrode. Bulk electrocatalytic oxidation of 2-propanol (0.41 M in THF) with 2 (3.1 mM) in the absence of  $Ar^{I}OH$  was performed at -355mV vs  $Fc^{+/0}$  (Figure 16A). Acetone was detected as the sole product with a modest average Faradaic efficiency of 78% and turnover number (TON) up to 4. The analogous controlled potential electrocatalytic oxidation in the presence of Ar<sup>1</sup>OH (2.5 mM in THF) was performed at -735 mV vs Fc<sup>+/0</sup> (Figure 16B). Acetone was the only product detected and the average Faradaic efficiency improved to 93%. Turnover numbers up to 8 with respect IrH 2 and 10 with respect to Ar<sup>1</sup>OH were calculated based on the yield of acetone. These data reveal that the addition of the phenol mediator noticeably improves turnover number and Faradaic efficiency at an operating potential 380 mV more cathodic than that of the unmediated electrocatalytic oxidation with IrH 2 alone. The presence of the phenoxyl mediator is imperative to the success of lowpotential mediated electrocatalytic oxidation, as no appreciable catalysis was observed in a control electrolysis performed at -735 mV vs Fc<sup>+/0</sup> in the absence of Ar<sup>1</sup>OH (Figure 16C).

Controlled potential electrocatalytic oxidation of 1,2benzenedimethanol under similar conditions resulted in exclusive conversion to phthalide (Figure 16D), which demonstrates the system's capacity for selective polyol oxidation. Esterificative coupling of primary alcohols, thought to result from the dehydrogenation of hemiacetal intermediates, is frequently observed in related bifunctional pincer catalysts.<sup>69–71</sup>

To assess whether electrocatalytic alcohol oxidation might be extended to other solvents, we briefly examined the cyclic voltammetry of IrH **2** in neat 2-propanol (100 mM NBu<sub>4</sub>BF<sub>4</sub> as supporting electrolyte) and the changes induced upon the addition of base ( $P_2$ -Et) and phenol Ar<sup>1</sup>OH (Figure 17). In



**Figure 17.** Comparison of IrH **2** oxidation (red, 1.1 mM IrH **2**), unmediated ECAT (orange, 1.1 mM IrH **2** + 71 mM P<sub>2</sub>-Et), and mediated ECHAT (blue, 1.1 mM IrH **2** + 1.8 mM **Ar**<sup>1</sup>**O**H + 71 mM P<sub>2</sub>-Et) in 100 mM NBu<sub>4</sub>BF<sub>4</sub> neat 2-propanol ( $\nu = 25$  mV/s).

the absence of base, the CV of IrH 2 (1.1 mM) exhibits an irreversible oxidation at approximately -0.63 V vs Fc<sup>+/0</sup> in 2propanol, comparable to that observed in THF (Figure 4). An increase in current at -0.63 V is observed upon addition of 71 mM P<sub>2</sub>-Et, consistent with an electrocatalytic current. When a similar experiment is carried out with the addition of 1.8 mM Ar<sup>1</sup>OH, a plateau-shaped wave is observed with an onset of -0.81 V vs Fc<sup>+/0</sup>. The addition of Ar<sup>1</sup>OH as a mediator lowers the onset potential of catalysis in neat 2-propanol by 180 mV  $(E_{\text{onset}(\text{unmediated})} = -0.63 \text{ V vs } Fc^{+/0} \text{ vs } E_{\text{onset}(\text{ArOH mediated})} = -0.81 \text{ V vs } Fc^{+/0}$ , Figure 17). For **Ar<sup>1</sup>OH**-mediated oxidation in 2-propanol, turnover frequencies up to 9.6  $s^{-1}$  are observed. The electrocatalytic rate law derived from the cyclic voltammetry is comparable to that observed in THF (Figures S45-S50), although the rates are slightly slower in 2-propanol than in THF  $(k_{1(iPrOH)} = 2960 \text{ M}^{-1} \text{ s}^{-1} \text{ vs } k_{1(THF)} = 4650 \text{ M}^{-1}$ s<sup>-1</sup>). These data suggest that electrocatalytic alcohol oxidation with phenol mediators is not limited to polar aprotic solvents such as THF, but might be profitably carried out in a variety of solvents. Further studies along these lines are in progress.

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#### CONCLUSIONS

Herein we demonstrated that electron-rich phenols function as effective mediators for the electrocatalytic oxidation of alcohols catalyzed by IrH 2. The addition of phenol mediators results in a significant decrease in the onset potential (420 mV in THF, 180 mV in neat 2-propanol) relative to that of the unmediated electrocatalytic oxidations. Mechanistic studies, voltammetric titrations, and KIE studies are consistent with a tandem electrocatalytic process in the presence of phenol mediators (Figure 15). The phenol functions as an electrochemically regenerable hydrogen atom acceptor to facilitate the reoxidation of transition metal hydrides generated in the course of the Ir-mediated oxidation of the alcohol. Turnover frequencies up to 14.6 s  $^{-1}$  and 9.6 s $^{-1}$  were observed by CV in THF and neat 2-propanol, respectively. Bulk oxidations of 2propanol in the presence of IrH 2 and phenol Ar<sup>1</sup>OH afforded acetone selectively, with an average Faradaic efficiency of 93%. This study demonstrates the capacity of electron-rich phenoxyls to improve thermodynamic performance in electrooxidative catalysis by providing an alternative to stepwise proton and electron transfer steps for the oxidation of transition metal hydrides.

#### ASSOCIATED CONTENT

#### **Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacs.0c09605.

General experimental methods, additional cyclic voltammograms, turnover frequency (TOF) calculations, controlled potential electrolysis studies, and chemical hydrogen atom transfer studies (PDF)

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#### Notes

The authors declare no competing financial interest.

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