Redox Potentials of Ligands and Complexes – a DFT Approach

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ABSTRACT

A review of the limited literature concerned with theoretical ways to predict experimentally measured redox potentials of ligands and complexes is presented. Electrochemical and related DFT studies involving series of para-substituted nitrobenzenes and \( \beta \)-diketone bidentate ligands are discussed. New studies involving ferrocenes and bimetallic complexes (containing both rhodium and iron) are additionally reported. Correlations of redox potentials with calculated descriptors; electron affinity (EA), group electronegativity (\( \chi G \)), electrophilicity index (\( \omega \)), LUMO energy (\( E_{\text{LUMO}} \)) and HOMO energy (\( E_{\text{HOMO}} \)) – obtained from calculated electronic energies of neutral, anionic and cationic molecules, are compared. Observed \( E'_0 \), \( E_{\text{PA}} \) or \( E_{\text{PC}} \) gave excellent correlations in the linear relationships between \( E_{\text{PC}} \) and \( E_{\text{LUMO}} \) (\( R^2 > 0.99 \)), and \( E_{\text{PA}} \) and \( E_{\text{HOMO}} \) (\( R^2 > 0.92 \)). Close correlation with the HOMO-1 energy was also found with the ferrocene-based second oxidation in the Rh complex.

1. Introduction

A variety of definitions had been invented to describe and quantify the direct or indirect effect and/or strength of electron-withdrawing and donating substituents in molecules. Following are some of these definitions that are of particular importance in computational chemistry.

Electron affinity (EA) of an atom or molecule is the associated energy change that occurs when an electron is added to the neutral species to form a negative ion,\(^2\) while ionization potential (IP) is the energy required to remove an electron from an atom, radical, or molecule.

The global electrophilicity index (\( \omega \)) representing the electrophilic power of atoms and molecules, as defined by Parr and coworkers,\(^3\) depends on both EA and IP.

In ‘group electronegativity’ (\( \chi G \)) electronegativity is associated more with different functional groups than with individual atoms.\(^4\)

Lastly, theoretically computed HOMO or LUMO energies of molecules are closely associated with the respective oxidation and reduction potentials of molecules.\(^5\)

Experimental oxidation and reduction potentials are obtained by means of cyclic voltammetry (CV), which is by far the most effective electro-analytical technique for the study of electroactive species. Peak separation in CVs is given by \( \Delta E_p = E_{p^+} - E_{p^-} \), where \( E_{p^+} \) and \( E_{p^-} \) are the respective peak potentials of anodic and cathodic scans associated with an electrochemical process. The formal reduction potential is defined as, \( E^\circ = (E_{p^-} - E_{p^+})/2 \). A redox couple is said to be electrochemically reversible if \( \Delta E_p / \Delta E_r \) is equal to unity. A peak separation of 90 mV \( \leq \Delta E_p \leq 150 \) mV is considered quasi-reversible, while \( \Delta E_p > 150 \) mV indicates electrochemically irreversible behaviour. A chemically irreversible system is where only reduction or oxidation can occur.

To different extents the former definitions have been related to experimentally observed oxidation and reduction potentials. Amongst these, some of the best results were obtained by correlating EA with one-electron reduction potentials. Hicks et al.\(^6\) computed EAs for a set of 29 mono-substituted benzal-acetophenones (chalcones), utilizing the B3LYP/6-31G* functional. A correlation coefficient of 0.969 in the linear relation with experimental formal reduction potentials (\( E^\circ \)) was found.\(^6\)

Bateni et al.\(^7\) did an EA DFT study of 19 metal-salen compounds (\( R^2 = 0.93 \)). Experimental reduction potentials of 14 different metal-salens were correctly predicted by the latter relationship with a mean unsigned error of 99 mV.\(^7\) Zubatyuk et al.\(^8\) found the mPWB1K/TZVP computational method to be providing the most accurate EA results for calculation of one-electron reduction potentials of nitro-aromatic compounds, with an RMS error of 0.1 eV. Together with the PCM (Bondi) method it also gave the most accurate difference in solvation energies between neutral oxidized and anion-radical reduced forms in a series of nitroaromatics. Compared with experimental values \( E^\circ \) was calculated with an RMS error of 0.10 V.\(^8\)

Here, theoretical calculations of \( E^\circ \) were performed in two steps, i.e. calculation of the free energy of reduction, and difference in solvation energies of oxidized and reduced forms.

In general, reduction potentials, i.e. where neutral species are turned into corresponding anions, are expected to correlate with EA, while oxidation potentials to correlate with IP. However, in some instances, correlations of IP with reversible oxidation potentials were found to be poor.\(^9\) Studies of both tetraalkylhydrazines\(^10\) and 3-substituted 2-oxa-3-azabicyclo
Employing the Hammett equation in the interpretation of redox potentials had also been reasonably successful, especially with regard to meta and para substituted species. Hammett constants for ortho substitution had hardly been used, largely due to failure to find good correlation as a consequence of proximity effects at the reaction centre. Through the years this approach had been refined, with some reviews written on the topic. According to Koopman’s theorem, ionization energy is equal to the HOMO energy of a molecule, but of opposite sign, with the consequence that oxidation potentials may be related to HOMO energies. In the same way LUMO energy is related to reduction potentials. Both HOMO and LUMO energies may easily be calculated theoretically. A great advantage of this method is that it ignores solvation energy and that these energies are conveniently available from computational molecular geometry optimizations. Regardless the fact that Koopman’s theorem was already published in 1933, practical applications in the context of this paper slowly started gaining ground only during the last decade. As Sereda et al. in 2006 rightfully stated, ‘The open-shell’ nature of the reduced species and often the necessity to take into account solvation makes the prediction of redox-potentials a challenging and time consuming computational problem. However, Koopmans’ theorem enabled us to relate redox-potentials of bicyclic quinones with their LUMO energies, which solely characterize the starting compound. Despite the neglected orbital relaxation that immediately follows the reduction, such correlations have proved to be an efficient tool for prediction of redox-potentials of anthra-cyclines, substituted antraecenes, and oligothiphenes. A rough correlation was also found between the first reduction potentials of substituted bicyclic quinones and LUMO energies, and second reduction waves and calculated LUMO+1 energies. Other related studies include semi-empirical calculations of correlated with reduction potentials of a series of chalcones ($R^2 = 0.92$), and a similar study on 16 catechol derivatives. For the latter, however, the $ab$ initio B3LYP/6-31+G* functional was used. Correlation coefficients varying from 0.70 to 0.88 were obtained.

As a consequence of the foregoing evidence we resolved to embark on a comprehensive study to find the most suitable means to theoretically predict redox potentials. The ongoing investigation was scheduled along the logical sequence of starting with the simple and progressing towards the complex. It was thus decided to commence with a series of 12 substituted nitrobenzenes, known for its well established reversible redox behaviour at the nitro group, while good communication exists between this redox active centre and any of a variety of para-substituents. To find the most accurate theoretical method at the outset, experimental reduction potentials were correlated with a variety of $ab$ initio computed descriptors, i.e.

electron affinity (EA = E – E$_{ANION}$),

ionization potential (IP = E – E$_{CATION}$),

calculated relative group electronegativities ($\chi_k = (IP + EA)/2$),

global electrrophilicity index ($\omega = \mu^2/2\eta, \mu = -(IP + EA)/2, \eta = (IP-EA)$),

and $E_{HOMO}$ & $E_{LUMO}$ of neutral molecules.

As additional experimental validation formal reduction potentials (E$_r$) were also correlated with $^1$H NMR chemical shifts, $^1$C NMR chemical shifts, and Infra-Red N-O stretching frequencies, $\nu_{\omega}$ as reported elsewhere.

Based on findings from the study of the former series of simple organic compounds, the computational investigation was extended to include a series of the well known bidentate $\beta$-diketone ligand as well, see Scheme 2. The ultimate goal was to also find a theoretical means to predict the effect of electronically altered ligands on the oxidation and reduction potentials of the metals it might be coordinated to. The latter study is newly reported here, and includes series of six ferroceny-containing $\beta$-diketones, and five ferrocenyl-containing $\beta$-diketonato(cod) rhodium(III) complexes (cod = 1,5-cyclooctadiene). The iron center in ferrocene provided the option to correlate calculated descriptors with the Fe$^{III-IV}$ transition, while the rhodium complex involves both Rh$^{II-III}$ and Fe$^{III-IV}$ metal-centered oxidations.

2. Experimental and Computational Methods

2.1. General

Spectroscopies, NMR, IR and cyclic voltammetry were performed as reported earlier.

2.2. Quantum Computational Methods

Density functional theory (DFT) calculations were performed using the PW91/TZP OLYP/TZP (Triple $\zeta$ polarized) and the B3LYP/6-311G(d,p) functionals and basis sets as implemented in the Amsterdam Density Functional (ADF2009) and GAUSSIAN09 packages. Calculations in solution were performed using the Conductor-like Screening Model (COSMO). Calculations were in gas phase unless specified otherwise.

Whether artificially generated atomic coordinates or coordinates obtained from X-ray crystal data (Cambridge Structural Database) were used in the input files, optimizations for each compound resulted in the same optimized geometry. No symmetry limitations were imposed during the calculations.

3. Results and Discussion

The cyclic voltammograms of a series of twelve para-substituted nitrobenzenes were obtained afresh, ensuring uniform conditions applied during all scans, see Fig. 1. Nitrobenzene shows one reversible couple according to Scheme 1. Formal reduction potentials, E$_r$, which is the average between peak oxidation and reduction potentials, are used here. Both the ‘pure’ classical OLYP functional and the hybrid B3LYP functional were used to calculate energies of neutral, cationic and anionic species, from which electron affinity, electrophilicity index and relative group electronegativity for each compound were calculated. LUMO energy, E$_{LUMO}$ was obtained directly from geometry optimized structures without further processing. These descriptors were correlated with experimentally measured formal reduction potentials, E$_r$, see Fig. 2.

Compared to related correlations referred to earlier (under Introduction), excellent agreement ($R^2 > 0.99$) between E$_r$ and
the theoretical descriptors $E_{\text{LUMO}}$ and $\omega$ was obtained, which is closely followed by $EA(0.98)$ and $\chi_{R}(0.95)$, see Fig. 2 and Table 2. Relationships between $E_{\text{LUMO}}$, $EA$, $\omega$ and $\chi_{R}$ for R-C$_6$H$_4$NO$_2$ that result from gas-phase adiabatic calculations, and $E^{0'}$ values generally gave the best fit (Table 2). Solution phase calculations were slightly less accurate than gas phase calculations, regardless the fact that electrochemical data were obtained in solution. One reason for calculated energies being independent of solvation effects could be the fact that redox potentials tend to be independent of solvent when structurally similar substances are examined in aprotic solvents.\(^3\)

The B3LYP functional yielded results that appear only slightly better than that obtained by the OLYP functional, see Table 1. Single point calculations on the optimized geometries of the neutral species for the anodic and cathodic species gave similar correlations for $E_{\text{LUMO}}$ vs. $E^{0'}$. Adiabatic, i.e. geometry relaxed calculations, gave much better results than corresponding single point calculations of $\omega$ and $\chi_{R}$, which indicates that cation and anion geometries also have to be optimized for improved accuracy. ‘Intrinsic group electronegativities’ calculated by De Proft et al.,\(^4\) where the EA and IP of isolated groups were calculated, correlate poorly to our formal reduction potentials (indicated in Fig. 2f). The fact that this method does not take the group’s molecular environment into account results in data that does not correlate with $E^{0'}$, as opposed to what is observed by us, where the entire molecule is taken into consideration.

From this initial study it became evident that $E_{\text{LUMO}}$ represents the descriptor of choice, both due to best correlation and the convenience of being directly available from computational results of the neutral molecule.

Secondly, β-diketone (1,3-substituted-propane-1,3-dione) was
employed. This molecule is slightly larger than nitrobenzene, and has two groups, R and R’, which may influence reduction potentials.

Diketones are known for more than a century and give rise to rich and interesting coordination chemistry. The electrochemistry of this class of compounds is well established, and is strongly influenced by substituents. CV’s of diketones show one electrochemically irreversible reduction peak between –1 and –2 V vs. \( \text{FcH/FcH}^+ \), see Scheme 2. The reduction potentials, \( E_{\text{pc}} \), of ten 1,3-substituted diketone \( \text{RCOCHC(OH)R’} \) derivatives were measured by cyclic voltammetry and used in correlations with calculated descriptors. Calculated descriptors; \( E_{\text{LUMO}} \), \( \omega \), and \( E_A \) obtained from computed electronic energies of the neutral, anionic and cationic molecules were correlated with corresponding first reduction potentials, \( E_{\text{pc}} \), see Table 2. The correlation coefficient of \( E_{\text{LUMO}} \) was followed by \( \omega \) (0.94) and \( E_A \) (0.84). DFT calculations were in support of experimental results in which the relative ease by which the \( \beta \)-diketone ligand may be reduced is brought about by the presence of R-groups, in the order, PhNO2 > CF3 > Th > Ph > CH3 > CMe3.

Already at this early stage it became clear that the more involved method to obtain EAs is significantly less accurate in estimating reduction potentials as compared to \( E_{\text{LUMO}} \). However, it was found that close correlations can only be obtained amongst related molecules, i.e. molecules with substituents on different phenyl positions correlate poorly if the substituent is not the same right through. For this reason ortho- and meta-substituents were not included in the nitrobenzene study (Scheme 1), where it was indeed observed that correlation coefficients decrease significantly when the latter is included with the para series. As the aim of these investigations was to find the best possible correlations of computational with electrochemical data, it was therefore evident that different series should be treated separately.

To extend the present study with eventual aim to also include metal-centered oxidations (or reductions), a series of five ferrocenyl-containing diketones was employed, see Scheme 3. These compounds differ by substitution at one position on the diketone moiety, varying this site from strongly electron donating ferrocenyl to strongly electron withdrawing trifluoromethyl.

**Table 1** Linear correlation coefficients obtained from different computational methods.

<table>
<thead>
<tr>
<th>Computational method</th>
<th>( E_{\text{LUMO}} )</th>
<th>( \omega )</th>
<th>( E_A )</th>
<th>( X_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B3LYP/6-311G(d,p)</td>
<td>0.995</td>
<td>0.997</td>
<td>0.983</td>
<td>0.963</td>
</tr>
<tr>
<td>OLYP/TZP</td>
<td>0.993*</td>
<td>0.865</td>
<td>0.973</td>
<td>0.681</td>
</tr>
<tr>
<td>Gas phase, single point</td>
<td>0.993</td>
<td>0.876</td>
<td>0.974</td>
<td>0.885</td>
</tr>
<tr>
<td>Solvent phase, adiabatic</td>
<td>0.990</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*\( E_{\text{LUMO}} \) single point and adiabatic calculations are similar because both methods optimize neutral species.

**Scheme 2** Reduction of enolized \( \beta \)-diketones. R, R’ (\( E_{\text{pc}} \) vs. \( \text{FcH/FcH}^+ \) in V) = CF3, PhNO2 (–1.046), CF3, CF3 (–1.283), CF3, Th (–1.581), CF3, Ph (–1.564), CF3, CH3 (–1.851), CF3, CMe3 (–1.860), Th (–1.867), Ph, Th (–1.884), Ph, Ph (–1.934) and Ph, CH3 (–2.138), where PhNO2 = (pNO2–C6H4), Th = theonyl (C4H3S), Ph = phenyl (C6H5) and Me = methyl (CH3).

**Scheme 3** FeII–III oxidation of electronically altered ferrocenyl-containing \( \beta \)-diketones. R (\( E_0’ \) vs. \( \text{FcH/FcH}^+ \) in mV) = CF3 (317), CCl3 (293), CH3 (236), Ph (231), Ru (213), Fc (188).

**Figure 3** Linear correlation graphs of 1,3-substituted \( \beta \)-diketone \( \text{RCOCHC(OH)R’} \) reduction potentials (\( E_{\text{pc}} \)) with calculated parameters (a) LUMO energy, (b) global electrophilicity index (\( \omega \)), and (c) electron affinity (EA). R and R’ are indicated on the graphs.
Here we focus only on the reversible oxidation of the ferrocenyl group and not on the reduction of the β-diketonato ligand. Cyclic voltammetry studies on these β-diketones were formerly done as a tool to obtain group electronegativities on the Gordy scale. A linear relationship between observed group electronegativity, \( \chi \), and \( E_\text{pa} \), as well as observed carbonyl stretching frequencies of methyl esters of the type, RCOOMe, yielded average \( \chi \) values of 1.87 for the ferrocenyl group and 2.82 for the ferrocenium group.\(^{26}\)

In addition to the previous reduction potential correlations with \( E_{\text{LUMO}} \), our investigation now also includes correlations of the \( \text{Fe}^{\text{II}} \rightarrow \text{Fe}^{\text{III}} \) first oxidation potential with \( E_{\text{HOMO}} \), as well as with the ionization potential, \( I_P \), and calculated group electronegativity using Mulliken’s formula, \( \chi \), see Fig. 4.

A correlation coefficient of 0.92 was found for \( E_{\text{HOMO}} \), involving the orbital from which an electron is lost during oxidation. Where as electron affinity is used in connection with reductions, ionization potential is related to the oxidation potential. This correlation, namely with \( I_P \), is somewhat worse, i.e. \( R^2 = 0.87 \). The global electrophilicity index was also tested but not shown here, as it gave a poor correlation (\( R^2 = 0.67 \)).

Lastly we extended our study to complexes that contain two metals, i.e. the ferrocenyl-containing β-diketonato rhodium(I) cod complex, \([\text{Rh}(\text{FcCOCHCOR})(\text{cod})]\) (cod = 1,5-cyclooctadiene, with \( R = \text{CF}_3, \text{CCl}_3, \text{CH}_3, \text{C}_6\text{H}_5 \) and Fc). Electrochemistry of these compounds revealed irreversible oxidation at the Rh(I) centre, involving a two-electron transfer process to form Rh(III).\(^{27}\) Figure 6 gives correlations between \( E_{\text{pa}} \) and \( E_{\text{HOMO}} \) for the \( \text{Rh}^{\text{I}} \rightarrow \text{Rh}^{\text{III}} \) 2-electron oxidation. Consistent with previous case studies presented here, a good correlation coefficient was again found, with \( R^2 \) being 0.94. Following the two electron oxidation of Rh(I) to Rh(III) in \([\text{Rh}(\text{FcCOCHCOR})(\text{cod})]\), is the oxidation of the ferrocenyl group at a slightly higher potential than the rhodium oxidation. Oxidation of the ferrocenyl group involves either removal of one of the electrons from the HOMO of rhodium(III), or from the HOMO-1 of the original rhodium(I) complex, see Scheme 4 and Fig. 5. Figure 6 (b) shows an excellent correlation between the formal oxidation potential of the ferrocenyl group in \([\text{Rh}(\text{FcCOCHCOR})(\text{cod})]\) and the energy of HOMO-1 of \([\text{Rh}(\text{FcCOCHCOR})(\text{cod})]\) (\( R^2 = 0.98 \)). Figure 7 displays the HOMO of \([\text{Rh}(\text{FcCOCHCOR})(\text{cod})]\), which is computed to be

\[ \text{Scheme 4} \]

\[ \text{Figure 4} \]

\[ \text{Figure 5} \]

\[ \text{Figure 6} \]
79% rhodium based. The HOMO-1, also displayed in Fig. 7, is 77% Fe based, thus confirming the location from which the second oxidation (Fe$^{II} \rightarrow $III) takes place.

Table 2 gives the linear equations of the trend lines for all correlations considered in this report. The corresponding correlation coefficients, $R^2$, gives an indication of the closeness of the data spread to linearity, with 1.0 representative of a perfect linear fit. The provided equations may be used to predict reduction potentials from theoretically obtained LUMO energy values, and oxidation potentials from theoretically obtained HOMO energies. This capability is anticipated to be of great aid in the pre-design (before synthesis) of molecules and complexes with specific required redox properties, without first having to work through often tedious and expensive experimental procedures.

4. Conclusion

Convincing evidence in favour of theoretically calculated orbital energies as means to predict redox potentials was presented. HOMO and LUMO energies are conveniently available from computationally optimized geometries of neutral molecules, without any additional processing. In the organic molecule studies (nitrobenzenes and β-diketones) reviewed here, correlations between first reduction potentials and LUMO energy values, and oxidation potentials from theoretically obtained HOMO energies. This capability is anticipated to be of great aid in the pre-design (before synthesis) of molecules and complexes with specific required redox properties, without first having to work through often tedious and expensive experimental procedures.

<table>
<thead>
<tr>
<th>Series</th>
<th>Linear equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrobenzenes</td>
<td>$E'<em>{pc} = -0.623 E</em>{LUMO} - 3.607$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>$E'_{pc} = 0.9415 \omega - 3.176$</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>$E'_{pc} = 0.6169 EA - 2.393$</td>
<td>0.84</td>
</tr>
<tr>
<td>β-Diketones</td>
<td>$E'<em>{pc} = -240 E</em>{HOMO} - 1146$</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>$E'_{pc} = 98 IP - 401$</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>$E'<em>{pc} = 2348 \delta</em>{Fe} - 77$</td>
<td>0.76</td>
</tr>
<tr>
<td>Ferrocene-β-diketones:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E'<em>{pc} = -0.339 E</em>{HOMO} - 1.257$</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>$E'<em>{pc} = -0.351 E</em>{HOMO-1} - 1.264$</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 2 Electrochemical and DFT linear correlation equations and coefficients of four chemical series.

Figure 6 Linear correlations between (a) $E'_{pa}$ and $E_{HOMO}$ for the first oxidation wave (Rh$^{I} \rightarrow $III), and (b) $E'_{pc}$ and $E_{HOMO-1}$ for the second oxidation wave (Fe$^{II} \rightarrow $III), for the [Rh(FcCOCHCOR)(cod)] complexes. $R$ is indicated on the graphs.

Figure 7 HOMO and HOMO-1 orbitals of [Rh(FcCOCHCH$_3$)(cod)]. The HOMO is mainly rhodium based and the HOMO-1 mainly Fe-based. The oxidation of [Rh(FcCOCHCOR)(cod)] firstly involves removal of 2 electrons from the HOMO, followed by oxidation of Fe$^0$ which involves an electron in the HOMO-1. Color scheme: C (charcoal), H (grey), O (red), Rh (green), Fe (purple).

Acknowledgement

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Erratum

In the article ‘Redox Potentials of Ligands and Complexes – a DFT Approach’ by K.G. von Eschwege and J. Conradie that appeared in the South African Journal of Chemistry, 2011, 64, 203–209, the y-axis units in Fig. 6 (p. 208) should have read V, not mV, thus

Fig. 6(a): \[ E_{pa} / V \text{ vs } \text{FcH/FcH}^+ \]  
Fig. 6(b): \[ E' / V \text{ vs } \text{FcH/FcH}^+ \]