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Dioxygenase-Like Reactivity of an Isolable Superoxo–Nickel(II) Complex

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Abstract: Although O_2 activation by metals such as iron and copper has been a matter of intensive research in the last decades, this type of chemistry for nickel systems is still in its infancy. Moreover, studies regarding the oxidizing ability of the resulting "Ni_n–O_2" species towards exogenous substrates are scarce. In this work, we report on the reactivity of an isolable and thermally stable mononuclear superoxo–nickel compound [Ni^{II}(β-diketiminato)(O_2)] (**1**) towards different types of organic substrates. In addition, we have been able to prove that the β-diketiminato ligand can undergo partial intramolecular oxidation due to close proximity between the isopropyl groups of the β-diketiminato-aryl and the superoxo subunits. Compound **1** performs hydrogen-atom abstraction from O-H and N-H groups and most importantly it shows an unprecedented dioxygenase-like reactivity in the oxidation of 2,4,6-tri-*tert*-butylphenol. The latter reaction most likely occurs through the mediation of a putative [Ni^{III}-oxo] intermediate, affording an unprecedented oxidation product of the phenol that incorporates two oxygen atoms from a single O_2 subunit. Results presented herein provide evidence of the striking oxidizing ability of dioxygen–nickel species and further support the viability to use such systems as oxidation catalysts analogous to its heavy metal congener, palladium.

Keywords: dioxygenases · H-atom abstraction · nickel · O–O activation · phenols

Introduction

One of the most important roles played by dioxygen in aerobic organisms is its implication in the synthesis of important biomolecules, usually involving the energetically favorable (exothermic) formation of C–O and O–H bonds.[1] However, direct reaction of O_2 with most organic substrates does not occur due to its inherent electronic structure. In order to overcome the high kinetic barrier associated to the reactions of triplet O_2 with organic (singlet) molecules, in biological systems dioxygen is reductively activated to superoxo (O_2^-), peroxo (O_2^{2-}) or oxo ($2O^{2-}$) forms by a metal center found in oxidase and oxygenase enzymes.[2]

Understanding the mechanisms by which molecular O_2 can be activated and used as oxidant in oxidative transformations is of crucial importance, not only due to the biological relevance of such reactions but also to the potential technological applicability that these processes may have. In the last decades, studies of synthetic systems that activate oxygen have been essentially focused on iron and copper, in part due to the prevalence of these two metals in O_2-activating metalloenzymes.[3–6] A wide range of species derived from the interaction of such metals with dioxygen (or its activated forms) have been synthesized and structurally characterized. Some of these structures, which range from multinuclear configurations to mononuclear metal–superoxo or high-valent metal–oxo species, are biologically relevant and they have found to be capable of performing bioinspired efficient and selective oxidation of organic substrates. Despite some advances in the last years[7] and the recent discovery of two nickel-based enzymes involved in processes using O_2,[8–11] studies based on the activation of molecular O_2 by synthetic nickel compounds are comparatively scarce. This is especially surprising if one takes into account that for decades complexes based on palladium, the second-row transition-metal counterpart of nickel, have been applied as oxidation catalysts in important industrial transformations, such as the Wacker process.[12,13]

In the last years some nickel complexes capable of activating O_2 have been characterized. The most common approach to synthesize such complexes involves the reaction of nickel(II) with peroxo compounds (that can be seen as a

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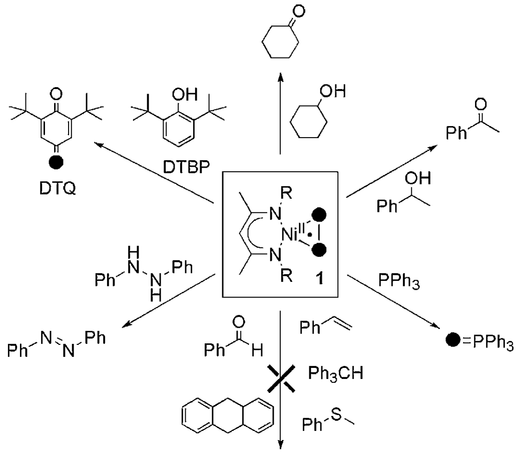
2e$^-$ reduced version of dioxygen) as most nickel(II) species are inert towards O_2. These configurations include dinuclear systems such as bis(μ-oxo)dinickel(III),[14–16] bis(μ-alkylperoxo)dinickel(II)[17] and (*trans*-μ-1,2-peroxo)dinickel(II)[18] or mononuclear systems like (alkylperoxo)nickel(II)[19] or (peroxo)nickel(III) compounds.[20] However, particularly designed ligand structures allow the synthesis of nickel(I) complexes (by reduction of the starting nickel(II) compounds) that can directly interact with O_2. Using this strategy three different mononuclear (superoxo)nickel(II) species resulting from the 1e$^-$ reduction of dioxygen by the nickel(I) center have been characterized. Riordan et al. were the first to demonstrate the viability of such species with the synthesis of two different mononuclear nickel-superoxo compounds.[18,21] However, both systems were found to be rather thermolabile and they could only be generated at low temperature, which prevented isolation and limited the study of their reactivity. On the contrary, we recently reported the straightforward synthesis of an isolable and strikingly stable [Ni^{II}(β-diketiminato)(O_2)] superoxo complex **1** (Scheme 1)[22] that can be crystallized and handled at room temperature. Its reactivity with other metals has already been reported by some of us.[23]



Scheme 1. Reactivity of **1** towards selected exogenous substrates. R = 2,6-iPr$_2$C$_6$H$_3$.

Despite the advances in the synthesis of several nickel–dioxygen configurations, little information has been gathered regarding their ability to oxidize exogenous organic molecules. One important drawback may be related to the strong oxidants generated during the oxygen activation process, which have a kinetic preference to perform intramolecular ligand hydroxylation rather than a process involving the intermolecular interaction with an exogenous substrate.[24,25] This phenomenon has been observed for selected dinuclear systems described above. For example, the well-defined bis(μ-oxo)dinickel(III) configuration can decompose through aromatic hydroxylation,[15] aliphatic hydroxylation[16] or N-dealkylation[14] of the supporting ligand. In the case of the mononuclear (peroxo)nickel(III) configuration reactivity studies with exogenous organic substrates indicate that it behaves as a nucleophile in the deformylation of aldehydes[20] while for (alkylperoxo)nickel(II) some electrophilic character (oxidation of triphenylphosphine and CO) has also been observed.[19] Finally, little is known about the chemistry related to mononuclear (superoxo)nickel(II) compounds. Up to date, the three reported examples of this type have proven to be suitable to oxidize triphenylphosphine to its phosphine oxide,[18,21,22] but nothing is known about their chemistry with other organic substrates.

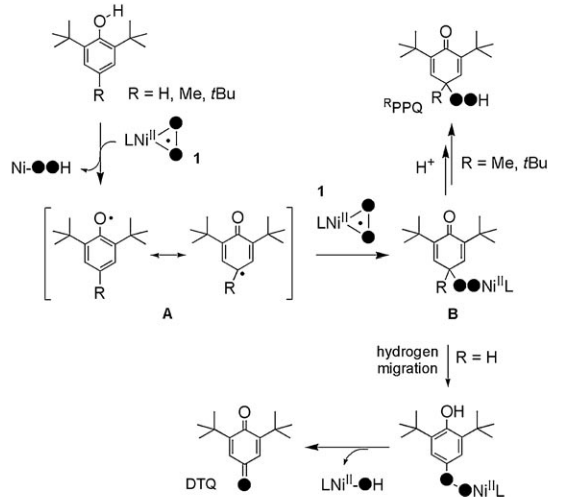
Encouraged by the few reactivity studies reported for this type of species and having in hand the stable [Ni^{II}(β-diketiminato)(O_2)] superoxide (**1**),[22] in this paper we wish to report the behavior of this species in the presence of different types of organic molecules. In particular, we report for the first time on its surprising reactivity in the oxidation of phenolic substrates.

Results and Discussion

As previously reported by some of us,[22] compound **1** can be obtained by reaction of the nickel(I) precursor [(Ni^I(β-diketiminato))$_2$(μ-η^3:η^3-C$_6$H$_5$Me)] with dry O_2 in toluene and isolated from the reaction mixture as thermally stable green crystals. Compound **1** was fully characterized by several spectroscopic techniques (X-ray, FT-IR, EPR, ^{1}H NMR, EI-MS). The collected spectroscopic data pointed towards an electronic configuration fully consistent with a Ni^{II}–superoxo species, a formulation also supported by DFT calculations. In the previous work, we already reported the ability of **1** to perform the oxidation of PPh_3, but the oxidation of other organic substrates was not probed.

In order to determine the oxidation properties of **1**, we studied its reactivity towards different types of substrates (Scheme 1). At first, we learned that **1** is inert towards alkenes, sulfides and aldehydes. Moreover, it remained also unchanged towards substrates bearing weak C–H bonds such as 9,10-dihydroanthracene or triphenylmethane. However, reaction of **1** with cyclohexanol afforded cyclohexanone in 18 % yield with respect to the amount of the starting nickel complex. A similar oxidation process occurred upon reaction with 1-phenylethanol giving acetophenone as oxidized product in 22 % yield. Moreover, reaction with 2,4-di-*tert*-butylphenol (DTBP) gave the corresponding 2,6-di-*tert*-butyl-1,4-benzoquinone (DTQ) in ~50 % yield. The ability of **1** to activate N–H bonds was probed by reaction with 1,2-diphenylhydrazine as a substrate, which afforded the expected azobenzene as the oxidized product. Most likely, these oxidation reactions take place through an initial hydrogen-atom abstraction from the O–H or N–H bond. Indeed, substituted phenols are usually the substrates of choice in order to probe the H-atom abstracting ability of transition-metal complexes.[26,27] Overall, from our initial substrate screening, it seems clear that **1** cannot perform oxygen-atom transfer to alkenes, sulfides or alkanes but it readily activates and oxidizes O–H and N–H bonds.

The oxidation of DTBP is an especially interesting transformation as it involves the incorporation of a new oxygen atom into the oxidized DTQ product. A deeper analysis of this transformation indicated that when ^{18}O-labeled **1** (generated by reaction of the Ni^{I} precursor with $^{18}O_2$) was used, approximately 85 % ^{18}O-atom incorporation occurred in the resulting DTQ, so that the oxygen atom incorporated into the oxidized product originates from **1**. Thus, in this particular case, compound **1** does not act only as an oxidant but also as an oxygenation reagent. This transformation may be explained by the mechanism depicted in Scheme 2 (R = H), which is reminiscent to the reaction path proposed for selected cobalt–superoxo systems.[28,29] Reaction starts with a hydrogen-atom abstraction from the O–H bond by the (superoxo)nickel(II) (**1**) to generate a phenoxyl radical which rapidly interacts with a second molecule of **1** to form a metal–arylperoxo compound (**B** in Scheme 2). After hydrogen migration and O–O bond cleavage, DTQ incorporating a new oxygen atom coming from the superoxo moiety is formed. Remarkably, the oxidation of DTBP requires the consumption of two equivalents of **1**, as a sacrificial (superoxo)nickel(II) unit is necessary to perform the initial H-atom abstraction event. This stoichiometry agrees with the experimental observation that DTQ is obtained in ~50 % yield with respect to the initial amount of **1**.



Scheme 2. Schematic representation of the mechanism of phenol oxidation by **1**.

The use of alkyl *para*-substituted-2,6-di-*tert*-butylphenols (R = Me, *t*Bu in Scheme 2) allowed us to get deeper insight into the mechanism of phenol oxidation by **1**. A priori, as the hydrogen migration step is prevented for *para*-substituted-2,6-di-*tert*-butylphenols, isolation of peroxy-*p*-quinol (^{R}PPQ) as the oxidized product would be expected. In fact, reaction of **1** with 2 equiv of 2,4,6-di-*tert*-butylphenol (TTBP) gave an oxidation product with a mass value of *m*/*z* 294 in 40 % yield with respect to **1**, which at first glance seems fully consistent with the formation of ^{tBu}PPQ (Figure 1, left). On the other hand, direct reaction of **1** with 1 equiv of the stable tri-*tert*-butylphenoxyl radical (**A** if R = *t*Bu, Scheme 2) afforded the same oxidation product in 90 % yield. This observation further confirms that during phenol oxidation 1 equiv of **1** is consumed in an initial hydrogen-atom abstraction event. Most remarkably, the oxidized product derived from the reaction between ^{18}O-labeled **1** and TTBP or tri-*tert*-butylphenoxyl radical showed a shift of four mass units (*m*/*z* 298) indicative that two ^{18}O-atoms were incorporated into the oxidized product (Figure 1, middle). UV/Vis monitoring of the reaction between 2,4,6-di-*tert*-butylphenol (TTBP) and **1** at 25 °C clearly showed the decrease of the characteristic band of **1** (λ_{max} = 980 nm) following a single exponential decay (Figure 2). The reaction was found to be first-order with respect to substrate concentration and a second-order rate constant of $k_2 = 0.0032\,M^{-1}s^{-1}$ was obtained. Moreover, with [D$_1$]-TTBP as the substrate, a kinetic isotope effect (KIE) of 2.1 was measured, indicating that the initial cleavage of the O–H bond is involved in the rate-determining step. Similar KIE values for the oxidation of TTBP have been measured in other metal systems in which a hydrogen-atom abstraction mechanism is postulated.[27,30]

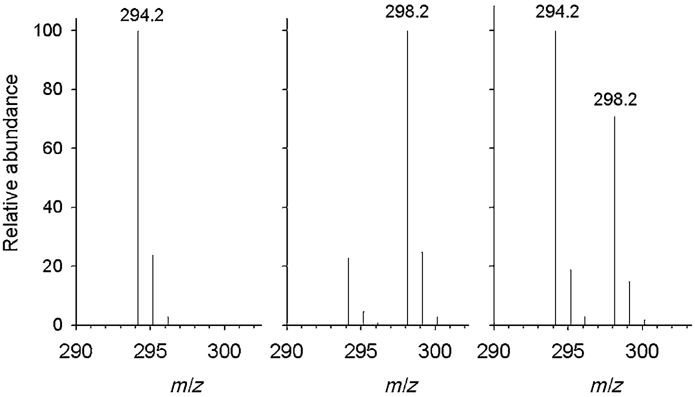


Figure 1. EI-MS spectrum of 2^{tBu} obtained after reaction of 1 equiv tri-*tert*-butylphenoxyl radical with **1** (left), ^{18}O-labeled **1** (middle) and a mixture of **1** and ^{18}O-labeled **1** (right).

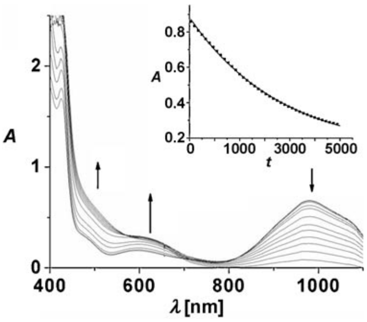


Figure 2. UV/Vis absorption spectra of the reaction of **1** with TTBP at 25 °C in toluene ([**1**] = 1 mM, [TTBP] = 0.18 M). Inset: time course of the decay of the 980 nm band (•••••) and the first-order fit (——).

Surprisingly, ^{1}H NMR analysis of the oxidized product from the reaction with TTBP failed to show the characteristic singlet at $\delta = 6.7$ ppm expected for ^{tBu}PPQ,[31] which suggests the formation of a structurally different oxidized species. By means of 1D and 2D ^{1}H and ^{13}C NMR spectroscopy, we could determine that, indeed, the oxidized species corresponds to compound **2**$^{t\mathrm{Bu}}$ (Figure 3), which is a structural isomer of $^{t\mathrm{Bu}}$PPQ. Its structure was finally confirmed by X-ray diffraction analysis (Figure 3).[32] FT-IR analysis of **2**$^{t\mathrm{Bu}}$ (Figure S1) showed two intense features at $\tilde{\nu} = 1721$ and 1685 cm^{-1} corresponding to the stretching frequencies of the two ketone subunits. The lower energy band is assigned to the α,β-unsaturated ketone, while the higher energy feature corresponds to the acyclic ketone subunit, which downshifts to $\tilde{\nu} = 1689$ cm^{-1} when ^{18}O-labeled **1** is used. Another isotope-sensitive band is found at 1120 cm^{-1} ($\Delta[^{18}O_2] = -17$ cm^{-1}) and it is assigned to the characteristic ν_{as}(C-O-C) vibration from the ether functionality. Thus, the two oxygen atoms incorporated during phenol oxidation end up in the acyclic ketone and in the ether group of **2**$^{t\mathrm{Bu}}$. In order to determine if these two oxygen atoms came from the same Ni^{II}-superoxo unit, we analyzed the oxidation of 1 equiv of tri-*tert*-butylphenoxyl radical with 0.5 equiv of **1** and 0.5 equiv of ^{18}O-labeled **1** (Figure 1, right). No mass peak at *m*/*z* 296 of the putative mixed-labeled product was detected, and instead only non-labeled (*m*/*z* 294) and doubly ^{18}O-labeled **2**$^{t\mathrm{Bu}}$ (*m*/*z* 298) were detected, proving that the two oxygen atoms incorporated in **2**$^{t\mathrm{Bu}}$ origin from the same (superoxo)-nickel(II) unit, and thus from the same O_2 molecule. The same reactivity pattern was observed for the reaction of **1** with 4-methyl-2,6-di-*tert*-butylphenol (R = Me in Scheme 2) affording compound **2**$^{\mathrm{Me}}$ as the oxidized species. These results clearly indicate that compound **1** can be considered as a dioxygenase-type of system in the oxidation of *para*-substituted-2,6-di-*tert*-butylphenols because the *two* oxygen atoms from a single dioxygen molecule end up into the substrate in a process in which the O–O bond is fully cleaved.

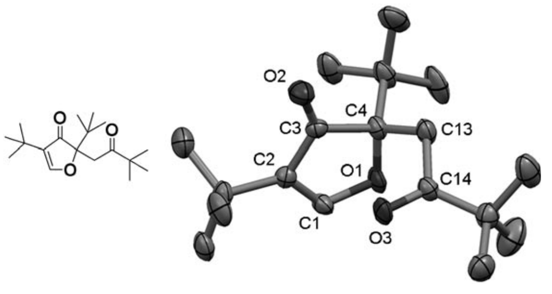
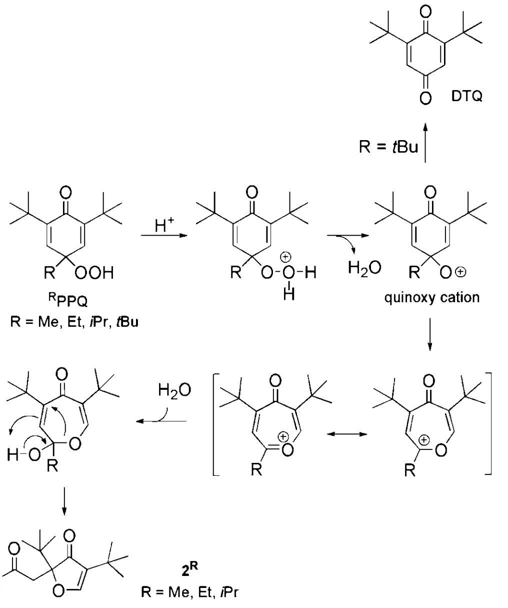


Figure 3. Left: Schematic representation of **2**$^{t\mathrm{Bu}}$. Right: X-ray structure of **2**$^{t\mathrm{Bu}}$. Hydrogen atoms have been omitted for clarity.

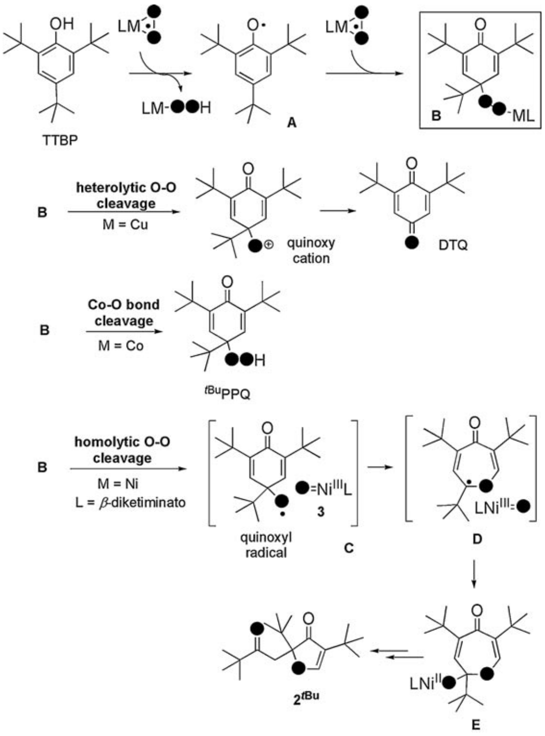
Although the reactivity of Ni–superoxo compounds versus phenols had never been reported before (in part, because of the few reported examples of this type of structures), other metal–superoxo species are known to be capable of oxidizing phenols. In particular and analogously to **1**, reaction of Cu–superoxo[33,34] and Co–superoxo[28,35,36] compounds with DTBP leads to the formation of DTQ. Instead, for the single reported Fe–superoxo species,[37] the same reaction does not result in oxygen incorporation into the substrate, but only in the formation of the coupling product derived from direct intermolecular reaction of two generated phenoxyl radicals. More interestingly, as far as we know, the reactivity with alkyl *para*-substituted-2,6-di-*tert*-butylphenols exhibited by **1** finds no precedent in the literature. For instance, oxygenation of this type of substrates by cobalt(II) complexes in the presence of O_2 gives the corresponding ^{R}PPQ.[38,39] Mechanistic studies point towards the mediation of a transient cobalt–superoxo species in these systems. Moreover, reaction of the isolated superoxo $[Co^{III}(CN)_5O_2]^{3-}$ with tri-*tert*-butylphenoxyl radical also leads to the same product.[40] On the other hand, reported reactivity of selected Cu–superoxo complexes with TTBP affords exclusively DTQ.[33,34] Remarkably, Tolman et al. reported the synthesis of the copper–superoxo analogue of **1**, namely [Cu^{II}(β-diketiminato)(O_2)],[41] but this compound behaves as a poor oxidant and it is inert toward phenols.[42] Thus, although phenol oxidation seems a common feature for most metal–superoxo complexes, only in the case of **1** it has been observed a dioxygenase behavior that leads to the formation of compound **2**$^{t\mathrm{Bu}}$ through an intriguing mechanism.

Nishinaga et al. demonstrated that compounds **2**$^{\mathrm{R}}$ can be formed by direct decomposition of ^{R}PPQ under strong acidic conditions (Scheme 3).[43] Heterolysis of the O–O bond assisted by a proton gives a quinoxy cation, which suffers a ring expansion and a final rearrangement to form **2**$^{\mathrm{R}}$. Interestingly, in the same work it is reported that compound **2**$^{t\mathrm{Bu}}$ could not be generated during the acidic decomposition of $^{t\mathrm{Bu}}$PPQ and instead DTQ was detected. This observation was reasoned on the basis of the susceptibility of the *tert*-butyl group towards β-scission due to the relative stability of the resulting *tert*-butyl cation. Nevertheless, in order to test if **2**$^{\mathrm{R}}$ could be generated during our work-up procedure, we subjected directly synthesized ^{Me}PPQ[31] to a silica column,



Scheme 3. Mechanism of decomposition of ^{R}PPQ under strong acidic conditions as reported by Nishinaga et al.[43]

following the same procedure as in our previous reactivity experiments with **1**. We found that ^{Me}PPQ remained unchanged under our experimental conditions and no trace of the corresponding $\mathbf{2}^{\mathbf{Me}}$ was detected.



Scheme 4. Proposed mechanism of oxidation of TTBP by different metal-superoxo compounds: Ni–superoxo (**1**) versus Co–superoxo and Cu–superoxo.

Putting it all together, both our experimental results with **1** and previously reported reactivities of other metal–superoxo species, oxidation of TTPB by such compounds could be explained by the mechanistic scenario depicted in Scheme 4. We propose that the key intermediate in the oxidation process is a common metal–arylperoxo compound **B** formed after initial hydrogen abstraction from TTPB and posterior coupling of the newly formed tri-*tert*-butylphenoxyl radical **A** with another metal–superoxo unit. The different reactivity patterns exhibited by cobalt and copper versus nickel suggest significant differences in the relative O–O and M–O bond strengths of the respective intermediates of type **B**. Formation of DTQ from Cu–superoxo species can be reasoned by a heterolytic O–O bond cleavage in **B** generating a quinoxy cation that suffers a β-scission to give a *tert*-butyl cation, following a mechanism similar to the decomposition of $^{t\mathrm{Bu}}$PPQ described by Nishinaga et al.[43] In the case of cobalt-superoxo species, the isolation of $^{t\mathrm{Bu}}$PPQ in the reaction with TTBP may be due to a direct Co–O bond cleavage in **B**. Finally, the unexpected generation of $\mathbf{2}^{t\mathbf{Bu}}$ in the reaction of **1** with TTBP can be explained by the homolysis of the O–O bond in **B** leading to a quinoxyl radical and a putative nickel(III)–oxo (or Ni^{II}-O$^{\bullet}$) (**3**) compound. Ring expansion of the quinoxyl radical[44] and final oxygen rebound with the newly generated **3** gives compound **E** that rearranges to the final isolated $\mathbf{2}^{t\mathbf{Bu}}$. Although Ni^{III}-oxo compounds have never been directly detected, they have been proposed as key intermediates in some oxidation processes.[45–47] In fact, the appearance of transient **3** in oxidative transformations was also previously proposed by us for the oxidation of triphenylphosphine by **1**.[22] Moreover, it has been computationally calculated that (β-diketiminato)-Ni^{III}–oxo species could be good candidates for facile oxidation of methane.[48] In fact, the active oxidizing character of the Ni–oxo unit has been directly experimentally proved in gas-phase reactions, where the oxidizing ability of this species in methane oxidation surpasses that exhibited by the other first-row metal–oxo compounds probed.[49]

We also checked the stability of **1** in solution at room temperature in order to determine if intramolecular oxidation processes took place when no substrate was present. The green-colored compound **1** slowly decomposed in toluene to give a brown mixture after five days. Ligand extraction by acidic work-up indicated the partial oxidation of the β-diketiminato ligand (*m*/*z* 418) to give a dehydrogenated product (*m*/*z* 416) in approximate 10% yield as ascertained by GC-MS. We suggest that the formation of this product derives partially from the dehydration under our work-up conditions of an initially generated hydroxylated β-diketiminato ligand. In fact, ESI-MS analysis of a solution of **1** in toluene showed the presence of a peak fully consistent with the monohydroxylated β-diketiminato unit ($[M+\mathrm{H}]^+$ 435.3). Most likely, hydroxylation occurs in the tertiary C–H bond of one of the ligand isopropyl groups situated in close proximity to the superoxo subunit. The oxygen atom incorporated into this hydroxylated species originates from the Ni–superoxo unit as ascertained by the use of ^{18}O-labeled **1** ($[M+\mathrm{H}]^+$ 437.3). As previously observed for selected cobalt and nickel-based species derived from O_2 activation, dehydrogenation of the isopropyl group may also be directly effected by metal–dioxygen species.[50–53] Indeed, in the present case, the presence of dehydrogenated ligand is also observed in the ESI-MS spectrum of the decomposition species derived from **1** prior to the acidic work-up but it appears not to be the major reaction pathway given the low intensity of the corresponding peak.

Remarkably, analysis of the reaction mixture after reaction of **1** with phenols indicated that similar oxidation processes of the β-diketiminato ligand took place. It is important to highlight here that Karlin et al.[34] recently reported a system in which intramolecular ligand hydroxylation occurred through a putative hydroperoxo–copper(II) species formed by reaction of a superoxo–copper(II) with a hydrogen-atom donor such as phenols. Analogously to the system described by Karlin, in the present case it is feasible the involvement of a transient hydroperoxo–nickel(II) species generated by hydrogen-atom abstraction (from phenol or alternatively from the solvent when no hydrogen-atom donor is present) by **1**. However, we do not have any definitive proof to rule out the superoxo–nickel(II) compound **1** as the active species in such intramolecular oxidations. It seems clear, though, that the bulkiness of the β-diketiminato ligand may be understood as playing two roles: on one hand it stabilizes the Ni–superoxo unit by sterically protecting it, but on the other hand, it constitutes a potential nearby substrate susceptible to be attacked that may partially hamper the interaction with exogenous substrates. Intramolecular ligand oxidation by well-defined dinuclear nickel–dioxygen species has been reported in a few cases[14–16] and it has also been observed for putative mononuclear nickel-dioxygen intermediates.[24,54]

Conclusion

In this work we have shown the distinct reactivity of a stable superoxo–nickel(II) compound **1** in the oxidation of O–H and N–H groups from exogenous substrates. In addition, we have been able to prove that the β-diketiminato ligand can undergo partial intramolecular oxidation due to close proximity between the isopropyl groups of the β-diketiminato-aryl and the superoxo subunits. Nevertheless, **1** shows dioxygenase-like activity when exposed to *para*-substituted-2,6-di-*tert*-butylphenols, affording the unprecedented oxidation product (**2**$^{\mathbf{R}}$) that incorporates two oxygen atoms from a single O_2 subunit. The mechanism of this transformation is proposed to occur through the mediation of a Ni^{III}-oxo species, which has already been suggested as a key oxidizing species in several oxidation processes, including the previously reported oxidation of triphenylphosphine by **1**. Results presented here are furthermore striking because unlike the reported reactivity of analogous superoxo–metal species containing cobalt, iron and copper, **1** shows dioxygenase-like activity with full O–O bond cleavage. Overall, reactivity studies on nickel species derived from the interaction with O_2 offer novel and interesting perspectives in understanding and designing metal-mediated dioxygen activation and selective oxygenation of organic substrates.

Experimental Section

Reactivity studies: Reaction with cyclohexanol, 1-phenylethanol, 2,6-di-*tert*-butylphenol (DTBP), benzaldehyde, styrene, triphenylmethane, 9,10-dihydroanthracene or thioanisole: In a typical experiment, **1** (4 mg, 7.9 μmol) was dissolved in toluene under N_2 and 10 equiv of the specific substrate were added. After stirring for 24 h at room temperature, biphenyl (internal standard) was added and the reaction mixture was passed through a short silica path (in order to remove the nickel complex), which was washed with ethyl acetate. The resulting filtrates containing the organic products were analyzed by GC-MS. The oxidized products, if formed, were identified by comparison of their GC retention times and GC-MS spectrum with those of authentic compounds and they were quantified by calibration curves using biphenyl as internal standard.

Reaction with 1,2-diphenylhydrazine: Compound **1** (4.5 mg, 8.8 μmol) was dissolved in toluene under N_2 and 2 equiv of 1,2-diphenylhydrazine (0.34 mL of a 52 mM solution in toluene) were added. An immediate color change occurred upon substrate addition and the initial green solution turned orange-brown. After stirring for 30 min at room temperature, the solvent from the reaction mixture was removed under reduced pressure. The resulting brown residue was dissolved in CH_2Cl_2 and passed through a short silica pad (in order to remove the nickel complex), which was washed with ethyl acetate. The solvent from the filtrates was removed under vacuum and the resulting residue was dissolved in toluene (12 mL). The yield of azobenzene (75 %) was determined spectrophotometrically by measuring the intensity of its characteristic absorption band at $\lambda = 442$ nm and correlation with a calibration curve.

Reaction with 2,4,6-tri-*tert*-butylphenol (TTBP): Compound **1** (19.0 mg, 37 μmol) was dissolved in toluene (20 mL) and 2 equiv of TTBP (19.6 mg, 74 μmol) were added at once. After stirring for 24 h the initial green solution turned brown. The solvent was removed under vacuum and the resulting brown residue was passed through a silica column. Initial elution with CH_2Cl_2 allowed the removal of excess TTBP. Elution with ethyl acetate afforded the oxidized product (**2**$^{t\mathbf{Bu}}$) together with β-diketiminato ligand. The solvent from these last eluates was removed under reduced pressure to yield a pale-yellow solid which was analyzed by ^{1}H NMR and GC-MS. Relative integration of the ^{1}H NMR signals of **2**$^{t\mathbf{Bu}}$ with respect to the β-diketiminato ligand indicated 40 % yield of **2**$^{t\mathbf{Bu}}$. GC-MS analysis showed a mass value of m/z 294 for **2**$^{t\mathbf{Bu}}$. A similar experimental procedure was followed for the oxidation of 4-methyl-2,6-di-*tert*-butylphenol, which afforded **2**$^{\mathbf{Me}}$ as ascertained by comparison of its ^{1}H NMR spectrum with the previously reported spectroscopic data for this compound.[43]

Reaction with tri-*tert*-butylphenoxyl radical: Compound **1** (62.4 mg, 0.12 mmol) was dissolved in toluene (60 mL) and 1 equiv of tri-*tert*-butylphenoxyl radical (32.0 mg, 0.12 mmol) was added. After stirring for 3 h, the initial turquoise solution turned brown. The solvent was removed under vacuum and the resulting brown residue was passed through a silica column. After initial elution with CH_2Cl_2, the column was eluted with ethyl acetate. The solvent from these last eluates was removed under reduced pressure to yield a pale-yellow solid (88 mg) consisting of a mixture of oxidized product (**2**$^{t\mathbf{Bu}}$) and β-diketiminato ligand as ascertained by ^{1}H NMR and GC-MS. Relative integration of the ^{1}H NMR signals of **2**$^{t\mathbf{Bu}}$ with respect to the β-diketiminato ligand indicated 90 % yield of **2**$^{t\mathbf{Bu}}$. GC-MS analysis indicated a mass value of m/z 294 for **2**$^{t\mathbf{Bu}}$.

^{18}O-Labeled experiments: Reactivity experiments were performed following exactly the same experimental procedure as described above but using ^{18}O-labeled **1** (generated by reaction of the Ni^{I} precursor with $^{18}O_2$).

Determination of the kinetic isotope effect (KIE): Kinetic studies were performed by adding appropriate amounts of TTBP or [D$_1$]-TTBP to 1 mM solutions of **1** in toluene at 25 °C. Spectral changes were directly monitored by UV/Vis spectroscopy. Rate constants, k_1, were determined by pseudo-first-order fitting of the decay of the absorption band at 980 nm. Plots of k_1 versus substrate concentration afforded the second order rate constant, k_2 (Figure S2). All reactions were performed under complete anaerobic conditions.

Characterization of 2$^{t\mathbf{Bu}}$: As stated above, reaction between **1** and tri-*tert*-butylphenoxyl radical afforded a mixture of **2**$^{t\mathbf{Bu}}$ and β-diketiminato ligand. Isolation of **2**$^{t\mathbf{Bu}}$ was achieved by treatment of this mixture with acetonitrile, filtration and removal of the solvent from the filtrates. The resulting solid was essentially **2**$^{t\mathbf{Bu}}$ free of β-diketiminato ligand which could be fully characterized by NMR, EI-MS and FT-IR. Crystals of **2**$^{t\mathbf{Bu}}$ were grown by slow evaporation of a saturated hexane solution of the compound. ^{1}H NMR (CDCl$_3$, 400 MHz, 298 K): δ = 7.76 (s, 1 H, **CH**), 3.37 (d, J = 15.9 Hz, 1 H, **CH$_2$**), 2.90 (d, J = 15.9 Hz, 1 H, **CH$_2$**), 1.25 (s, 9 H, ^{tBu}**CH$_3$**), 1.11 (s, 9 H, ^{tBu}**CH$_3$**), 0.98 ppm (s, 9 H, ^{tBu}**CH$_3$**); ^{13}C NMR (CDCl$_3$, 100 MHz, 298 K): δ = 209.8 (**C**=O), 205.7 (**C**=O), 170.1 (**C**H), 129.3 (**C$_q$**), 91.0 (**C$_q$**), 44.4 (^{tBu}**C$_q$**), 38.6 (**C**H$_2$), 37.6 (^{tBu}**C$_q$**), 29.6 (^{tBu}**C$_q$**), 28.2 (^{tBu}**C**H$_3$), 26.0 (^{tBu}**C**H$_3$), 24.5 (^{tBu}**C**H$_3$); EI-MS: m/z: 294.218 $[M]^+$; FT-IR (KBr): $\tilde{\nu}$ = 3082 (m), 2958 (s), 2906 (m), 2869 (m), 1721 (s), 1685 (s), 1610 (s), 1478 (m), 1463 (m), 1394 (w), 1362 (s), 1345 (m), 1336 (m), 1225 (w), 1120 (s), 1075 (w), 1049 cm^{-1} (w).

Intramolecular ligand oxidation: Compound **1** (22.6 mg, 44 μmol) was dissolved in toluene (20 mL) and the green solution was stirred at room temperature for 5 days. The solvent from the resulting brown mixture was removed under vacuum and the residue was treated with concentrated HCl (8 mL) and vigorously stirred for 1 hour. After extraction with CH_2Cl_2 (3×10 mL), the organic phases were combined, dried over $MgSO_4$, filtered and the solvent removed under vacuum. The resulting solid was analyzed by GC-MS indicating the presence of the starting β-diketiminato ligand (*m/z* 418) together with ≈10% of dehydrogenated ligand (*m/z* 416). A control experiment starting from $[\mathrm{Ni^{II}}(\beta\text{-diketiminato})(\mu\text{-Br})_2(\mathrm{Li})(\mathrm{THF})_2]$[55] failed to show the presence of dehydrogenated product.

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