The importance of nickel oxyhydroxide deprotonation on its activity towards electrochemical water oxidation†

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Nickel oxyhydroxide (NiOOH) is extensively used for energy storage and it is a very promising catalyst for the oxygen evolution reaction (OER). However, the processes occurring on the NiOOH surface during charge accumulation and OER are not well understood. This work presents an in situ Surface Enhanced Raman Spectroscopy (SERS) study of the pH dependent interfacial changes of the NiOOH catalyst under the working conditions used for OER. We demonstrate the important effect of the electrolyte pH on the degree of surface deprotonation of NiOOH, which crucially affects its OER activity. Our results show that the deprotonation of NiOOH produces negatively charged (or proton-deficient) surface species, which are responsible for the enhanced OER activity of NiOOH in highly alkaline pH. Moreover, we provide spectroscopic evidence obtained in an 18O-labeled electrolyte that allows us to assign this surface species to a superoxo-type species (Ni−OO−). Furthermore, we propose a mechanism for the OER on NiOOH which is consistent with the observed pH-sensitivity, and that also explains why NiOOH is not a suitable catalyst for applications in neutral or moderately alkaline pH (in the range 7–11), apart from the lower stability of the catalyst under these conditions.

Introduction

Nickel-based oxides are extensively used for secondary batteries and super capacitors.1–3 These materials are also very promising catalysts for the OER,4–10 which is one of the major bottlenecks for solar energy conversion into storable fuels.11,12 However, the mechanism of nickel charging and its activation towards OER are still a matter of debate. The Bode scheme is one of the accepted mechanisms for the charge/discharge process of the nickel (hydr)oxide, according to which the freshly prepared α-Ni(OH)2 oxidizes to form γ-NiOOH;13 these phases convert into the more crystalline β-Ni(OH)2/β-NiOOH phases upon (electro) chemical ageing. It has been proposed that the formal oxidation state of nickel in the γ-NiOOH lies in the range 3.5–3.67,9,14 which suggests that some nickel sites in this compound have NiO2-like character that may be seen as tetravalent nickel sites; this hypothesis has been supported with X-ray adsorption spectroscopy (XAS), by matching the position of the Ni K-edge of the γ-NiOOH samples with the K-edge of reference compounds in which nickel was thought to be in the NiIV state (BaNiO3 or KNiO2).15,17 However, the values reported for the oxidation state of nickel in those reference compounds did not consider the possibility of oxygen vacancies, which affect the formal valence of nickel in the compounds and make the conclusions derived from the XAS data uncertain.18,19 Since the OER activity of NiOOH is strongly pH-dependent,21–25 the appearance of the SERS feature attributed to the “active oxygen” should also correlate with the pH, if this species...
is related to the formation of OER catalytically active sites in the structure of NiOOH. Following this hypothesis, we present here a systematic in situ SERS study of the pH dependence of the catalytic activity of NiOOH towards electrochemical O2 generation. Our electrodes consist of NiOOH electrodedeposited on gold in a rigorously Fe-free electrolyte; the importance of removing such impurities was recently demonstrated by the Boettcher group.26 The elimination of the Fe impurities from the electrolyte allows us to conclusively rationalize pH-dependent activity changes to observed spectral changes in the γ-NiOOH catalyst. Based on these results, we will suggest a mechanism for OER reaction on first-row transition-metal oxides that we believe will be useful for guiding future first-principles calculations of novel catalysts.

Experimental section

All glassware was rigorously cleaned before starting experiments by boiling in concentrated H2SO4 to remove metals and organic contaminations, and was subsequently boiled five times in Millipore Milli-Q water (resistivity > 18.2 MΩ cm), which was also used to prepare the solutions for the electrochemical experiments.

The chemicals used in this work were of ultra-high purity: Ni(NO3)2·6H2O (Aldrich trace metal basis, 99.999%), HClO4 (Aldrich TraceSelect® for trace analysis, 67–72%) and iron-free NaOH. The purification of commercial NaOH followed the procedure reported by Boettcher’s group,26 by shaking a 1 M solution of NaOH (30% solution in H2O, TraceSelect® for trace analysis) with Ni(OH)2 that was precipitated from the 99.999% Ni(NO3)2·6H2O salt. The NaClO4 used as supporting electrolyte was prepared by neutralizing the Fe-free NaOH solution with HClO4, to minimize the amount of iron impurities present in the solution. The pH of the solutions used in all the experiments of this work was adjusted with HClO4, and veriﬁed by measuring the equilibrium potential of platinum in a solution of 0.124 M NaClO4 saturated with H2.

Nickel was plated on the roughened gold electrode by galvanostatic electrodeposition from a 5 × 10−3 M Ni(NO3)2·6H2O solution, using 0.1 M NaClO4 as supporting electrolyte. The deposition was carried out by applying a cathodic current (10 μA) for a given time, in order to obtain ca. five monolayers of coverage; the time for nickel plating was calculated according to the real surface area of the working electrode in order to deposit 5 × 726 μC cm−2 for the charge for one monolayer of gold oxide.28 The surface area obtained from this measurement was used to calculate the current density in the cyclic voltammetry reported in the work. The capacitance-corrected plots of catalytic activity were obtained from the cyclic voltammetry curves by averaging the current of the backward and forward scans.31–32

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All potentials in this work are reported versus the reversible hydrogen electrode (RHE) in the working pH, unless otherwise stated. The potentials were converted into the RHE scale according to the eqn (1).

$$E_{\text{RHE}} = E_{\text{Ag/AgCl(sat. KCl)}} + E^0_{\text{Ag/AgCl(sat. KCl)}} + 0.059 \Delta pH$$

(1)

where $E_{\text{RHE}}$ is the potential on the RHE scale, $E_{\text{Ag/AgCl(sat. KCl)}}$ is the potential applied experimentally and $E^0_{\text{Ag/AgCl(sat. KCl)}}$ is the standard potential of the Ag/AgCl redox couple (in a solution saturated with KCl) on the normal hydrogen electrode scale (0.197 V).34 $\Delta pH$ accounts for the difference in pH of the working solution with respect to the conditions used for the normal hydrogen electrode ($pH = 0$). Eqn (1) was verified by measuring the equilibrium potential of platinum in a solution NaOH 0.1 M (pH 13) saturated with H2.

The Raman experiments in H2-18O (98% isotopic purity, GMP standard, purchased from CMR) were performed at pH 13
The electrolyte for these experiments was used without further purification, and the electrochemical cell had a smaller internal volume (ca. 1 mL); schematic details of this cell can be found in ref. 28.

Results and discussion

The cyclic voltammetry (CV) in Fig. 1a shows the Ni(OH)$_2$/NiOOH (Ni$^{II}$/Ni$^{III}$) redox transition in the potential region 1.3–1.5 V vs. RHE. The potential at which the redox transition occurs does not show significant pH dependence (see Fig. S1a and b in the ESI†). However, the OER activity (expressed as current density) does depend on the pH of the electrolyte, as confirmed in the capacitance-corrected plot of OER activity as function of the applied potential in Fig. S2 in the ESI†. Fig. 1a show that the OER activity at pH 11.0 is negligible and increases with the electrolyte pH, with a tendency to saturate at the highest pH values (see Fig. S3 in the ESI†).

The potential of the Ni$^{II}$/Ni$^{III}$ transition and the OER current of NiOOH in 1 M NaOH (see Fig. 1a) compares well with the results reported by Boettcher’s group, and confirms that the hydroxide solution was free of iron traces. We can therefore assert that our NiOOH catalyst is not contaminated with Fe during the electrochemical experiments, and the pH effect is not an artifact caused by impurities in the electrolyte. The elimination of Fe impurities in the electrolyte is important because the presence of Fe in the electrolyte shifts the OER onset potential to lower values due to the formation of NiFe mixed oxyhydroxide (Ni$_{1-x}$Fe$_x$OOH), which has a higher catalytic activity for oxygen evolution than NiOOH itself; the formation of Ni$_{1-x}$Fe$_x$OOH also affects the position of the Ni$^{II}$/Ni$^{III}$ redox transition, and produces an apparent pH dependence of the redox pair (compare Fig. S1c and d to Fig. S1a and b†). Fig. S3a and b in the ESI† shows polarization curves of Ni(OH)$_2$ deposited on Au, obtained in purified (Fe-free) and non-purified electrolytes, respectively. The cyclic voltammetry in the Fe-containing electrolyte (Fig. S3b in the ESI†) differs from the one obtained in Fe-free electrolyte: the Ni$^{II}$/Ni$^{III}$ redox peaks of NiOOH shift with pH and the OER activity increases ca. 20-fold from pH 11 to pH 13 whereas the enhancement is about 10-fold for the purified electrolyte. In general, the activity measured in the Fe-containing electrolyte is ca. 10-fold higher than in the Fe-free electrolyte.

The interfacial structural changes during the electrochemical oxidation of Ni(OH)$_2$ and subsequent OER were studied by means of in situ SERS at different pH, keeping the ionic strength of the electrolyte constant; Fig. 2 shows the results obtained from these experiments.

The SERS spectra acquired at potentials below ca. 1.4 V vs. RHE show two weak peaks at 457 cm$^{-1}$ and 504 cm$^{-1}$ (see left panel of Fig. 2a–c), which can be assigned to the A$_{1g}$ stretching modes of Ni–OH and Ni–O, respectively, in the Ni(OH)$_2$. The stretching mode of the dehydrated form of nickel hydroxide (Ni–O peak at ca. 504 cm$^{-1}$) has been attributed to a potential-assisted dehydration process of the nickel hydroxide to NiO-like structures, as expressed in eqn (2).

$$\text{Ni(OH)}_2 \xrightarrow{E} \text{NiO + H}_2\text{O}$$ (2)
Scheme 1 shows the Ni$^{II}$/Ni$^{III}$ oxidation process of a polymeric hydrous nickel(ii) hydroxide ([(Ni$^{II}$)$_2$(OH)$_6$(H$_2$O)$_3$]$^{2-}$), which is the actual state of the hydroxide on the electrode surface as reported by Lyons et al. This redox process is a OH$^-$/e$^-$ coupled reaction which should exhibit no pH dependence on the RHE scale.

The [(Ni$^{II}$)$_2$O$_2$(OH)$_6$(H$_2$O)$_3$]$^{2-}$ may be further deprotonated if the pH of the electrolyte is higher than pH 13, that solution is NaOH 0.1 M. The left panel presents the spectra in the wavenumber region 300–800 cm$^{-1}$ and the right panel presents the wavenumber region 800–1300 cm$^{-1}$:

(a) pH 11, (b) pH 12.0, (c) pH 13.0.

**Fig. 2** SER spectra obtained at constant potential during the electrochemical oxidation of Ni(OH)$_2$ and the subsequent OER on NiOOH at different pH's. The ionic strength of the solution was fixed to 0.1 M with NaClO$_4$ except for pH 13, that solution is NaOH 0.1 M. The left panel presents the spectra in the wavenumber region 300–800 cm$^{-1}$ and the right panel presents the wavenumber region 800–1300 cm$^{-1}$:

(a) pH 11, (b) pH 12.0, (c) pH 13.0.

The Ni(OH)$_2$/NiOOH redox transition occurs at potentials higher than ca. 1.35 V vs. RHE (see Fig. 1a), and the SERS spectra in the left panel of Fig. 2a–c show the appearance of two well-defined peaks at ca. 482 cm$^{-1}$ and 562 cm$^{-1}$ that can be assigned to the eg bending vibration and the A$_{1g}$ stretching vibration modes, respectively, of Ni–O in NiO(OH). The Raman peaks of Ni(OH)$_2$ are weak in comparison with the intensity observed for the peaks assigned to NiO(OH)$_2$, as previously reported by Bell's group; this has been attributed to the low Raman scattering cross-section of Ni(OH)$_2$, in contrast to the stronger bands observed for NiO(OH) due to a resonance enhancing effect. At higher potentials, we observe the peak attributed to "active oxygen" in the oxyhydroxide structure in the 800–1150 cm$^{-1}$ wavenumber region. The spectra in the right-hand panel of Fig. 2a–c show that the intensity of this peak increases as the pH of the electrolyte becomes more alkaline (spectra taken at pH 11.5 and 14 are shown in Fig. S4 in the ESI†).

Our electrochemical results indicate that the oxidation of Ni(OH)$_2$ occurs via a hydroxide-mediated deprotonation process that can be described by Scheme 1.
nature of the shallow minimum in both spectra in Fig. 3 is unknown but suggests the existence of two spectroscopically discernible O–O species on the surface.

The superoxodic nature of the species in the SER spectra can be further confirmed by comparing the above SERS results to the existing DFT calculations of NiO2 complexes; the calculations show that NiO2 has vibrational modes in the wavenumber region 900–1150 cm⁻¹,²⁶ when the O2 in NiO2 is of peroxidic or superoxodic character, i.e. the 900–1150 cm⁻¹ region corresponds to O–O stretching modes.

The dependence of the activity and the corresponding Raman bands on pH suggests that the species is formed upon deprotonation of the γ-NiOOH phase, which has been shown to be the more OER active phase of NiOOH.²⁶ Moreover, in the light of the abovementioned results reported for the photocatalytic OER on cobalt oxide,²⁴ the comparison to DFT calculations, the shift of the “active oxygen” Raman peak due to isotopic labeling and its pH-dependence, we conclude that this species is of superoxo nature and acts as precursor for oxygen evolution. As a consequence, we propose two possible mechanisms for the electrocatalytic OER on NiOOH that are similar to the one reported by Nocera et al.²⁶ for the OER on nickel borate, and by Frei et al.²⁴ for the light-assisted water oxidation on Co3O4. Our mechanisms incorporate a deprotonation step of the polymeric hydrous nickel oxyhydroxide towards formation of either oxide (NiO⁻) or superoxo species (NiOO⁻), as shown in Scheme 3. These mechanisms propose O₂ formation via decomposition of the negatively charged surface species (O₂⁻), which differs from the “classical” concerted OH⁻/e⁻ transfer mechanism that only considers uncharged adsorbates (or adsorbates with all equal charge).

The surface character of the pH-dependent active precursor (NiO⁻ or NiOO⁻) species is suggested by the Langmuir-type dependence of the OER activity on the NaOH concentration; a plot of 1/j versus 1/CNaOH gives a reasonably straight line (see Fig. 1b). The deviation from linearity in the plot of Fig. 1b can be partially attributed to the strong pH dependence of the OER Tafel slope, as can be shown in Fig. 1c and d. The Tafel slope for OER on nickel oxyhydroxide varies from ca. 271 mV dec⁻¹ at pH 11 to ca. 148 mV dec⁻¹ at pH 13. Lyons et al.⁹ reported a similar trend in the values of the Tafel slope in experiments performed at higher concentrations of NaOH (0.1–5 M).

The decoupled OH⁻/e⁻ transfer mechanisms proposed in Scheme 3 consider two possible deprotonation pathways: OH_ads deprotonation towards negatively charged surface oxide (O_ads⁻), or OOH_ads deprotonation towards negatively charged surface superoxide (O2_ads⁻); in both pathways the O₂ formation occurs via decomposition of the negatively charged surface superoxide. The pH-dependence of the NiOOH activity towards OER may in principle be ascribed to both pathways: deprotonation giving rise to the negatively charged surface oxide (O_ads⁻) and subsequent formation of the O–O bond, or OOH_ads deprotonation giving rise to the negatively charged surface superoxide. Ultimately, the (surface) pKₐ of the corresponding acid–base equilibrium needs to be determined in order to assess which of the two explains the observed pH dependence. The importance of proton loss for generating localized reactive intermediates was also emphasized by Bediako et al., who speculated that changes...
Concerted OH-/e- transfer OER mechanism:

\[ \text{OH}^- \rightarrow \text{OH}_\text{ads}^- + e^- \]
\[ \text{OH}_\text{ads}^- + \text{OH}_\text{ads}^- \rightarrow \text{O}_\text{ads} + \text{H}_2\text{O} + e^- \]
\[ \text{OH}_\text{ads}^- + \text{OOH}_\text{ads}^- \rightarrow \text{O}_\text{ads}^- + \text{H}_2\text{O} + e^- \]
\[ \text{O}_\text{ads}^- \rightarrow \text{O}_\text{ads} + e^- \]

Scheme 3 Comparison between the classical OER mechanism via concerted OH-/e- transfer and the decoupled mechanisms via decomposition of the negatively charged superoxo (O\textsubscript{2}\textsuperscript{−}) adsorbate generated by hydroxide-mediated deprotonation steps. The charges on the surface intermediates labeled in red should not be considered absolute, but as differential charges with respect to the surface species from which they are formed.

in ligand field strength upon deprotonation could localize the unpaired spin density to favor further reactivity.\textsuperscript{20}

The relevance of negatively charged species, either of “O” or of “OO” character, on the surface of the catalyst during the OER has been suggested for many types of (transition-metal) oxide catalysts.\textsuperscript{9,20,21,23,25,36,46} However, theoretical descriptions of the OER mechanism employing density functional theory calculations have not yet incorporated this important pH effect in the reaction kinetics.\textsuperscript{49} We believe that the data reported here and the associated mechanism suggested in Scheme 3 provide another clear experimental example of the importance of negatively charged (surface) intermediates in generating pH dependent electrocatalytic activities, in agreement with a general model reported previously.\textsuperscript{48} Further understanding of the role of the o xo (MO\textsuperscript{−}) and superoxo (MOO\textsuperscript{−}) intermediates in the OER kinetics would require detailed DFT calculations that consider the pK\textsubscript{a} and the relative stabilities of these intermediates. Future computational approaches towards modeling OER should account for this important acid–base surface chemistry.

Conclusions

In this paper, we have provided spectro-electrochemical evidence for the active species that is responsible for the pH dependent OER activity of rigorously Fe-free NiOOH in alkaline electrolytes. We identify this species as a deprotonated γ-NiOOH surface phase in which stable (i.e. Raman observable) O-O bonds are formed. Based on our observations and other literature data on pH dependent OER kinetics, we propose a mechanism for the OER on NiOOH which is consistent with the observed pH-sensitivity: it involves the formation of a superoxo-type intermediate (NiOO\textsuperscript{−}) that acts as a competitive oxygen precursor at pH > 11. The proposed OER mechanism also considers the possibility of O\textsubscript{2} formation via decomposition of OOH intermediates formed from the negatively charged surface oxide (NiO\textsuperscript{−}). However, theoretical calculations to determine the (surface) pK\textsubscript{a} of the corresponding acid–base equilibrium need to be performed to ultimately assess the relative importance of the NiOO\textsuperscript{−} and NiO\textsuperscript{−} intermediates in the OER mechanism. The pH dependence presented in this work rationalizes the unsuitability of NiOOH as electrocatalyst for applications in neutral or moderately alkaline pH (in the range 7–11), apart from the lower stability of the catalyst under these conditions.

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