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Unraveling the H₂ Promotional Effect on Palladium-Catalyzed CO Oxidation Using a Combination of Temporally and Spatially Resolved Investigations

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ABSTRACT: The promotional effect of H₂ on the oxidation of CO is of topical interest, and there is debate over whether this promotion is due to either thermal or chemical effects. As yet there is no definitive consensus in the literature. Combining spatially resolved mass spectrometry and X-ray absorption spectroscopy (XAS), we observe a specific environment of the active catalyst during CO oxidation, having the same specific local coordination of the Pd in both the absence and presence of H₂. In combination with Temporal Analysis of Products (TAP), performed under isothermal conditions, a mechanistic insight into the promotional effect of H₂ was found, providing clear evidence of nonthermal effects in the hydrogen-promoted oxidation of carbon monoxide. We have identified that H₂ promotes the Langmuir−Hinshelwood mechanism, and we propose this is linked to the increased interaction of O with the Pd surface in the presence of H₂. This combination of spatially resolved MS and XAS and TAP studies has provided previously unobserved insights into the nature of this promotional effect.

KEYWORDS: CO oxidation, TAP, XAFS, spatially resolved, SPACI-FB

INTRODUCTION

To optimize heterogeneous catalytic performance, a full understanding of the correlation between structure and reactivity is required. The deficiency of such knowledge has resulted in excessive loading of precious metals in order to guarantee the desired performance.1,2 However, this is not an economically viable methodology. Ultimately, a better understanding of catalytic processes and indeed the correlation of
catalyst structure and activity are required. This can be achieved via a combination of in situ catalyst characterization and kinetic measurements.3

The promotion of CO oxidation in the presence of hydrogen is a reaction of interest, particularly for proton-exchange membrane fuel cells (PEMFCs).4,5 PEMFCs have high efficiency, operate at low temperature (80 °C), and are fueled by H2 produced from steam reforming, partial oxidation, or autothermal reforming of natural gas and other liquid fuels.6,7 As CO, even in trace amounts (1 ppm), is a poison for PEMFCs at low temperature, all CO must be removed. Large amounts of CO are initially reduced to ∼1% by the water-gas shift reaction. To further reduce the concentration, CO oxidation over supported noble-metal catalysts8 is a suitable method, showing high conversions at low temperatures. The presence of a small amount of H2 in the feed shifts the light-off to a lower temperature, a phenomenon which has been widely reported for platinum9−15 and gold,16 but there are only limited observations in the case of palladium.17,18 However, it is not well understood why the presence of hydrogen has a promotional effect on CO oxidation. There are currently two theories on this promotional effect:

(i) H2 combustion produces heat, thereby increasing the rate of reaction for CO oxidation.19

(ii) H2 promotes CO oxidation through a physico-chemical effect.20

There is also the possibility that both thermal and physico-chemical effects contribute in tandem to promote CO oxidation. While thermal effects are always likely to contribute under operand conditions, in this study the contribution of any nonthermal effects (physico-chemical) to the CO oxidation in the presence of H2 over a Pd/Al2O3 catalyst is investigated. This study employed a combination of temporal analysis of products (TAP) measurements and a combined spatially resolved X-ray absorption spectroscopy (XAS) and spatially resolved mass spectrometry analysis.

In order to investigate the elementary steps of the reactions, a transient pulse response methodology was employed using a TAP reactor.21−25 This technique has been proven to provide key insights into elementary steps of catalytic processes.26,27 However, despite the ability to screen varying oxidation states via multi-pulse experiments,28 TAP is not typically used to determine structure−activity correlations. TAP is, however, ideally suited to determine the role of any nonthermal effects due to operation in the Knudsen diffusion regime, owing to the use of small amounts of reactive gases.29 In this regime gas−gas interactions are eliminated and experimental conditions maintained such that an isothermal catalyst zone is created:30 i.e., no promotional thermal effects. The well-defined transport regime of Knudsen diffusion has allowed for the development of well-established moment based analytical methodologies,31,32 which are utilized herein to determine conversions and residence times of gases.

As structural characterization is typically conducted with the aid of spectroscopic techniques,33 there is a growing trend in the development of operando methods.34−39 In addition, there has also been a development of spatially resolved methodologies to monitor the evolution of reactant concentrations,40−45 as well as

**Figure 1.** Variation of coordination to Pd and O and the conversion of CO, O2, and H2 along the length of the catalyst bed for (a) CO oxidation and (b) CO oxidation in the presence of H2. Coordination numbers are plotted with the temperature profile for (c) CO oxidation and (d) CO oxidation in the presence of H2.
significant advances in the imaging of spatial heterogeneities within catalytic reactors. With this in mind, the minimally invasive SPACI-FB technique has been coupled with X-ray absorption fine structure (XAFS) for the first time, providing spatially resolved correlations of gas-phase concentrations, catalyst bed temperatures, and information on the catalyst structure (via XAFS). This combination of techniques (to be known as SPACI-FB-XAFS) enables a profile of the gas-phase concentrations and temperature through a fixed catalytic bed, to be correlated to the structure of the catalyst at the same axial position in the bed. Consequently, we are able to report on the contribution of both chemical and structural effects in the promotion of CO oxidation by hydrogen.

### RESULTS AND DISCUSSION

From the combined SPACI-FB-XAFS measurements we were able to correlate changes in the catalyst structure (from the coordination numbers determined from the extended X-ray absorption fine structure (EXAFS) analysis) with the reaction profile along the catalyst bed (from the MS data). These profiles are shown for CO oxidation in both the absence and presence of H₂ in Figure 1. In comparison to CO oxidation without H₂ (Figure 1a), in the presence of H₂ (Figure 1b), light-off occurs much closer to the beginning of the catalyst bed, confirming the promotional effect of H₂. As can be clearly observed from Figure 1, the structural change also occurs much earlier in the bed in the presence of H₂. It should be noted that the changes in temperature and structure (Figures 1c,d) do not follow the same trends and, therefore, are not likely to be entirely connected, indicating the likely presence of both thermal and nonthermal promotional effects. However, in both the absence and the presence of H₂, the onset of CO conversion only occurs once the Pd catalyst has reached a similar local coordination (Figure 1a,b), with coordination to O and Pd of 1.5 and 5, respectively.

These spatially resolved measurements were performed after heating the catalyst to reaction temperature under reactant gases and allowing the system to attain steady state. The EXAFS spectra collected during both reactions can be fitted to two scattering paths, an O path at 1.97 Å and a Pd path at 2.74 Å, the Pd distance being consistent with metallic Pd (highlighted in blue and green in Figures 2b,c). The Pd–Pd scattering path at 3 Å, characteristic of PdO, could not be fitted to these data, at any point along the catalyst bed; this feature is highlighted in yellow in Figure 2a. For CO oxidation both with and without H₂ the catalyst structure is consistent with a Pd nanoparticle (NP) with coordination to an adsorbed low-Z-number element (O, CO, or OH). The fitting parameters and examples of the fits are shown in Tables S1–S3 and Figures S4–S6 in the Supporting Information.

The fresh catalyst, however, is consistent with PdO, the data fitting well to one O and two Pd scattering paths at 2.015, 3.05, and 3.44 Å, respectively. Heating the catalyst in reaction gases resulted in removal of O from the PdO structure, as a consequence of PdO reaction with the reductant gases present in the feed (CO or CO and H₂). However, during the ramp and attainment of steady state this O could not be replenished from the gas phase and so the catalyst during both reactions is a reduced Pd NP with adsorbed surface O (or other low-Z-number element).

The relative changes in catalyst structure during CO oxidation with and without H₂ are observed in Figure 2b,c. For CO oxidation without H₂ the front and middle of the bed are dominated by Pd scattering, whereas during CO oxidation with H₂ the increase in scattering from a low-Z-number element has already occurred by the middle of the bed. From a linear combination fit (LCF) of the XANES spectra we can follow the changes in the relative oxidation state of the Pd NPs during the reaction, by fitting the data to contributions of Pd²⁺ and Pd⁰ (Figure 3).

The increase in Pd²⁺ contribution follows the same trend as the change in O coordination observed from the EXAFS fitting (Figures 1a and 3a). As adsorbed CO has a neutral charge and adsorbed O a 2− charge, we can therefore be confident that the increase in Pd²⁺ contribution coincides with an increase in the concentration of adsorbed O and so the low-Z-number element observed in the EXAFS analysis is coordination to adsorbed O. The fact that CO conversion only reaches 50% under CO oxidation with and without H₂ after the catalyst has attained the same local coordination (O of 1.5 and Pd of 5) would imply a certain concentration of surface O is required for reaction to occur. The difference between the two reactions is how this surface O concentration is obtained. Under CO oxidation conditions it appears that a certain temperature is required before CO oxidation occurs (see Figure 1c), starting at 165 °C (5 mm along the bed). After this temperature is reached, CO conversion increases slowly as surface O content increases. The maximum rate of change of structure of the Pd nanoparticles occurs as the exotherm reaches a maximum at 195 °C. We
propose that an initial small amount of CO conversion results in a small localized increase in temperature, thus enabling more CO to react and desorb, leaving more sites available for O adsorption. This results in an autocatalytic type change to the surface coverage, as previously observed for CO oxidation using XPS.49

Under CO oxidation in the presence of H2, an initial increase in surface O content is observed very early in the catalyst bed, which coincides with H2 consumption. This early change in structure is thought to occur through a promotional effect of H2 or hydroxyls on the Pd surface. It could be envisioned that dissociatively adsorbed H2 on the Pd surface can react with O2 to produce adsorbed hydroxyl species, with which CO can more easily react than with oxygen. Although from this combined SPACI-FB-XAFS study we have no direct evidence of the presence of OH species, the promotional effect of hydroxyls has previously been investigated using a variety of techniques such as XPS, inelastic neutron scattering (INS), and isotopic exchange experiments.50−52 From XPS and catalytic activity studies comparing anhydrous and hydrous PdO, only the latter was found to be active and the water of hydration was found to be in the form of OH groups. These authors proposed two roles for the OH species: the oxidation of CO by OH and the formation of PdO through the formation of water from reaction of two OH groups.50 Direct evidence for the involvement of OH species in CO oxidation is shown in the INS study, where a decrease in the Pd–OH hydroxyl band intensity at 900 cm−1 was observed on reaction.51 Further evidence of the role of OH groups comes from an isotopically labeled O2 study, used to investigate a Pd/Al2O3 catalyst during CO and propene oxidation.52 In that work, the oxidation of CO was found to be due to interaction with OH species and not from reaction with O2.52 The current work would suggest a Langmuir–Hinshelwood mechanism, where the reaction is dependent on the coverage of CO species and not from reaction with O2.52

Figure 3. Relative contributions of a Pd metal standard and PdO as a function of position in the catalyst bed during (a) CO oxidation and (b) CO oxidation with H2.

CO oxidation is shown in the INS study, where a decrease in the Pd–OH hydroxyl band intensity at 900 cm−1 was observed on reaction. Further evidence of the role of OH groups comes from an isotopically labeled O2 study, used to investigate a Pd/Al2O3 catalyst during CO and propene oxidation.52 In that work, the oxidation of CO was found to be due to interaction with OH species and not from reaction with O2.52 The current work would suggest a Langmuir–Hinshelwood mechanism, where the reaction is dependent on the coverage of CO species and not from reaction with O2.52

The contribution of Pd52 is less under CO oxidation with H2 than without H2, which could be linked to the adsorption of other types of species, potentially hydroxyls.

It should be noted that even at the end of the catalyst bed under both sets of reaction conditions, where all the CO (and H2) has been consumed, the catalyst does not re-oxidize to form a bulk PdO structure. The temperatures reached in the catalyst bed are not sufficient for a complete re-oxidation of the catalyst, requiring temperatures typically over 200 °C for bulk oxidation to start.53

TAP experiments were conducted, providing further insight into the CO oxidation with and without H2 from both a mechanistic and kinetic point of view. For the latter purpose, the TAP data were treated according to the moment based analysis and basic kinetic coefficient methods.54 From the obtained values of adsorption rate constant kθ of CO for the experiments without H2 (2.36 s−1) and with H2 (1.13 s−1), it is clear that CO adsorsbs more slowly in the presence of H2, which would indicate that there is some competition for adsorption sites between CO and H2. When CO oxidation is performed over the pre-reduced or pre-oxidized catalyst, a clear increase in CO conversion for the former material is observed: i.e., 99% over the pre-reduced catalyst in comparison to 71% conversion for the pre-oxidized catalyst (Figure 4a). This would imply that the presence of Pd, most likely present in the prereduced catalyst, promotes activity. This is consistent with the XAFS data, which showed that the catalyst was already in a reduced state prior to reaction both with and without H2. PdO appears to be less able to convert CO to CO2, i.e. provide O, and from the XAFS results we propose that a certain coverage of adsorbed oxygen species (in the case of CO oxidation) is required for conversion. This indicates the presence of a Langmuir–Hinshelwood type mechanism over the Pd NPs which is promoted in the presence of H2.

In order to identify the kind of oxygen species participating in CO oxidation to CO2, TAP experiments were conducted in the presence and absence of H2. The surface of the catalyst was pretreated with 16O2 and then subjected to sequential pulses of 18O and 16O2.16CO2 was the main carbon dioxide isotope upon CO oxidation in the absence of H2, thus proving that strongly adsorbed 16O species (formed upon catalyst pre-treatment) participated in the oxidation reaction (Figure 4b). When H2 was in the reaction feed, a greater contribution of 18O-containing carbon dioxide was observed. To check if H2 simply promotes an oxygen isotopic exchange between C16O and 18O2, the components were pulsed together over the catalyst at 200 °C following a 16O2 pre-treatment at 300 °C. No 16CO2 and only small amounts of C16O18O were detected (less than a 10% fraction (Figure S7)) in comparison to 50% C18O18O formed
H2 is proposed to occur through the formation of surface OHs. It appears to proceed via reaction with strongly adsorbed 16O, with where there is no formation of OHs, the oxidation of CO occurs, the majority of product being C16O2.

Such a species could be 18OH when the XAFS measurements are considered, where the promotional effect of H2 once the same local coordination of the Pd NPs (coordination to O and Pd of 1.5 and 5, respectively) has been reached.

There is a competitive adsorption between hydrogen and carbon monoxide, as evidenced in TAP results by the slowing of the rate of adsorption of carbon monoxide in the presence of hydrogen.

There is a significant interaction of hydrogen with the catalyst surface (TAP 1st moment data).

The presence of hydrogen has in fact promoted the Langmuir–Hinshelwood mechanism.

**CONCLUSIONS**

From this combination of TAP reactor studies and spatially resolved SPACI-FB-XAFS measurements, we conclude that the H2 promotion on CO oxidation over Pd/Al2O3 proceeds through a physico-chemical effect. During CO oxidation in both the absence and presence of H2 the catalyst structure is consistent with a Pd nanoparticle with adsorbed surface O, with a specific surface concentration of O (or OHs) which appears to be required before light-off is observed. In the presence of hydrogen the activation of the catalyst occurs at a place closer to the front end of the bed, most likely via the reaction of H2 and gas-phase O2 to form adsorbed OHs, which from previous studies have been shown to more readily react with CO in comparison to surface O. TAP reactor studies confirm the presence of a nonthermal effect and, through O-isotopic experiments, confirm the increased interaction of gas-phase O2 on CO oxidation with H2 in comparison to CO oxidation in the absence of H2. We propose that this is due to the formation of surface hydroxyls in the presence of H2, which then preferentially react with CO over adsorbed O.

The ability to show that the activation of the catalyst shifts in the catalyst bed and to correlate with the gas-phase products and thus catalyst conversion demonstrates the strength of this combination of techniques. Our results show that the structure evidently changes through the bed and, crucially, during the actual reaction. This allows for a clearer picture of the overall catalyst performance via SPACI-FB-XAFS, information which, to our knowledge, has not been reported previously.

**EXPERIMENTAL METHODS**

**Catalyst Preparation.** The 1 wt % Pd/Al2O3 catalyst used in this work was prepared by wetness impregnation of y-Al2O3 (Alfa Aesar, SA = 232 m2/g). The Al2O3 support was ground to a particle size of <150 μm and mixed with an aqueous solution containing Pd(NO3)2. The mixture was vigorously stirred and heated to 60 °C for 4 h until the excess amount of water was removed and the mixture became a slurry. The catalyst was then dried at 110 °C overnight, after which the catalyst was calcined at 550 °C for 4–6 h. The fresh catalyst was characterized by powder X-ray diffraction and TEM. These results are shown in Figures S1–S3 of the Supporting Information.
**SPACI-FB-XAFS Experiments.** Figure 5 is a schematic of the SPACI-FB system, while Figure 6 is a photograph of the experimental setup in place on B18 at the Diamond Light Source, UK. Further experimental setup details of the SPACI-FB-XAFS system are reported elsewhere. Critically, precise alignment of the X-ray beam, the thermocouple, and holes in wall of the sampling capillary is required in order to ensure that coincident measurements are examining the same part of the catalyst bed. This was achieved through laser alignment and micrometer precision stages. A quartz reactor was used to hold the catalyst which the X-rays passed through to measure the Pd K edge transmission XAFS data. A catalyst bed length of 12 mm was utilized, and the data points (gas composition and XAFS) were collected over 15 min every 1 mm of the reactor to obtain sufficient signal to noise and spatial resolution. The XAFS experimental details are provided in the Supporting Information.

**TAP Experiments.** An ultrahigh-vacuum (UHV) TAP-2 system was utilized for this study. In this setup, pulse valves are at atmospheric pressure with the outlet of the quartz microreactor (i.d. 6 mm, length 40 mm) in direct contact with the UHV analysis chamber, where the exit flow is analyzed by a quadrupole mass spectrometer (Hiden HAL RC 301). The Pd/Al2O3 catalyst (20 mg) was packed between two layers of quartz (sieve fraction of 250–355 μm) within the isothermal zone of a quartz tube microreactor. Before transient experiments the catalyst was pretreated at 300 °C in a flow of 16 mL min⁻¹ N2 with 4 mL min⁻¹ O2 (oxidized) or H2 (reduced) for 0.5 h. Hereafter, the reactor was exposed to vacuum (10⁻⁵ Pa) with a simultaneous decrease of temperature to 200 °C unless otherwise stated. CO:Ar = 1:1, ³¹O2:CO:Ar = 1:1:2, H2:Ne = 1:1, CO2:Ar = 1:1, and ¹⁸O2:Ne = 1:1 mixtures were used in these experiments. The reaction mixtures were prepared using O2 (Air Liquide 5.5), ³¹O2 (CAMPRO scientific, 97% ³¹O), CO (Linde, 3.7), CO2 (Linde, 4.5), H2 (Air Liquide, 5.0), Ar (5.0), and Ne (Linde, 5.0) without additional purification. The following atomic mass units were used for mass spectrometric identification of different compounds: 48 (C18O2), 46 (C16O16O), 44 (16CO2), 36 (18O2), 34 (18O16O), 32 (16O2), 30 (C18O, C18O16O), 28 (C16O, C18O2), 18 (H2O), 2 (H2), 20 (Ne), and 40 (Ar). Operation within the Knudsen diffusion regime (and by extension isothermal conditions), which is essential for TAP moment based analysis, was also confirmed via comparison of inert gas (argon) experimental pulse response with theoretical Knudsen diffusion pulse response for argon.
The data were analyzed using the well-established moment based approach,\(^{54}\) and reported results are derived from the averages of three experimental data sets, each one consisting of 200 pulses.

**ASSOCIATED CONTENT**

# Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acscatal.8b01509.

EXAFS analysis, results of the linear combination fit of the XANES, and equations relating to the TAP analysis (PDF)

The XAFS spectra, TAP data, mass spectrometry files, TEM and XRD data underpinning the results shown in the manuscript can be accessed from the University of Glasgow and Queen’s University Belfast’s data repositories: http://dx.doi.org/10.5525/gla.researchdata.654 and https://doi.org/10.17034/e97ee975-90e2-41f8-b28a-1ae1438dc91.

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**Notes**

The authors declare no competing financial interest.

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