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The Role of Oxidizing Conditions in the Dispersion of Supported Platinum Nanoparticles Explored by Ab Initio Modeling

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Abstract

Achieving fine control over the dispersion of supported platinum nanoparticles (Pt) is a promising avenue to enhance their catalytic activity and selectivity. Experimental observations suggest that exposing ceria-supported Pt nanoparticles to O₂ at 500 °C promote their dispersion into smaller particles and eventually single atoms. The exact role of oxygen in this process is not well understood yet. Past density functional theory studies of ceria-supported Pt have typically narrowed down their scope to single atoms and clusters of a few atoms. Herein we combine several approaches and types of models in a consistent atomistic framework to evaluate the relative stability of ceria-supported Pt as a function of the degree of oxidation of Pt and of the particle size, ranging from single atoms to nanoparticles of 1.5 nm of diameter. We find that the largest nanoparticles remain the thermodynamically most stable species on the lowest energy facet of ceria even under oxidizing conditions, suggesting that stronger adsorption sites are required to stabilize smaller clusters and single atoms and promote oxidative dispersion.

Introduction

The surface properties, stability, and poisoning resistance of platinum make it an exceptional catalyst for a wide variety of industrial processes, including selective hydrogenation and dehydrogenation reactions,^{1,2} water-gas shift (WGS) for H₂ production,^{3,4} non-oxidative coupling of methane,^{5,6} dealkylation of toluene,^{7,8} isomerization of hydrocarbons,^{9,10} oxidation of CO and NO,¹¹ and the electrocatalytic hydrogen evolution and oxygen reduction reactions,¹² among others.

Depending on the application, different Pt particle sizes are preferred. Achieving fine control over the particle size (dispersion) and tailoring the catalyst for its specific application is a promising approach for enhancing the activity and selectivity. However, like other noble metal catalysts, Pt suffers from sintering, i.e. the process of agglomeration or coalescence of single atoms and small particles into larger ones, which results in a decrease in the surface area, leading to a reduction in the number of available active sites and the catalytic activity (degradation).^{13–15} Sintering depends on the support and gas mixture composition, but it typically takes place at reaction temperatures above 500 °C.^{16,17} Careful engineering of the catalytic particles and their interaction with the support can mitigate the sintering process. Some strategies in that regard include optimization of the Pt concentration and uniformity,¹⁵ encapsulation in a metal oxide shell or other protective layers,¹⁸ incorporation in porous supports like zeolites,¹⁹ and doping of the support.²⁰ Nevertheless, such strategies only slow down the sintering, and cannot prevent it from occurring under operating conditions.

For this reason, there is an increasing interest in developing protocols that make use of the structural dynamics of the catalyst to control Pt dispersion and tune the particle size in situ at mild operating conditions, by cycling between oxidative and reductive conditions.²¹ To tune the Pt dispersion via redox cycling, cerium oxide (ceria) has been proposed as a viable support since its stronger interaction with Pt compared to the classic Al₂O₃ support allows for a more gradual evolution of the particle size and morphology.^{22,23} In particular, it has been recently shown that oxidative treatments exposing the catalyst to 1–1.5 mbar

of O₂ at ~500 °C promote the dispersion of ceria-supported Pt nanoparticles into smaller oxidized Pt species, eventually forming single atoms, which can be exploited in a controlled manner to enhance the catalyst’s performance for low-temperature CO oxidation.^{24–27}

The current understanding of the oxidative dispersion phenomenon remains very limited.²⁸ Strong metal-support interactions lower the barrier for the spillover of Pt atoms from parent nanoparticles, to form new bonds with the support. The low-barrier diffusion of dissociated atoms on the support usually causes sintering, via their incorporation into larger nanoparticles (Ostwald ripening).^{29–31} However, spillover can instead lead to atomically dispersed Pt species, provided they are effectively trapped by the support.^{31,32} The larger spacing between nanoparticles at low coverage increases the probability of atoms being captured by strong adsorption sites rather than colliding with nanoparticles.

Overall, many questions remain regarding the factors governing the dispersion process, such as the role of oxygen, the impact of the initial particle size, and the types of sites required for trapping Pt single atoms. The experimental investigation of these questions is challenging. Potential structural changes induced by the electron beam in transmission electron microscopy (TEM), or by probe molecules used in infrared spectroscopy, make these techniques unreliable.^{33–35} Moreover, TEM typically displays weak contrast between atomically dispersed species and small clusters, and thus cannot conclusively differentiate them.^{32,36} Similarly, low-energy He⁺ scattering (ISS) detects the transition from multi-layer to mono-layer clusters, but cannot identify single atoms.³⁷ Extended X-ray absorption fine structure (EXAFS) analysis is a powerful tool for identifying single atoms by probing the local environment of platinum.^{38,39} However, the exact coordination of such single atoms remains difficult to determine.⁴⁰ Pt–O₄ on CeO₂(100),^{28,41–43} Pt–O₅ at step edges,⁴⁴ and Pt–O₆^{27,28,43,45} have been reported as possible coordinations for Pt. Moreover, since EXAFS is dominated by scattering from the sample’s majority species, some single-atom intermediates might not be detected if they migrate rapidly to stronger adsorption sites.³⁵ For this reason, theoretical studies are a promising avenue to shed light on this phenomenon and

understand the transition from Pt nanoparticles to single atoms.

Past theoretical studies of ceria-supported Pt have focused on single-atom models (Pt_1O_y), because of their relevance as single-atom catalysts (SACs) for a variety of reactions.^{36,46–49} Several density functional theory (DFT) studies have reported the structure and stability of atomically dispersed Pt on both low-index and high-index (stepped) surfaces.^{25,28,50–54} The gas-phase structure of Pt_1O_y has been investigated as well.⁵⁵ On the other hand, computational studies of Pt nanoparticles are less common in the literature. They usually disregard the support and focus on understanding finite-size effects and establishing d-band correlations for isolated nanoparticles.^{56–60} Recent works have begun to consider the dynamic structure of Pt nanoparticles supported on metal oxides and exposed to reactants, by combining heuristically postulated cluster models,^{44,61–63} structures resulting from global optimization,^{37,64} and large nanoparticles derived from the bulk or gas-phase structures.^{65–67}

In this work, we aim to gain atomic-level insight into the oxidative dispersion of Pt nanoparticles supported on ceria by performing a computational DFT study combining various approaches in a consistent theoretical framework. We investigate the relative stability of Pt_xO_y species adsorbed on ceria as a function of size and degree of oxidation. Although Pt adsorbs more strongly on less stable surface terminations such as $\text{CeO}_2(100)$ and the stepped $\text{CeO}_2(211)$, which are present in nanostructured catalysts (nanorods, nanocubes),^{28,42,68} $\text{CeO}_2(111)$ should prevail as the most abundant surface in regular polycrystalline catalysts.^{69–71} Since Pt oxidative dispersion appears to be a universal phenomenon on ceria,^{26,27,72} we opt to model it on $\text{CeO}_2(111)$. Heuristic exploration of adsorption sites, stochastic sampling via grand canonical genetic algorithms, and ab-initio molecular dynamics (AIMD) simulations are combined to generate models of ceria-supported Pt single atoms, subnanometer rafts, and nanoparticles of diameter larger than 1 nm, both reduced and oxidized.

Methods

Computational Details

Density functional theory calculations were performed using VASP 6.2.1.^{73,74} The exchange-correlation energy was calculated within the generalized gradient approximation (GGA), with the Perdew-Burke-Ernzerhof (PBE) exchange-correlation functional.⁷⁵ Long-range dispersion was implemented using Grimme’s D3(BJ) correction.^{76,77} The valence electrons were treated on a plane-wave basis with an energy cutoff of 400 eV, whereas the core electrons were represented with the projector-augmented wave (PAW) method.⁷⁸ Total energies were calculated with a numeric precision of 10^{-6} eV (10^{-5} for the genetic algorithm sampling). The DFT+U approach was implemented with Dudarev’s scheme,⁷⁹ to consider strong electronic correlation effects due to charge localization and compensate for the self-interaction error,^{70,80–83} with U_{eff} set to 4.5 eV for Ce(4f).^{84,85} The forces of the nuclei were converged to ± 0.02 eV/Å. The Brillouin zone was sampled using a $2 \times 2 \times 1$ k-point grid for (3×3) supercells, and only the gamma point for larger supercells, namely (4×4) , (6×6) and (8×8) .

Models

The CeO₂(111) surface was modeled using supercells derived from the CeO₂ bulk with the equilibrium lattice parameter of $a_0 = 5.455$ Å, and consisting of 6 atomic layers (two O–Ce–O trilayers, TL) separated by a 23 Å vacuum layer. The bottom trilayer was kept fixed during geometry optimization. A (3×3) expansion was used for PtO_y systems, (3×3) – (4×4) for Pt₂O_y, (4×4) – (6×6) for Pt₁₃O_y, and (6×6) – (8×8) for Pt₁₄₇O_y systems, ensuring a sufficiently long distance between periodic replicas of the adsorbed Pt nanoparticles, to prevent undesired lateral interactions between them. To account for the Ce⁴⁺/Ce³⁺ redox couple, spin-polarized calculations were systematically performed, except for supported 147-atom nanoparticles, due to the computational cost.

PtO_y structures were generated by following published results reporting the most stable structures after exploration of the adsorption sites of the surface.^{25,51–54,86} Single Pt atoms adsorb on a twofold bridge position on the CeO₂(111) surface and adopt a triplet spin multiplicity (Figure 1a) ($d_{\text{Pt-O}} = 2.00 \text{ \AA}$). Although their adsorption energy on oxygen vacancies is stronger,^{52,87} it is not enough to compensate for the formation of O-defective CeO₂(111) under oxidizing conditions, overall resulting in a less stable configuration (Figure S1a). The substitution of surface oxygen by Pt coupled with the formation of a surface peroxo group is not favorable either (Figure S1c). Regarding oxidized Pt single atoms, PtO binds linearly on top of surface oxygen (O_{surf}), forming an O–Pt–O_{surf} species (Figure S1e). PtO₂ adsorbs forming a Pt–O_{surf} (2.31 Å) and an O–Ce bond (1.97 Å), with the remaining O atom pointing away from the surface (Figure 2a). An alternative configuration forming two O–Ce bonds exists, but it is less stable by 0.23 eV (Figure S1g). Finally PtO₃ adopts a twofold configuration with two O–Ce bonds (2.48 Å) and the third O atom pointing up (Figure S1j). Oxidation of PtO_y to PtO_{y+1} by surface oxygen from the support was evaluated as well, but it resulted unfavorable for all cases considered. That is, PtO_{y+1} accompanied by an oxygen vacancy is less stable than PtO_y on the stoichiometric support. Details are provided in Tables S1 and S2.

The Pt₂ structure is based on the literature as well.⁸⁸ On the other hand, for oxidized Pt₂O_y systems a grand canonical genetic algorithm (GCGA) was used to generate 100 structures, and the most competitive ones were selected for each stoichiometry, i.e. for each O/Pt ratio (Figure S2). The genetic algorithm was implemented using the GOCIA package,⁸⁹ with a population size of 25 and a mutation rate of 0.4. In this process, the number of Pt atoms is fixed to 2, and the system is allowed to exchange oxygen with a reservoir with a given O₂ chemical potential. The chemical potential is derived from statistical thermodynamics, setting the temperature to 500 °C and the partial pressure of O₂ to 0.2 bar. The resulting Pt₂ dimer binds asymmetrically, with Pt–O_{surf} bonds of 1.91 Å and 1.98 Å (Figure 1b). On the other hand, Pt₂O₄ adsorbs in a symmetric configuration forming two Pt–O_{surf} bonds

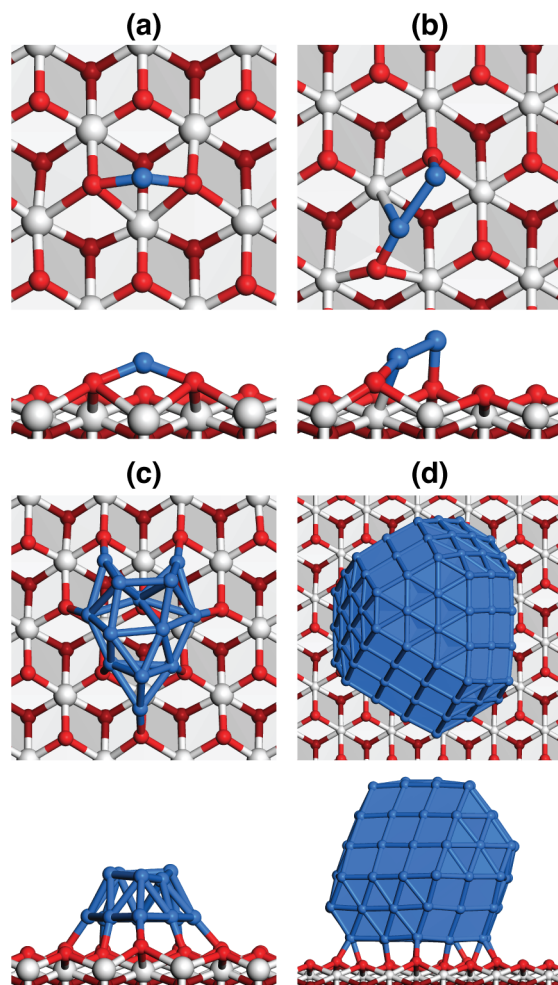


Figure 1: Top and side views of the optimized structures of non-oxidized Pt atom and Pt nanoclusters supported on CeO₂(111). (a) Pt single atom, (3×3) cell. (b) Pt₂ dimer, (3×3) cell. (c) Pt₁₃ cluster, (4×4) cell. (d) Pt₁₄₇ nanoparticle, (6×6) cell. Ce in gray, surface O in light red, subsurface O in dark red, Pt in blue.

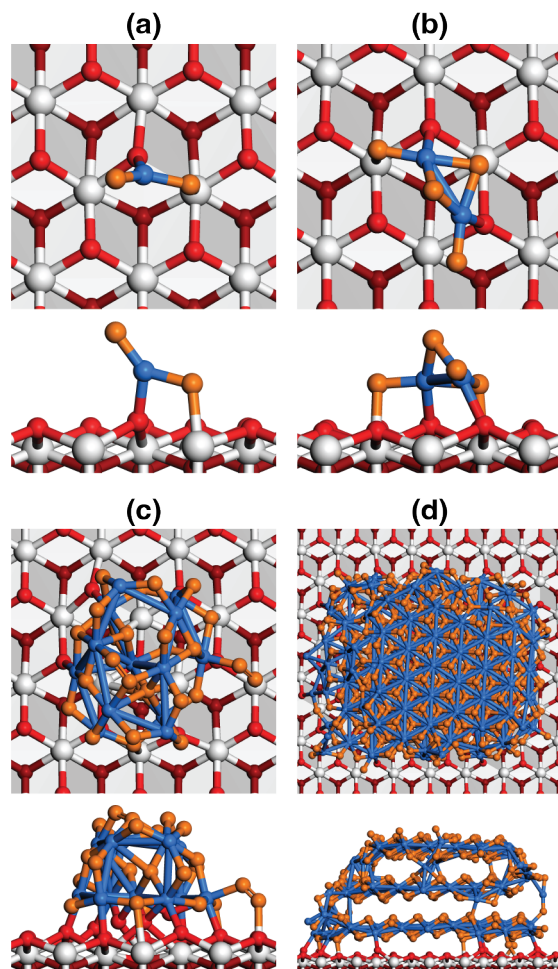


Figure 2: Top and side views of the optimized structures of oxidized Pt_xO_{2x} species supported on $CeO_2(111)$. (a) PtO_2 , (3×3) cell. (b) Pt_2O_4 , (4×4) cell. (c) $Pt_{13}O_{26}$ cluster, (6×6) cell. (d) $Pt_{147}O_{294}$ nanoparticle, (8×8) cell. Ce in gray, surface O in light red, subsurface O in dark red, excess O (with respect to the support's stoichiometry and defined as belonging to the Pt oxide) in orange, Pt in blue.

(2.03 Å) and two O–Ce bonds (Figure 2b). Table S3 summarizes all the structures generated by the genetic algorithm.

For Pt_{13}O_y clusters, three different competitive 13-atom starting geometries were considered, namely cuboctahedron ($\text{Pt}_{13}\text{cubo}$), Mackay icosahedron (Pt_{13}ico), and 13-atom truncated decahedron (Pt_{13}ino) (Figure S3a–c). The latter is the most stable in vacuum among the three, with $\text{Pt}_{13}\text{cubo}$ being less stable by 0.34 eV and Pt_{13}ico by 0.46 eV. These clusters were adsorbed on the $\text{CeO}_2(111)$ surface and covered with oxygen at two different oxygen contents: Pt_{13}O_7 and $\text{Pt}_{13}\text{O}_{13}$. Due to the large fluxionality at this cluster size, geometry optimization may result in structures very far from the global minimum, whereas sampling via genetic algorithms becomes too expensive at this supercell slab size. For this reason, a search for more competitive structures was done via the annealing of each of the three starting geometries, performing AIMD simulations with a time step of 5 fs and a velocity rescaling thermostat at 800 K to sample a variety of configurations for ~ 10 ps. The lowest potential energy structure of each trajectory was selected and quenched back to 0 K by geometry optimization (Table S4). The most stable structure for each stoichiometry was selected as the representative model. For the clean Pt_{13} cluster the AIMD simulation lead to a bilayer 8+5 cluster, as shown in Figure 1c, whereas oxide clusters adopt amorphous structures (Figure S4). A fourth stoichiometry $\text{Pt}_{13}\text{O}_{26}$ was obtained by extracting a 2-layer fragment from the bulk of hexagonal $\alpha\text{-PtO}_2$, adsorbing it on $\text{CeO}_2(111)$ and carrying out the same annealing procedure (Figure 2c).

Finally, to model the Pt nanoparticles of a size larger than 1 nm, the most stable high-symmetry isomer of Pt_{147} in gas-phase was selected, namely a strongly irregular truncated octahedron, with a diameter of ~ 1.5 nm (Figure S3d).⁹⁰ This nanoparticle exhibits a variety of (100)- and (111)-type facets offering diverse adsorption sites for oxygen atoms. Adsorption of oxygen on the nanoparticle was first examined by probing several adsorption sites for single atoms and 3-atom arrangements (see Table S5). From this we obtained general guidelines for the “decoration” of the nanoparticle with oxygen atoms, such as: (i) adsorption on the

edges is favorable over adsorption on the facets, (ii) edges between a (100) and a (111) facet are preferred, where O adsorbs twofold, followed by edges between two (111) facets, where O adsorbs on fcc sites near the edges and distributing between the two facets, (iii) on (111) facets, fcc sites are preferred, (iv) adsorption on subsurface sites is not favorable at low coverage. With this information, models with 33, 47, and 80 oxygen atoms were proposed (corresponding to coverages of 0.33–0.83, with coverage defined as the ratio between adsorbed O and surface Pt). Subsequently, AIMD simulations were run using a velocity rescaling thermostat at 800 K with a time step of 5 fs, to find better local minima by sampling variations on the adsorption sites due to coverage effects accessible within reasonably short MD trajectories (< 3 ps). The lowest potential energy structures were then selected and optimized.

The clean Pt_{147} and the O-covered $\text{Pt}_{147}\text{O}_y$ nanoparticles were adsorbed on $\text{CeO}_2(111)$ (Figures 1d and S5a–d), with their largest facet in contact with the support, to maximize the Pt-ceria interaction, forming 14 $\text{Pt-O}_{\text{surf}}$ bonds. Oxygen was removed from the adsorption facet, so the resulting systems are $\text{Pt}_{147}\text{O}_{32}$, $\text{Pt}_{147}\text{O}_{43}$ and $\text{Pt}_{147}\text{O}_{72}$ adsorbed on $\text{CeO}_2(111)$.

Attempts to obtain nanoparticles with a higher coverage by following the aforementioned protocol (adsorption of O atoms) resulted in the formation of O_2 molecules, indicating that 0.83 approaches the surface saturation coverage for this nanoparticle. Therefore, to consider a higher O/Pt ratio, platinum oxide nanoparticles were generated. $\text{Pt}_{147}\text{O}_{147}$ was modeled as a core-shell cluster, by removing the exposed outer shell of the Pt_{147} nanoparticle supported on $\text{CeO}_2(111)$, and replacing it with an equivalent shell (same number of Pt atoms) derived from the bulk of hexagonal $\alpha\text{-PtO}_2$ (Figure S5e). On the other hand, $\text{Pt}_{147}\text{O}_{294}$ was generated directly from the bulk, extracting a 3-layer fragment and adsorbing it on $\text{CeO}_2(111)$ as is (Figure 2d and S5f). Details are provided in Table S6.

Results and Discussion

To understand the effect of the oxidizing environment on the dispersion of Pt species supported on cerium oxide, we evaluate the Gibbs free energy of formation per Pt atom (ΔG_f) for all the different sizes considered, namely single atoms, dimers, Pt₁₃ clusters, and Pt₁₄₇ nanoparticles, by using ab initio atomistic thermodynamics and assuming equilibrium with a gas reservoir of fixed temperature and pressure. $\Delta G_f(T, P_{O_2})$ is calculated as follows:

$$x \text{ Pt} + \text{ CeO}_2 + \frac{y}{2} \text{ O}_2(\text{g}) \longrightarrow \text{ Pt}_x\text{O}_y/\text{ CeO}_2$$

$$\Delta G_f(T, P_{O_2}) = \frac{1}{x} (E_{\text{Pt}_x\text{O}_y/\text{ CeO}_2} - TS_{\text{conf}} - xE_{\text{Pt}} - E_{\text{CeO}_2} - \frac{y}{2}\mu_{\text{O}_2}(T, P_{O_2}))$$

Where $E_{\text{Pt}_x\text{O}_y/\text{ CeO}_2}$ is the total electronic energy of the supported Pt species provided by the DFT calculations, E_{Pt} and E_{CeO_2} are those of the isolated Pt single atom and the CeO₂(111) surface, and μ_{O_2} is the chemical potential of O₂, which is a function of temperature and partial pressure of O₂. Details on the calculation of this chemical potential can be found in the Supporting Information. Finally, S_{conf} is the configurational entropy, calculated as follows:⁹¹

$$S_{\text{conf}} = k_B \frac{n_{\text{sites}}!}{(n_{\text{sites}} - n_{\text{species}})! n_{\text{species}}!}$$

In this equation, for a given Pt_xO_y/CeO₂ system, $n_{\text{species}} = 147/x$ is the number of Pt species to distribute on the ceria surface, and $n_{\text{sites}} = n_{\text{species}}/0.1$ the number of free sites those species can occupy. 0.1 is an arbitrary coverage factor, to compare all systems at an equivalent low content of Pt. Under this approach, we account for the difference in the nature of the adsorption site at different particle sizes, simply by assuming that an adsorption site for a Pt_xO_y nanoparticle corresponds to x adsorption sites for a Pt₁O_y species. The configurational entropy reflects the number of ways in which the Pt species can be spatially arranged on the ceria surface. Although this contribution is typically disregarded in the calculation of adsorption free energies of reactants and products, when considering

a single adsorbed Pt species that splits into hundreds of individual species, the change in configurational entropy is significant, and hence it must be considered in the study of the dispersion process.^{92,93}

In the following subsections we use the free energy of formation as a stability descriptor, focusing first on investigating the gradual oxidation of Pt species adsorbed on CeO₂(111) at different sizes separately, and next comparing them with each other, at simulated conditions consistent with redispersion experiments, to evaluate the dispersion of large nanoparticles into smaller particles or single atoms.

Oxidation of platinum

ΔG_f can be calculated for a grid of temperatures and pressures to generate phase diagrams showing the thermodynamically stable content of oxygen at different conditions for each particle size (Figure 3).

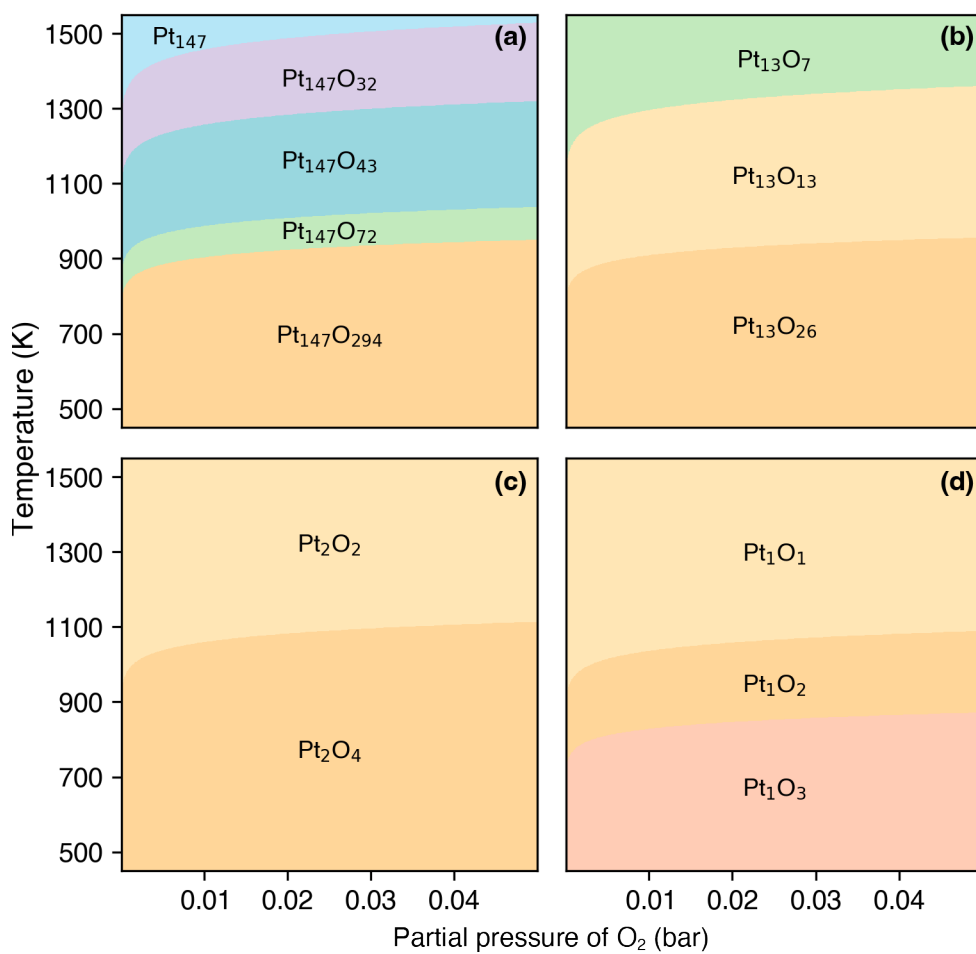


Figure 3: Thermodynamic phase diagrams of Pt/CeO₂(111) under oxidizing conditions. The evaluated temperature and O₂ partial pressure ranges are 450–1550 K and $1 \cdot 10^{-4}$ – $5 \cdot 10^{-2}$ bar, respectively. (a) Pt₁₄₇ nanoparticles, (b) Pt₁₃ clusters, (c) Pt₂ dimers and (d) Pt single atoms.

We observe that Pt_xO_{2x} -type oxide species remain the most stable structures even at low O_2 pressure up to ~ 900 K. Only at very high temperature the desorption of O_2 to the gas phase becomes favorable, stabilizing structures with lower oxygen content.

In the case of the Pt_{147} nanoparticle, all the spectrum from metallic Pt_{147} to $\text{Pt}_{147}\text{O}_{294}$ is observed within the temperature range evaluated, although very high temperatures are required to stabilize non-oxidized Pt_{147} particles. In addition, $\text{Pt}_{147}\text{O}_{147}$ does not appear in the diagram, indicating it is not the most stable state at any combination of temperature and pressure. This result could reflect that such a stoichiometry occurs only as a short-lived intermediate state in the transition from O-covered Pt to Pt oxide, but it could also be ascribed to the fact that the $\text{Pt}_{147}\text{O}_{147}$ species that we have evaluated is far from that stoichiometry's global minimum. Either way, we can conclude that at the Pt dispersion temperature ($500\text{ }^\circ\text{C} = 773.15\text{ K}$), highly oxidized nanoparticles are the most stable species.

In the case of smaller systems, the non-oxidized species do not appear in the diagram, and O/Pt ratios lower than 2 become harder to access. For instance, Pt_{13}O_7 , corresponding to an O/Pt ratio of about 0.5, is stable at high temperatures for Pt_{13} , but the equivalent Pt_2O_1 species is not stable in this temperature range. Similarly, for a pressure of 1.5 mbar, the transition from $\text{Pt}_{13}\text{O}_{26}$ to $\text{Pt}_{13}\text{O}_{13}$ takes place at 860 K, whereas for the equivalent transition from Pt_2O_4 to Pt_2O_2 a temperature of 1102 K is required. Overall, these thermodynamic phase diagrams suggest that small Pt species can only be present in oxidized form, regardless of temperature. This is consistent with experiments in the literature showing that reductive treatments result in an increase in particle size (sintering), rather than in the formation of reduced single atoms.^{26,72}

To understand why it is easier to oxidize Pt as the nanoparticle size decreases we calculate the 0 K oxidation energy, i.e. the energy released in the reaction $\text{Pt}_x + x \text{O}_2(\text{g}) \longrightarrow \text{Pt}_x\text{O}_{2x}$ (Figure 4). We find that this phenomenon can be associated almost exclusively with changes in the intrinsic stability of the Pt species, and is rather independent of the interaction with the ceria support. This can be inferred first from the comparison of the oxidation energy

of an isolated Pt species to PtO_2 , of $\Delta E_{\text{ox}} = -5.63$ eV, with the corresponding oxidation energy of bulk Pt to bulk $\alpha\text{-PtO}_2$, which is only $\Delta E_{\text{ox}} = -2.83$ eV per Pt atom. Although the stoichiometry is the same in both cases, significantly less energy is gained when oxidizing bulk Pt than when oxidizing isolated Pt atoms. This is most likely because of the varying coordination of Pt. An isolated Pt atom gains 2 Pt–O bonds ($d_{\text{Pt-O}} = 1.70$ Å) when oxidized to PtO_2 , and loses no bond. Instead, in bulk fcc Pt ($d_{\text{Pt-Pt}} = 2.78$ Å) each atom has a coordination number of 12, giving a formation energy from isolated Pt of -6.25 eV, whereas in oxidized bulk PtO_2 , each Pt atom has 6 oxygen atoms in its first sphere of coordination ($d_{\text{Pt-O}} = 2.03$ Å) and 5 Pt atoms further away in a second sphere ($d_{\text{Pt-Pt}} = 3.17$ Å), and the formation energy from isolated PtO_2 species is only -3.45 eV, thus making the oxidation of bulk Pt less exothermic.

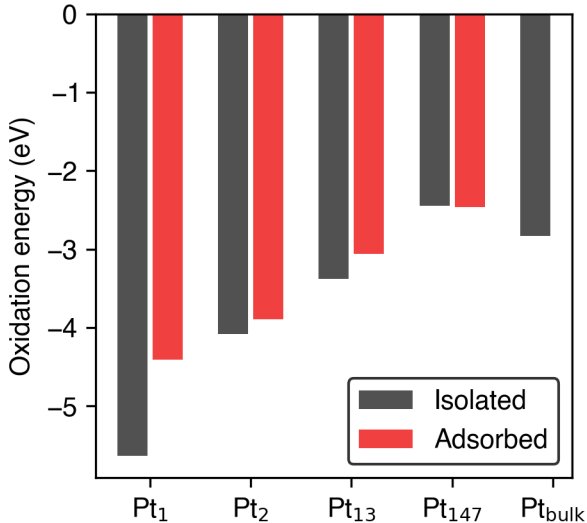


Figure 4: Energy involved in the oxidation of Pt_x species to the corresponding Pt_xO_{2x} species at 0 K.

Following the same trend, the oxidation of species in between PtO_2 molecules and bulk PtO_2 should fall in between, i.e. more favorable than the bulk but less than a single atom, and indeed we observe this behavior for the oxidation of isolated Pt_2 and Pt_{13} species to Pt_2O_4 and $\text{Pt}_{13}\text{O}_{26}$. In the case of Pt_{147} , the oxidation seems to be even less exothermic than that of the bulk, but we ascribe this result to the limitations in the generation of the

model, since global optimization is not computationally viable at this size. In other words, there should exist a more stable oxidized $\text{Pt}_{147}\text{O}_{294}$ nanoparticle than the one proposed in this work, in which case the oxidation of Pt_{147} would be more exothermic than that of the Pt bulk.

Regarding the effect of the support, we observe that its impact on the 0 K oxidation energy is more significant for single atoms (change of 1.22 eV) than for larger clusters (changes under 0.31 eV) (cf. red bars in Figure 4), and overall it does not change the trend previously described.

Having examined the oxidation of each particle size separately, in the following section we address the question of the competition between these different particle sizes under oxidizing conditions, to gain insight into the process of dispersion of Pt supported on ceria.

Dispersion of platinum

The stabilization of species of different sizes depends on a variety of factors, including the Pt–ceria interaction, the formation of Pt–Pt bonds, the oxygen content, and the configurational entropy at a given coverage. These properties rule whether or not Pt nanoparticles can be redispersed into single atoms reversing the sintering process.

To study the dispersion of Pt nanoparticles under oxidizing conditions, the collection of structures considered before are compared at fixed oxidative conditions of temperature and pressure, namely 500 °C and ambient pressure of O_2 (0.21 bar), as shown in Figure 5a.

The results indicate that single atoms are not accessible on the $\text{CeO}_2(111)$ surface under these conditions, since the difference in ΔG_f between any of the systems considered and $\text{Pt}_{147}/\text{CeO}_2$ is greater than zero (i.e. the points are above the dashed line in Figure 5a), except for the case of PtO_3 , for which it is slightly exergonic. The contribution of the configurational entropy, despite being relatively small, plays a role in this comparison, since its impact on the free energy of formation of single-atom systems (about 0.1 eV) is higher than on that of large nanoparticles. In fact, the inclusion of this contribution changes whether the

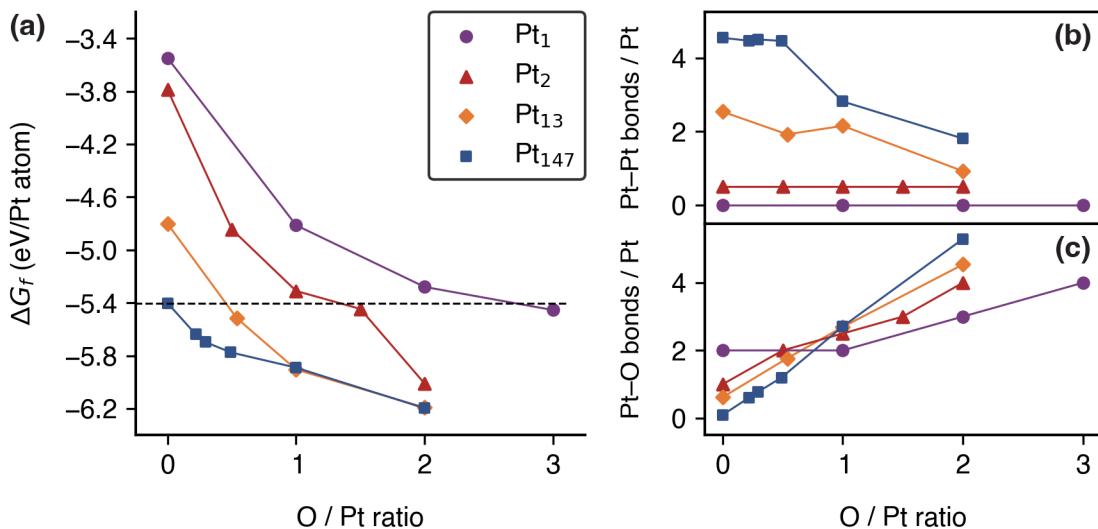


Figure 5: (a) Free energy of formation of the Pt/CeO₂(111) systems under oxidizing conditions ($T = 773.15$ K, $P_{O_2} = 0.21$ bar). The dashed line corresponds to the free energy of formation of clean Pt₁₄₇. Note that Pt₁₃O₂₆ and Pt₁₄₇O₂₉₄ are very close in energy (a difference of 0.02 eV/Pt atom), so they appear overlapped. (b) Number of Pt–Pt bonds per Pt atom. (c) Number of Pt–O bonds per Pt atom.

dispersion of Pt₁₄₇ into PtO₃ is predicted to be exergonic or not. Nevertheless, even when considering the configurational entropy, the formation of PtO₃ is still less favorable than a simple oxidation of Pt₁₄₇ into Pt₁₄₇O₂₉₄, which involves no Pt dispersion.

Therefore, these calculations suggests that the oxidizing treatment at 500 °C cannot disperse Pt particles into single atoms on the CeO₂(111) surface. Although the oxidative dispersion of Pt nanoparticles into single atoms has been observed experimentally at very high temperatures of 800 °C,²⁸ under those conditions the dispersion has been explained as the product of a reconstruction of the ceria support, which takes place due to the very high temperature and the interaction of ceria with Pt, and results in the formation of step edges and (100)-type sites where Pt single atoms adsorb more strongly.^{44,54} Such a surface reconstruction is not expected at 500 °C.

Furthermore, although oxidation has a more significant stabilizing effect on smaller Pt species compared to large nanoparticles, which reduces the gap in stability between them, overall the dispersion of the large nanoparticle into smaller clusters remains unfavorable with respect to a simple oxidation of the large nanoparticle with no dispersion. In the case

of Pt_{13} , upon oxidation to $\text{Pt}_{13}\text{O}_{26}$ its stability becomes comparable to that of $\text{Pt}_{147}\text{O}_{294}$, suggesting its formation could be competitive depending on kinetics, although in absolute terms $\text{Pt}_{147}\text{O}_{294}$ is still lower in energy (see Tables S4 and S6). Overall, for any given O/Pt ratio, the largest nanoparticle is always the most favorable structure among the ones evaluated.

This can be understood by looking at the evolution in the number of Pt–Pt and Pt–O bonds as a function of the O/Pt ratio, for each particle size considered (Figures 5b and c), normalized by the number of Pt atoms in the particle. In this analysis the label Pt–O comprises both the bonds to oxygen belonging to the ceria surface and additional oxygen incorporated upon oxidation. We observe that single atoms and dimers incorporate oxygen without cleavage of any Pt–Pt bond. However, a small number of Pt atoms also means the number of Pt–O bonds formed is limited, going from 2 in Pt to 4 in PtO_3 , and from 1 in Pt_2 to 4 in Pt_2O_4 . On the other hand, larger particles lose Pt–Pt bonds upon oxidation, which has a destabilizing effect, but this is compensated by a faster formation of Pt–O bonds (on average, 3 Pt–O bonds are formed per O atom added to the Pt_{147} nanoparticle), resulting in an increase from 0.1 in Pt_{147} to 5.3 in $\text{Pt}_{147}\text{O}_{294}$. Moreover, the Pt–O bond is stronger than the Pt–Pt bond (0.52 against 2.36 eV, in the respective Pt and PtO_2 bulks), and thus it has a stronger stabilizing effect. Hence, the formation of Pt–O bonds compensates the loss of Pt–Pt bonds making the larger nanoparticles the most stable systems at these operating conditions, regardless of the oxidation degree. The complete bond analysis is presented in Table S7.

In summary, the results presented here indicate that although dispersed PtO_y species are stabilized with respect to single Pt atoms under oxidizing conditions, larger nanoparticles remain the most stable Pt species on the $\text{CeO}_2(111)$ surface. In other words, oxidation is not sufficient to achieve the redispersion observed experimentally, suggesting that the trapping of single atoms must be promoted by different factors. The interaction with contaminants (OH^- , Cl^-) could strengthen the binding of single atoms or small clusters to the

support,^{55,94,95} promoting the dispersion. Alternatively, the dispersion of Pt might occur exclusively on very reactive facets like CeO₂(100) and surface defects such as step edges, which offer very strong adsorption sites for PtO_y species.^{28,68,96} Nanostructuring the support to maximize the availability of these types of sites could be a mean to achieve quantitatively significant dispersion of Pt and establish sintering-redispersion cycles for the regeneration of ceria-supported Pt catalysts.

Conclusions

We present a computational DFT study of the dispersion of Pt on the CeO₂(111) surface, evaluating various particle sizes ranging from clusters of about 1.5 nm of diameter to single atoms, and comparing them under the same theoretical framework. To generate representative models, we employ diverse methods, selected depending on the targeted size, corresponding complexity, and computational cost. In particular, we model four different systems: Pt₁, Pt₂, Pt₁₃, and Pt₁₄₇, at varying oxidation degrees. Single-atom models are obtained by comprehensive exploration of the surface adsorption sites. Pt₂ and Pt₁₃ require more sophisticated sampling methods like genetic algorithms and ab initio molecular dynamics. Finally, large supported Pt₁₄₇ nanoparticles are derived from chemical intuition and DFT calculations in vacuum, since sampling is out of reach at this size.

We find that Pt oxide species are prevalent and difficult to reduce at subnanometer particle sizes, for a wide range of temperatures and pressures. Metallic Pt species only become thermodynamically favorable for the case of larger particle sizes at high temperatures. With respect to the dispersion of Pt, Pt₁₄₇ particles remain more stable than smaller particles on the CeO₂(111) surface, regardless of the oxygen content, indicating that the dispersion of Pt is not favorable on this surface. To stabilize Pt single atoms a stronger metal-support interaction is required, suggesting that the dispersion observed experimentally must be promoted by contaminants stabilizing Pt single atoms, or occur on sites of ceria where the adsorption

of single atoms is more favorable, such as step edges or sites provided by more reactive surface terminations like $\text{CeO}_2(100)$.

In conclusion, this work provides insight into the relative stability of Pt on the most stable $\text{CeO}_2(111)$ surface across a wide range of particle sizes and oxidation degrees. Our findings suggest that stronger adsorption sites are required for Pt dispersion into single atoms. Potential sites satisfying these conditions include those of doped ceria, as well as sites on other low-index and high-index facets in nanostructured ceria, which will be studied in future works.

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Supporting Information Available

Details on the calculation of the chemical potential of O_2 . Structures and details of the ceria-supported Pt_xO_y systems generated (Figure S1, S2, S4, and S5, Tables S1–S6). Structure of the gas-phase Pt_{13} and Pt_{147} clusters used as a starting point for the generation of ceria-supported Pt_{13}O_y and $\text{Pt}_{147}\text{O}_y$ species (Figure S3). Bond analysis (Table S7).

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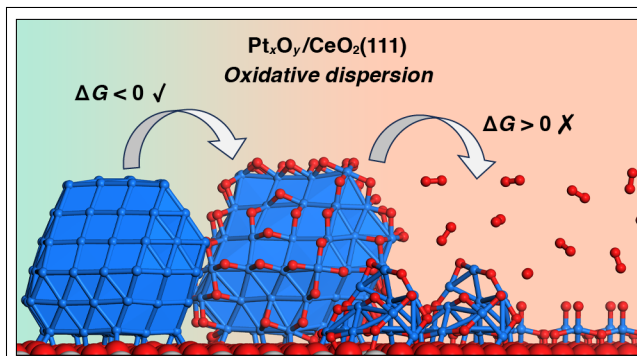
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