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A DFT study of molecular adsorption on titania-supported AuRh nanoalloys

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A B S T R A C T

AuRh/TiO2 nanocatalysts have proved their efficiency in several catalytic reactions. In this work, density functional theory calculations are performed to investigate the effect of the TiO2 support on the structures of fcc 38-atom and 79-atom AuRh nanoalloys and their adsorption properties towards the reactants CO and O2. d-band centre analysis shows that the d-band model captures the trends better for both larger and supported alloy clusters due to reduced mechanical effects. Calculations reveal metal-to-support electron transfer, depending mainly on which metal atoms lie at the interface with the support. The adsorption strengths of CO and O2 molecules on experimentally-relevant Janus segregated structures are slightly lower than on pure Rh clusters, which may reduce poisoning effects, while maintaining the high reactivity of Rh. In addition, higher adsorption energies are predicted for the less stable AucoreRhshell structure, which may lead to adsorption-induced restructuring under reaction conditions.

1. Introduction

Nanosized clusters have drawn the attention of many researchers due to their catalytic and other properties which are often different from their bulk counterparts. Nanoclusters are ideal catalysts since they possess a higher proportion of less-coordinated active sites in addition to their high surface/volume ratio. One well known example is ultra-fine gold nanoparticles, for which Haruta et al. [1] showed exceptional catalytic properties toward CO oxidation although gold is catalytically inert in the bulk [2].

Catalytic properties of metals can be improved by alloying different metals, due to synergistic effects, and nanoalloying allows catalytic properties to be tuned by varying composition and chemical ordering [3]. Furthermore, alloying an expensive but efficient catalyst (e.g. rhodium) with another, cheaper metal opens the possibility to reduce the cost of the catalyst without losing efficiency, or even sometimes improving it.

Among metal nanoalloys, the AuRh system has been scarcely studied [4–14] since the metals are immiscible in the bulk [15]. However, AuRh catalysts have been recently shown to be efficient in catalysing several reactions. For example, with respect to its monometallic counterparts, AuRh/TiO2 showed increased catalytic stability in tetralin hydrogenation in the presence of H2S [6], and improved selectivity for guaiacol hydrodeoxygenation [8].

The catalytic properties of multimetallic nanoalloys depend both on the chemical ordering and structures of the nanoparticles, which may vary with the molecular environment and the presence of a support. It is well known in the literature that the binding of ligands can change the chemical ordering and/or the structure of nanoparticles, thin films, and bulk surfaces [16–23]. For example, Tao et al. reported reversible core-shell inversion for Rh-Pd nanoparticles by controlling the molecular environment and suggested the design of “smart catalysts” that may catalyse different reactions depending on the gaseous environment [17,18]. Recently, our previous study of free Au-Rh nanoalloys also predicted, computationally, that the chemical ordering of Au-Rh nanoclusters can be changed due to CO or O2 molecular environment [24]. Structure [25–27] and/or chemical ordering [7,28,29] of the nanoparticles also depends on the nature of the support. For the Au-Rh system, we have shown that the Janus-type phase-segregated nanoalloy structures become energetically competitive with the gas-phase core-shell structures when supported on TiO2, and can be formed depending on the applied thermal post-treatment [6–8]. In practical heterogeneous catalysis applications, nanoalloys are usually deposited or grown on supports. Understanding support effects on the catalyst structure and the cluster-adsorbate interaction is...
important, since the catalytic performance depends on both factors.

Adsorption of reactants is a key step in catalytic reactions, and can serve as a descriptor of the overall reactivity. According to Sabatier’s principle, if reactive species are adsorbed too weakly, they may not be activated to undergo reaction, whereas if they are adsorbed too strongly, the desorption rate decreases and poisoning may occur. The d-band model [2,30] has been shown to be particularly useful in understanding metal-adsorbate interactions, especially for extended metal surfaces. In this model, the d-band energy centre of the metal surface or particle is used as a descriptor to predict the metal-adsorbate interaction strength.

In this work, we have studied the effect of the TiO$_2$ support on both the structures and reactivities of AuRh nanoalloys, focussing on the adsorption of CO and O$_2$ on AuRh clusters anchored on a rutile TiO$_2$(110) surface, to model the titania nanorods used in experimental studies. In the following section, details are presented of our computational model. In the third section, the effect of the TiO$_2$ support on the chemical ordering of Au-Rh nanoalloys is presented. In the fourth and fifth sections, results are presented for CO and O$_2$ adsorption on AuRh/TiO$_2$, respectively, and a comparison is made to previous results obtained for free clusters. In the last section, adsorption properties are discussed within the framework of the d-band model.

2. Methodology

38-atom and 79-atom fcc-packed truncated octahedra (TO) were chosen as models for the bimetallic nanoparticles due to the high symmetry of the parent TO structure (Oh). Different compositions and alloying morphologies were covered by constructing several nanoalloy models within TO structures including mixed (ordered alloy), core-shell, Janus, and ball-cup [7] particles. For supported TO$_{38}$ clusters, the surface-decorated “hex” structure (h-Au$_{32}$Rh$_6$) [20] is also considered for comparison purposes.

Although 38- and 79-atom TO structures are smaller than the experimental particles (ca. 3 nm) [6–8], previous results showed that the mixing properties and energetics of Au-Rh nanoalloys scale well up to at least the 260-atom TO (~2 nm) [24], which is closer to the size range of the experimental particles.

The 38-atom Au, Rh and Au-Rh TO clusters are initially placed in three different orientations on the TiO$_2$(110) surface, as shown in Fig. 1. For TO$_{79}$ clusters, only position-1 was considered because it was found to maximise the cluster-surface interaction. Adsorption studies on both free and TiO$_2$(111)-supported nanoalloy clusters were carried out for CO and O$_2$ molecules. The adsorbates are placed on the TiO$_2$(111)-supported nanoalloy clusters according to the previous results obtained for free clusters, for all possible adsorption sites and coordination modes [24]. On supported clusters, adsorbates are placed both at positions close to and far from the cluster-substrate interface, in order to evaluate the effect of the substrate.

All density functional theory (DFT) calculations were performed with the Vienna ab initio Simulation Package (VASP) [31–34]. The generalized gradient approximation (GGA) Perdew-Burke-Ernzerhof (PBE) [35] exchange-correlation functional was adopted. The valance electron density was expanded in a plane wave basis set with a plane wave cut-off energy of 400 eV. The interaction between valence electrons and ionic cores was described by the projector augmented wave (PAW) method [36,37]. Methfessel-Paxton smearing, with a $\sigma$ value of 0.01 eV, was implemented to improve convergence of metallic systems [38]. Spin polarization was included in all DFT calculations.

A sufficiently large unit cell was used to avoid interactions between periodic images of both free and supported metal clusters: resulting in a $3 \times 6$ TiO$_2$ supercell with lateral dimensions of $a = 17.74$ Å and $b = 19.55$ Å for both TO$_{38}$ and TO$_{79}$. For supported cluster calculations, a nine-atomic layer TiO$_2$ slab was used to model the TiO$_2$(110) substrate. The bottom three atomic layers of the slab were frozen during DFT optimizations to model bulk atoms. A vacuum spacing of over 10 Å vacuum was introduced for the supported cluster calculations to eliminate spurious cluster-surface interactions with the underneath of the surface slab. Only one k-point ($\Gamma$) was used to sample the Brillouin zone due to the large size of the unit cell. Apart from the bottom three atomic layers of the TiO$_2$ slab, all other atom positions were optimized until all the forces on the atoms were lower than 0.01 eV/Å. Electronic ground states were determined after reaching a total energy convergence of $10^{-6}$ eV.

A mixing (or excess) energy term ($\Delta$) was calculated to enable comparison of the energetics of nanoalloys with different compositions:

$$\Delta = E_{tot}(A_m B_n) - m \frac{E_{tot}(A_{m+n})}{m+n} - n \frac{E_{tot}(B_{m+n})}{m+n}$$

(1)

where the total energy ($E_{tot}$) of the nanoalloy $A_m B_n$ is compared to the pure metal clusters of $A$ and $B$ of the same size ($m + n$). Hence, a negative value of $\Delta$ means an energy decrease upon mixing and therefore favourable mixing, whereas positive values indicate a demixing tendency. To determine the effect of the support and adsorbed molecules on nanoalloy energetics, $\Delta'$ was defined in the same manner as $\Delta$ by replacing the $E_{tot}$ values with the total energy of the corresponding supported and/or molecule-adsorbed (nanoalloy and pure metal) clusters. The adsorption energy ($E_{ads}$) values

![Fig. 1. Initial cluster-surface configurations for TO$_{38}$ on TiO$_2$(110). Example is given for a Au cluster.](image-url)
were calculated as the differences in energy between the combined and separated systems.

3. Results

3.1. Supported Au-Rh cluster structure

Fig. 2 summarises the adsorption energies of the nanoalloy clusters for the three considered cluster binding positions (orientations). For TO$_{38}$, while the pure Au cluster prefers position–3 ($E_{\text{ads}} = -5.88$ eV), the pure Rh cluster prefers position–1 ($E_{\text{ads}} = -8.98$ eV). The cluster-surface binding strength is higher for Rh than for Au for all positions. The Au cluster shows distortion from its initial TO structure while the Rh cluster preserves its structure and adapts to the surface via rotation in positions 2 and 3. For the Janus cluster, the binding strength is very similar to that of the pure Rh cluster if it is bonded to the TiO$_2$ surface via the Rh, while position–1 is the preferred position as for pure Rh ($E_{\text{ads}} = -8.93$ eV) since this configuration maximises Rh-O interactions. However, if the Janus cluster is attached to the surface via Au, the binding strength decreases (by 2.54 eV for the best configuration) relative to the pure Au case, due to both electronic (less charge transfer than pure Au) and mechanical (Rh layers do not permit Au atoms to reconstruct sufficiently on the support) effects. Similarly, the binding strength for the Rh$_{\text{core}}$Au$_{\text{shell}}$ particle ($-2.89$ eV) is smaller than for the pure Au and Janus particles ($-5.88$ eV and $-3.35$ eV, respectively), since the core-shell structure restricts Au structural relaxation more than in the Janus particle although the extent of charge transfer is the same for the Janus structure.

Since the interaction with the TiO$_2$ surface is higher for Rh than Au, position–3 is the preferred position for the h-Au$_{32}$Rh$_6$ structure, where all the Rh atoms can interact with the TiO$_2$ surface. However, the binding strength is lower than for the pure Rh cluster due to the weaker Au-surface interaction energy.

The cluster-surface interaction energies for the Au$_{\text{core}}$Rh$_{\text{shell}}$ configuration are similar to those for the pure Rh cluster. Although it has almost the same value for position–1, it is increased for positions 2 and 3. For position–2, while pure Rh adapts to the support by rotation, the larger Au core expands the structure so that the Rh atoms on the bottom (100) facet are closer to the titania surface in the Au$_{\text{core}}$Rh$_{\text{shell}}$ configuration.

In principle, the total energy values give a direct comparison of stabilities of same composition clusters. However, as we cannot directly compare the total energies of different supported clusters with different compositions, such as Janus and Rh$_{\text{core}}$Au$_{\text{shell}}$, we have used a supported mixing energy term ($\Delta'$) to compare the stabilities, as shown in Fig. 3. Note that, by definition, the mixing energy differences of clusters with the same composition are equal to their total energy differences. When we compare the mixing energies of homotops with the same composition (supported h-Au$_{32}$Rh$_6$ and Rh$_{\text{core}}$Au$_{\text{shell}}$) the energy difference decreases to 3.0 eV for position–1 and position–2 and 1.7 eV for position–3, from the value of 5.28 eV for unsupported clusters, due to the excess adsorption energy. The energy difference is smallest for position–3, where the h-Au$_{32}$Rh$_6$ cluster benefits from all 6 Rh atoms being bonded to the TiO$_2$ support. According to Fig. 3, the Rh$_{\text{core}}$Au$_{\text{shell}}$ configuration is destabilised for all positions (more positive values than unsupported cluster), whereas h-Au$_{32}$Rh$_6$ maintains a similar stability for positions 1 and 2, but is stabilised in position–3. The Janus particle is stabilised relative to the other mixed clusters in all positions if it is bonded to the support via Rh atoms, while it is destabilised for all positions when bonded via Au atoms. For positions 1 and 3 the $\Delta'$ values also change sign and become negative for the Janus particle and for position–3 the energy difference with the Rh$_{\text{core}}$Au$_{\text{shell}}$ decreases to 0.12 eV from the value of 5.39 eV for the unsupported clusters. The Au$_{\text{core}}$Rh$_{\text{shell}}$ particle is also stabilised by bonding to the support, however the supported mixing energy value is still highly positive due to the unfavourable “inverse” core-shell configuration.

When we move to the larger TO$_{79}$ clusters on the TiO$_2$ support, the binding properties remain similar. The detailed results for supported TO$_{79}$ clusters have been reported elsewhere [24].

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Fig. 2. Binding positions (orientations) and adsorption energies of Au, Rh, and Au-Rh TO$_{38}$ nanoalloys on TiO$_2$ (110) support. Blue, yellow, cyan and red spheres represent Rh, Au, Ti and O atoms, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
TO₃₈, the metal-support binding is found to be stronger for Rh than for Au in the case of TO₇₉.

In summary, the binding strength for nanoalloy clusters is governed by the type of atoms in contact with the TiO₂ surface. The Janus and ball-cup clusters, whose Rh atoms bind to the TiO₂ surface, become more stable on the support, whereas the initially stable RhcoreAushell cluster is destabilised.

3.1.1. Electronic analysis

Bader charge analysis [39] reveals Rh-to-Au electron transfer for free alloy clusters, as expected since Rh is more electropositive than Au (see Table 1). For RhcoreAushell and Janus clusters the transferred charge is almost the same (~1.3 e) in the case of small clusters (TO₃₈), while for larger clusters (TO₇₉) the charge transfer increases as the core proportion of Rh increases. Charge transfer is significantly lower from shell Rh to core Au in the AucoreRhshell clusters, which is consistent with the fact that in homometallic Rh clusters the surface sites actually tend to be negatively charged relative to the core. When supported, we observe metal to support charge transfer for both pure and alloy clusters. The metal-to-support charge transfer is generally greater for larger particles, with the exception of Au₃₈. This is probably because the TO structure of Au₃₈ is highly reconstructed on TiO₂, while for alloy clusters the presence of the Rh atoms reduces Au atom relaxation. Metal to

Table 1
Total charges on Au atoms and on Rh atoms together with d-band centre values of all Au and all Rh atoms for all free and supported clusters. Charges on the TiO₂ support are also included for the TO₃₈/TiO₂ systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Charge (TiO₂)</th>
<th>Charge (Au)</th>
<th>Charge (Rh)</th>
<th>d-centre (Au)</th>
<th>d-centre (Rh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO₃₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>–</td>
<td>0.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>RhcoreAushell</td>
<td>–</td>
<td>-1.35</td>
<td>1.35</td>
<td>-2.78</td>
<td>-1.32</td>
</tr>
<tr>
<td>Janus</td>
<td>–</td>
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<td>1.31</td>
<td>-2.87</td>
<td>-1.58</td>
</tr>
<tr>
<td>AucoreRhshell</td>
<td>–</td>
<td>-0.35</td>
<td>0.35</td>
<td>-4.16</td>
<td>-1.47</td>
</tr>
<tr>
<td>Rh</td>
<td>–</td>
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<td>0.00</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>2.22</td>
<td>–</td>
<td>-3.43</td>
<td>–</td>
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<tr>
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<td>1.40</td>
<td>-2.95</td>
<td>-1.62</td>
</tr>
<tr>
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<td>1.44</td>
<td>-3.09</td>
<td>-1.81</td>
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<tr>
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<tr>
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<td>-4.21</td>
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<tr>
<td>Rh</td>
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<td>-1.87</td>
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<tr>
<td>TO₇₉/TiO₂</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>0.00</td>
<td>–</td>
<td>-2.94</td>
<td>–</td>
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<tr>
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<td>2.15</td>
<td>-3.01</td>
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<td>–</td>
<td>0.00</td>
<td>–</td>
<td>-1.83</td>
</tr>
<tr>
<td>TO₇₉/TiO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1.90</td>
<td>–</td>
<td>-3.10</td>
<td>–</td>
</tr>
<tr>
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<td>3.23</td>
<td>-3.11</td>
<td>-1.73</td>
</tr>
<tr>
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<td>-0.13</td>
<td>2.10</td>
<td>-3.14</td>
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</tr>
<tr>
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<td>1.83</td>
<td>-3.15</td>
<td>-1.75</td>
</tr>
<tr>
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<td>-3.15</td>
<td>-1.84</td>
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<td>4.71</td>
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</tr>
<tr>
<td>Rh</td>
<td>-3.31</td>
<td>–</td>
<td>3.31</td>
<td>–</td>
<td>-1.94</td>
</tr>
</tbody>
</table>

Fig. 3. Supported mixing energy (Δ) values versus Rh proportion for TO₃₈/TiO₂ at three binding positions, compared to unsupported TO₃₈.
support charge transfer is also found to be greater when Rh is in contact with the TiO$_2$ support.

DOS analysis shows an upward shift of the Rh d-band centre for alloy clusters for both sizes (see Table 1). For TO$_{38}$, the Rh d-band centre shift is highest for Rh$_{core}$Au$_{shell}$ and lowest for the Janus particle, both for supported and free clusters. However, for the larger TO$_{79}$, clusters the Rh d-centre shift is greatest for Au$_{core}$Rh$_{shell}$, while Rh$_{core}$Au$_{shell}$ and Janus particles behave similarly. The Au d-band centre shows a slight downward shift upon alloying, with the exception of Rh$_{core}$Au$_{shell}$ and Janus particles for smaller TO$_{38}$.

For Rh$_{core}$Au$_{shell}$ and Janus configurations of TO$_{38}$, the d-band centre shifts upwards significantly relative to pure Au. On the TiO$_2$ support, all the d-band centres showed a downward shift by 0.01–0.20 eV compared to the unsupported counterparts. However, this shift is not just due to the lower occupation of the d-band since the d-band centres are integrated over all d-states, including unoccupied ones.

3.2. Molecular adsorption on supported Au-Rh nanoalloys

Position-1 binding of the clusters has been chosen for the molecular adsorption studies because it maximises the nanocluster-support interaction, especially for the more favourable Rh-support-contact case. CO and O$_2$ molecules are placed systematically on convenient sites according to their adsorption properties on free Au-Rh nanoalloys [24]. For both TO$_{38}$ and TO$_{79}$, CO molecules were initially placed at bridge positions on the edges of the metal particles in a $\mu_2\eta^1$ type binding fashion, one being close to the support and the other far from it. Here the symbol $\mu$ stands for the number of metal atoms to which the adsorbate binds and the symbol $\eta$ stands for the number of atoms in the adsorbate which are bonded to the metal. O$_2$ molecules are also placed on edges of metal particles though with $\mu_2\eta^2$ type binding since both O atoms tend to bind metal atoms. For O$_2$ molecules interfacial sites, where the O$_2$ molecule bridges a cluster metal atom and a surface Ti atom, were also included.

3.2.1. CO adsorption on supported TO$_{38}$

Fig. 4 shows the structures and adsorption energies of CO molecules adsorbed on $\mu_2\eta^1$ bridge sites on TiO$_2$-supported TO$_{38}$ nanoalloy clusters, both for positions close to and far from the cluster-support interface. As for the unsupported clusters [24], the CO adsorption energies for the supported alloy clusters are significantly higher when the CO molecule is adsorbed on Rh atoms than on Au atoms. For supported Au$_{38}$, the CO adsorption strength decreases by $\sim$0.5 eV on the TiO$_2$ support relative to the unsupported cluster for both adsorption sites considered. CO adsorption close to the support is 0.14 eV more stable than far from the support. On the contrary, for pure Rh, CO adsorbed far from the support is 0.05 eV more stable than close to the support. For supported Rh$_{38}$, the CO adsorption strengths are increased by 0.03 eV and 0.05 eV for adsorption sites far from and close to the support, respectively, relative to their unsupported counterparts.

For Rh$_{core}$Au$_{shell}$, which is the most stable isomer for the free Rh-Au clusters, the CO adsorption strength increases relative to the unsupported case by 0.16 eV for CO close to the support and 0.19 eV for CO adsorbed far from the support. It has been shown that for free clusters, the CO adsorption strength decreases for Rh$_{core}$Au$_{shell}$ relative to the pure Au cluster [24]. However, with the inclusion of the support, the adsorption strengths become similar due to the reverse effect of the TiO$_2$ support on pure Au and Rh$_{core}$Au$_{shell}$ Clusters. In contrast, for the Au$_{core}$Rh$_{shell}$ cluster, which is the least stable isomer in free space, the CO adsorption energies for close to the support and far from the support show opposite trends as compared to adsorption on free clusters. The adsorption strength increases slightly (by 0.02 eV) for the position far from the support, as in pure Rh$_{38}$, while it decreases for the position close to the support by 0.20 eV, contrary to pure Rh$_{38}$.

For the Janus particle attached to the support through Au (Janus-Au), which is relatively unstable, the CO adsorption strength on the Au side increases by 0.16 eV relative to the free cluster, similar to the Rh$_{core}$Au$_{shell}$ case. When the CO molecule is adsorbed on the Rh side, however, the adsorption strengths decrease for sites both far and close to the support, unlike for the pure Rh case. For the Janus particle attached to the support through Rh side (Janus-Rh), which is stabilised due to the support, the CO adsorption strength on the Au side decreases when it is far from the support (similar to pure Au$_{38}$) while it increases slightly for CO adsorbed close to the support (similar to Rh$_{core}$Au$_{shell}$). When the CO molecule is adsorbed on the Rh side, the adsorption strength decreases by 0.20 eV relative to the unsupported cluster, unlike for pure Rh$_{38}$.

3.2.2. CO adsorption on supported TO$_{79}$

For larger particles, the effect of the support on CO adsorption is found to be more straightforward than for TO$_{38}$ because mechanical effects such as strain and relaxation are reduced. Fig. 5 shows the structures and adsorption energies of CO molecules adsorbed on TiO$_2$-supported TO$_{79}$ nanoalloy clusters both for sites close to and far from the cluster-support interface. For Rh$_{core}$Au$_{shell}$ and Rh$_{shell}$Au$_{cup}$, in which the core Rh atoms make the cluster structure more rigid, the CO adsorption strength on the Au side is almost
unchanged. The maximum change (0.03 eV) with respect to free clusters is found for Rh$_{ball}$Au$_{cup}$ when it interacts with the support via Au atoms, which allows larger distortions at the interface. Similarly, on the Janus particle, the adsorption strength significantly increases (by 0.19 eV) when the Au layers are at the interface with the TiO$_2$ support. For pure gold, the adsorption strength is reduced on supported clusters, and “close” adsorption sites are preferred over “far” ones. The change in the adsorption strength is greater for far positions, where there is more structural distortion of the Au particle. The strongest adsorption for CO molecules on Au atoms is found for the Janus-Au case, which is relatively unstable, both for supported and free clusters. When we compare the stable supported clusters, CO adsorption is weaker on the Au sides of alloy clusters than on pure Au.
CO adsorption on the Rh sides of nanoalloys is much stronger than on the Au sides, as expected. Due to the effect of the support, the CO adsorption strength is reduced (by \(\sim 0.05\) eV), except for Janus and Rh\(_{\text{ballAucup}}\) clusters when they are linked to the support via Au atoms. The adsorption strength is a maximum for the Au\(_{\text{core}}\)-Rh\(_{\text{shell}}\) cluster, which is the least stable configuration both for free and supported clusters. For the Janus and Rh\(_{\text{ballAucup}}\) clusters, which are stable on TiO\(_2\) via Rh contact, the CO adsorption strengths are found to be the same (1.95 eV) and slightly lower (0.05 eV) than for pure Rh\(_{79}\), respectively.

3.2.3. \(\text{O}_2\) adsorption on \(\text{TO}_{38}\)

Fig. 6 shows the structures and adsorption energies of \(\text{O}_2\) molecules adsorbed on \(\mu_2\text{\(\eta_2\)}\) bridge sites on TiO\(_2\)-supported TO\(_{38}\) nanoalloy clusters for close, far and interfacial positions. On pure Au, the adsorption strength of \(\text{O}_2\) drops significantly compared to free clusters. However, on Rh\(_{\text{coreAushell}}\) the \(\text{O}_2\) adsorption strength is still lower than on pure Au\(_{38}\), although it is increased slightly (by 0.05 eV) relative to the unsupported cluster when close to the support. \(\text{O}_2\) adsorption on Au side of the Janus cluster is stronger than on pure Au\(_{38}\), unlike for free clusters. For Janus particles, the \(\text{O}_2\) adsorption strength on the Au side increases when the metal cluster has Rh in contact with the support, while it decreases for Au contact, as for CO adsorption.

On the Rh side of supported 38-atom alloy clusters, \(\text{O}_2\) adsorption strength increases relative to the unsupported counterparts, except for the Janus particle when it is attached to the support through Au side. For this Janus configuration, the adsorption strength is 0.12 eV lower than for pure Rh, although it was 0.13 eV higher for free clusters. However, when the Janus particle is attached to the support via Rh atoms, the \(\text{O}_2\) molecule spontaneously dissociates on neighbouring Rh atoms. For the unstable Au\(_{\text{core}}\)-Rh\(_{\text{shell}}\) the adsorption is found stronger than pure Rh.

When \(\text{O}_2\) molecule is adsorbed on interfacial sites of 38-atom metal clusters supported on titania, the adsorption strength increases significantly when Au sides of the particles are involved, with the pure Au one having the highest adsorption strength. However, although being approximately 1 eV stronger than on Au sides, peripheral positions on Rh sides of metal clusters are less favourable than \(\text{O}_2\) molecules binding to two neighbouring Rh atoms.

3.2.4. \(\text{O}_2\) adsorption on supported \(\text{TO}_{79}\)

When particle size increases, the effect of the support is lower for \(\text{O}_2\) adsorption on 79-atom nanoalloy clusters (see Fig. 7). Only pure Au and Rh\(_{\text{coreAushell}}\) structures show more than 0.05 eV differences from free clusters. Adsorption energies on Au sides are very small (between \(-0.10\) eV and \(-0.25\) eV) when the \(\text{O}_2\) molecule is bonded to two neighbouring Au atoms, while Rh\(_{\text{coreAushell}}\) has the highest adsorption strength. Adsorption strength increases when \(\text{O}_2\) binds one Au atom and one surface Ti atom. For this configuration, pure Au and Rh\(_{\text{coreAushell}}\) lead to the strongest and weakest adsorption, respectively. The Janus and Rh\(_{\text{ballAucup}}\) structures behave similarly in adsorption of \(\text{O}_2\) on both their Au and Rh sides. For Rh\(_{\text{ballAucup}}\), since the considered adsorption site close to the support does not allow both O atoms to bond to adjacent Rh atoms on the cluster surface, one O atom binds to an Au atom. Thus, the adsorption energy (\(-1.09\) eV) is lower than on Rh, while it is similar to that of an \(\text{O}_2\) molecule bridging a Ti atom and an Au atom (\(-1.10\) to \(-1.34\) eV). For larger particles (TO\(_{79}\)), the \(\text{O}_2\) adsorption strength is maximal for Au\(_{\text{core}}\)-Rh\(_{\text{shell}}\) clusters, both for free and supported clusters, as in the CO case. Similarly, \(\text{O}_2\) adsorption is weaker on phase-segregated Janus and Rh\(_{\text{ballAucup}}\) structures for free and supported clusters.

3.2.5. d-band centre analysis

Surface d-bands of metal alloys are affected by both ligand [40,41] and strain [42,43] effects. It is difficult to separate these two effects for extended surfaces [44], but it is possible for finite clusters [24]. However for the latter, one should be careful since low-coordinated sites [45] complicate the picture relative to extended surfaces, in addition to more prominent relaxation [46,47] and reconstruction [21,48,49] effects, which may be induced by adsorbates.

According to the d-band model [30], an upshift in the d-band centre should correlate with higher adsorption strength. However, our previous results on molecular adsorption on free 38-atom AuRh clusters showed strong deviations from the d-band model, mainly because of mechanical effects such as strain and relaxation effects [24]. Higher deviations are observed for the adsorption of
CO and O₂ on the Au side of clusters, because of the greater structural flexibility of Au atoms than Rh atoms, which enhances mechanical effects. In addition, there is a repulsive contribution between the valence electrons of the adsorbates and the filled Au d-band [50], which is increased due to Rh to Au charge transfer.

Fig. 8 shows plots of adsorption energies versus d-band centres on free and supported TO₃₈ and TO₇₉ clusters. For TO₃₈ clusters, the deviations are larger for free clusters (R² values are 0.78 for CO and 0.79 for O₂) than on the support (R² values are 0.91 for CO and 0.93 for O₂). This is possibly because alloying-induced cluster strain effects are generally reduced when the clusters are pinned on the support. For example, the average Au-Au distance increases for TO₃₈ clusters on the support by 0.03–0.05 Å when they bound to the support through Au atoms. Mechanical effects are also reduced on increasing the cluster size so that the d-band model is more relevant for the larger TO₇₉ clusters. When we compare the free and supported clusters, there is a 0.10 eV downward shift on average of the d-band centre values. Thus, the adsorption strength of CO and O₂ molecules on supported clusters is generally slightly reduced compared to their free counterparts.
4. Conclusions

The effect of the TiO₂ support on both the structures of AuRh nanoalloys and their adsorption properties towards CO and O₂ have been investigated using first-principles DFT calculations. In agreement with experiments, on the TiO₂ support phase-segregated Janus-type structures are found to compete with the more stable free RhcoreAushell structures. Bader charge analysis shows that there is metal-to-support electron transfer, which is higher when the more electropositive Rh atoms are located at the interface with the titania support. As for the free clusters, the adsorption strengths of reactant molecules such as O₂ and CO are greater on the Rh part than on the Au part of the supported nanoalloy clusters. The adsorption properties of smaller clusters are more diverse for free clusters because the mechanical effects reduce with the increasing size. With the presence of the support, however, mechanical effects also decrease for small clusters and it reduces the scattering in the d-band model. A downward shift of the d-band, which is accompanied by a slight reduction in CO and O₂ adsorption strengths, is observed for the supported AuRh nanoalloys compared to their free cluster counterparts.

Concerning the experimentally more relevant Janus-type structures, having Rh atoms at the interface with the TiO₂ surface, adsorption strengths on the Rh side of the cluster were found to be slightly lower than for pure Rh clusters. This may modify the catalytic properties, e.g. reduce poisoning, while still preserving the high reactivity of pure Rh. Although the AucoreRhshell structure is highly unstable for free clusters, its relative instability is reduced in the presence of the support, and it may be stabilised further by tuning the molecular environment [24].

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