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Contrasting the EXAFS obtained under air and H₂ environments to reveal details of the surface structure of Pt-Sn nanoparticles

Haoliang Huang, Abu Bakr Ahmed Amine Nassr, Verónica Celorrio, Diego Gianolio, Christopher Hardacre, Dan J. L. Brett and Andrea E. Russell

Understanding the surface structure of bimetallic nanoparticles is crucial for heterogeneous catalysis. Although surface contraction has been established in monometallic systems, less is known for bimetallic systems, especially of nanoparticles. In this work, the bond length contraction on the surface of bimetallic nanoparticles is revealed by XAS in H₂ at room temperature on dealloyed Pt-Sn nanoparticles, where most Sn atoms were oxidized and segregated to the surface when measured in air. The average Sn-Pt bond length is found to be ~0.09 Å shorter than observed in the bulk. To ascertain the effect of the Sn location on the decrease of the average bond length, Pt-Sn samples with lower surface-to-bulk Sn ratios than the dealloyed Pt-Sn were studied. The structural information specifically from the surface was extracted from the averaged XAS results using an improved fitting model combining the data measured in H₂ and in air. Two samples prepared so as to ensure the absence of Sn in the bulk were also studied in the same fashion. The bond length of surface Sn-Pt and the corresponding coordination number obtained in this study show a nearly linear correlation, the origin of which is discussed and attributed to the poor overlap between the Sn 5p orbitals and the available orbitals of the Pt surface atoms.

Introduction

Bimetallic nanoparticle catalysts are of research interest as they offer routes to obtain catalysts with improved activity, stability and selectivity, as compared to their monometallic counterparts. Studies of bimetallic nanoparticles mainly focus on the ratio of the two constituent metals, and on the lattice strain of the de-allyed shell in core-shell structures. Less attention has been paid to the structure of bimetallic crystals, which is crucial in assessing the role of the second metal in catalysis. In particular, questions remain regarding the validity of assuming that the atomic arrangement on the surface is the same as that measured for the bulk. For example, it is established that clean solid surfaces usually contract due to unsaturated surface bonding, and on monometallic single crystals the extent of contraction has been found to increase when the atomic packing and density of the surface decreases. Surface contractions have also been found on monometallic nanoparticles and assessed using several approaches. The size-dependent lattice contraction of clean nanoparticles has been ascertained by bulk analytic techniques, such as X-ray absorption spectroscopy (XAS) and X-ray diffraction, and electron diffraction. Coherent electron diffraction accompanied by modelling studies was used to further ascertain that the lattice contraction originates from the outermost layers and can be correlated to the coordination number. The recent development of atomic resolution electron tomography has enabled visualization of the surface displacement of each atom.

Ascertaining the details of the surface structure of bimetallic nanoparticles remains a challenge, especially the extent of surface contraction. Some understanding can be obtained using XAS, as it not only provides structural information regarding coordination environments, but also can extract the information of the guest metal independently from that of the host metal. However, the results must be interpreted with caution as the environment in which the XAS data were acquired can have a significant effect. The well-studied Pt-Sn nanoparticles (Pt as the host metal and Sn as the guest), catalysts for alkane dehydrogenation and electrocatalysts for CO and alcohol oxidation, may be used as an example. Decreases in the Sn-Pt bond length of 0.03 to 0.15 Å have been reported compared to that of the Pt₃Sn structure. In some cases, the surface was oxidized, which changes the surface structure; whilst in other cases, harsh reduction conditions were used, which induces diffusion of Sn atoms into the interior of the nanoparticles. Although the varying results from such XAS results seem discouraging, we will show in the study described herein that XAS remains as a powerful tool to probe the structure of bimetallic nanoparticles.
means of revealing the surface contraction for such bimetallic nanoparticles if the experiment is better designed to let XAS ‘see’ a clean, bimetallic surface without interference or with separable interference from the bulk.

In this study, H₂ at room temperature was selected as an appropriate environment during XAS measurements to produce such clean bimetallic surfaces on dealloyed Pt-Sn nanoparticles, as this condition is capable of reducing the Pt surface oxides and, as will be demonstrated below, the oxidised surface Sn atoms of the Pt-Sn nanoparticles, whilst not resulting in diffusion of Sn. XAS data were first collected in air at room temperature to understand the Sn speciation and the surface-to-bulk Sn ratio, and the subsequent measurements in H₂ at room temperature allowed assessment of the effect of the freshly formed Pt-Sn surface on the average Pt-Sn bond length. Pt-Sn nanoparticle samples with different surface-to-bulk Sn ratios were analysed using the same approach. The Pt-Sn bond length and the corresponding coordination number (CN), related specifically to the surface, were extracted using an improved fitting model combining the data measured in air and in H₂. These two parameters were also obtained from two control samples, prepared such that the Sn was only present on the surface, and a correlation between bond length and coordination number is summarised and discussed.

Experimental

Preparation of dealloyed Pt-Sn: Three Pt-Sn samples, all with the same Pt:Sn ratio and total metal loading, were prepared as described previously²⁹ by annealing a common parent Pt-Sn/C catalyst in different atmospheres. The parent Pt-Sn/C with a metal loading of 20 wt% was synthesized by a conventional polyol method. Briefly, 200 mg of the Vulcan XC-72R carbon black and 200 mg of NaOH were dispersed into 50 ml of ethylene glycol/H₂O (3:1 v/v) solution. Into this suspension, 100 mg of H₂PtCl₆·6H₂O and 16 mg of SnCl₂·2H₂O were dissolved. After being stirred for 1 hour and then sonicated for 15 min, the suspension was heated to 160 °C and maintained at this temperature for 2 hours. The product was collected using a centrifuge, washed with a 50% ethanol aqueous solution and dried under vacuum at 80 °C. The parent Pt-Sn/C was annealed at 250 °C in air, in Ar and in H₂ (5%, balanced by N₂), yielding dealloyed Pt-Sn, partly alloyed Pt-Sn, and alloyed Pt-Sn, respectively.

Preparation of SnO₂-Pt/C: SnO₂-Pt/C was synthesized by hydrolysing SnO₂·5H₂O in a suspension of a commercial (Johnson Matthey) Pt/C (60 wt%, ~3 nm diameter Pt particles determined via TEM). 150 mg of the Pt/C was dispersed in 75 ml of H₂O by sonication. To the suspension, 412 μl of 100 mg/ml Na₂SnO₃·3H₂O aqueous solution was added, followed by 30 min stirring and 5 min sonication. The suspension was then heated to 90 °C and maintained at this temperature for 1 hour. The sample was collected by centrifugation, washed with water for at least 3 times and dried under vacuum.

Preparation of SnₓPt/C: SnₓPt/C was prepared by depositing Sn ad-atoms on the commercial Pt/C using the surface organometallic chemistry (SOMC) approach. 120 mg of the Pt/C was loaded in a gas-tight Schlenk tube. After the air inside the tube was replaced by flowing N₂ for 20 min, the gas was switched to H₂ (FIRE RISK, never let Pt nanoparticles meet H₂ and air at the same time) and maintained in constant H₂ flow for 20 min to reduce surface oxides of the Pt nanoparticles. The resulting water vapour was removed by heat treatment at ~100 °C for 30 min under N₂ flow. After the reduced and dried Pt/C was cooled down under N₂ flow, 2 ml anhydrous heptane solution containing the calculated amount of tetrabutyltin (SnBu₄, 96%, ACROS Organics) was added into the reaction tube using a syringe. The suspension was stirred for 10 min in N₂. Then, the atmosphere was switched to H₂, followed by 30 min stirring at room temperature, 30 min at 50 °C and 2 hours at 90 °C. The solid product was allowed to cool down to room temperature. The residual H₂ inside the reaction tube was replaced by N₂, and the gas out-of the reaction tube was open to ambient atmosphere overnight, to passivate the synthesized catalyst by a small amount of air leaking into the reaction vessel (FIRE RISK, never expose the freshly reduced sample to air directly). The sample was stored in a gas-tight vial.

Characterisation: X-ray absorption (XAS) measurements were carried out at the Pt L₃ and Sn K edges on the B18 beamline at Diamond Light Source (UK) using Quick EXAFS mode with a ring energy of 3.0 GeV and a ring current of 299–302 mA. Each sample was prepared by grinding and mixing with boron nitride (BN) to form a homogeneous mixture, and then pressed into a pellet. The pellets were loaded into a gas-tight cell with Kapton windows, in which the atmosphere was either air or H₂. The XAS spectra were measured in transmission using ion chambers, with the exception of those for the SnO₂-Pt/C sample measured in fluorescence using a 36-element Ge detector. In all cases, a Pt or Sn foil was measured in the reference channel along with the sample to provide energy calibration.

The data reduction and curve fitting of the measured XAS spectra were carried out using the Demeter software package (ATHENA and ARTEMIS)³⁵. The edge step of each spectrum was normalized by subtracting the linear pre-edge and quadratic post-edge function, and the energy shift was calibrated by choosing the zero crossing in the second derivative of all spectra to be E₀ and then assigning the E₀ of reference spectra to the corresponding tabulated value provided by ATHENA. The background of extended X-ray fine structure (EXAFS) was subtracted using the AUTOBK algorithm present in ATHENA. EXAFS fitting was carried out in ARTEMIS. Values for the amplitude reduction factor, extracted from fitting of the Pt foil and a SnO₂ standard, were determined to be 0.84 for Pt and 1.03 for Sn.

Results and discussion

As reported in our previous work regarding carbon-supported Pt-Sn electrocatalysts²⁹, the surface-to-bulk Sn ratio (or the extent of alloying) of the Pt-Sn bimetallic particles can be varied by the atmosphere in which the parent Pt-Sn sample is annealed, whilst keeping the Pt-to-Sn ratio constant. Annealing in H₂ results in well-alloyed nanoparticles, partially alloyed nanoparticles result from annealing in Ar, and dealloyed...
nanoparticles, in which most of Sn is segregated to the surface, by annealing in air. Basic structural characterisations of the Pt-Sn samples, such as TEM, XRD and XPoS, as well as CO stripping voltammograms can be found in Figure S1–S4 and Table S1. In the study reported, herein, the detailed structure and the configuration of Sn species of the dealloyed Pt-Sn sample were further analysed using XANES and EXAFS.

After being dealloyed by heat treatment in air at 250 °C for 2 h, both the Sn and Pt are oxidized, as indicated by the similarity of the Sn K-edge XANES to that for a SnO2 reference (Figure 1) and by the increased whiteline intensity compared to a Pt foil at Pt L3-edge (Figure S5). Further inspection of the Sn K-edge XANES spectra reveals a small yet discernible decrease of the whiteline intensity compared to that of the reference, suggesting not all Sn atoms were fully oxidized into SnIV, as in SnO2.

The local coordination of the oxidized Sn species was then studied by Sn K-edge EXAFS in k-space and R-space (Figure 2). Compared to a SnO2 reference, the dealloyed Pt-Sn shows similar oscillations in the low k (3–9 Å) and low R (1–2 Å) with lower intensity, but loses fine structures in the high k (>9 Å) and high R (3–4 Å). Since the features at high k and high R mainly correspond to two Sn-Sn scattering paths in the SnO2 rutile structure (Figure S6), the Sn species of the dealloyed Pt-Sn sample, although coordinated to oxygen atoms, lack long-range order.

To further identify the coordination environment of the Sn atoms in the dealloyed Pt-Sn sample, a double-dataset EXAFS fit was carried out; combining the data of the Sn K-edge and the Pt L3-edge by setting the R and σ2 of interatomic scattering paths as equal, that is, R(Sn–Pt) = R(Pt–Sn) and σ2(Sn–Pt) = σ2(Pt–Sn). The fitting results are shown in Figure S7 and Figure S8 and the obtained structural parameters listed in Table 1. At both edges, oxygen neighbours are found in the first shell, consistent with the oxidized surface of the dealloyed Pt-Sn. At the Sn edge, 5.0 ± 0.7 oxygen neighbours are found with R = 2.04 ± 0.01 Å, and 2 ± 1 Pt neighbours are with R = 2.82 ± 0.02 Å, which are similar to that of the SnO2 reference (2.056 ± 0.004 Å, Table 1) and that of the bulk PtSn (2.829 Å, ICSD 105796), respectively. Given the similarity with the corresponding standards and because intermediate Sn species coordinating with both Pt and O are unlikely to exist on Pt-Sn samples annealed in air, it is suggested that the Sn species are a mixture of alloyed Sn0 inside Pt lattice and fully oxidized Sn (denoted as [Sn0]+O3 due to lack of long-range order), which also reconciles the decreased whiteline intensity and the unsaturated oxygen shell of Sn (6 oxygen neighbours for Sn3+ in SnO2). The phase segregation of the Sn species is attributed to the dealloying process of heat treatment, in which most of the oxophilic Sn atoms migrate to the surface of Pt-Sn nanoparticles and get oxidized by O2, forming [SnIV]+O3 species. The similar model for phase segregation and Sn oxidation of supported PtSn nanoparticles was also suggested by in situ time-resolved XAFS32, 36. The presence of alloyed Sn in the current study is probably due to the relatively low temperature (250 °C) used in heat treatment, which limits the extent of phase segregation. Therefore, the Sn species of the dealloyed Pt-Sn can be considered as spatially separated, with [SnIV]+O3 on the surface layer (with Pt oxide) and a small amount of alloyed Sn in the metallic Pt core (Figure 3).

The surface [SnIV]+O3 species are reduced when being measured in H2. The XANES spectrum at the Sn K-edge shows a sharp decrease of whiteline intensity from ~1.46 to ~1.22 and a negative shift of the edge position (defined as the first maxim of the derivative around the rising edge) by ~3 eV (Figure 1), indicating that the oxidation state of the Sn decreased significantly in H2. The reduction of the Sn is also supported by the decreased amplitude of the Sn–O component in EXAFS spectra (Figure 2). For the Pt edge data measured in H2, the whiteline intensity decreases and becomes less than that of Pt foil (Figure S9), suggesting the complete reduction of the Pt surface oxide and the alloying with Sn, which results in a downshift of the d-band center of Pt37, 38.

The reduction product was further studied by EXAFS fitting using the same model as that used for the data acquired under air. The fitting results are shown in Figure S9, with the obtained structural parameters listed in Table 1. The CN of Sn–O decreases to 1.8 ± 0.2 and that of Sn–Pt increases to 5 ± 1, with no Sn neighbours found in the first shell of Sn, suggesting that the reduction of [SnIV]+O3 coincides with the formation of Sn-Pt bonds. Since the common oxidation states of Sn are 0, +2 and +4, the Sn-Pt bonds may come from alloyed Sn (Sn3+)-Pt, intermediate Sn (Pt-SnIV)+O3, or both. The presence of the intermediate Sn is negligible, as no significant change in the Sn–O distance was observed (Table 1 and Figure S10), which should be seen if Pt-Sn0 or SnO is present. Thus, the formation of Sn-Pt bonds is attributed to Sn0 alloyed with Pt, which is the reduction product of [SnIV]+O3 in H2.

Figure 1  Sn K-edge XANES spectra of the dealloyed Pt-Sn samples measured in air and in H2, along with their 1st derivative at the rising edge. The comparison shows a decreased whiteline intensity and a shift of edge position (vertical dash lines) towards low energy when the dealloyed sample was exposed to H2, indicating the reduction of SnIV.
Table 1 Structural parameters obtained from individual double-dataset fits of the dealloyed Pt-Sn data collected in air and in H\textsubscript{2}. The fits use 18 variables out of ~27 independent points for the data collected in air, 17 out ~27 for the improved fit and 15 out of ~27 for the data collected in H\textsubscript{2}. The first element in the scattering path indicates the absorption edge Pt (L\textsubscript{3}) or Sn (K).

<table>
<thead>
<tr>
<th>Samples</th>
<th>Scattering path</th>
<th>N</th>
<th>R (Å)</th>
<th>(\sigma^2 \times 10^3) Å(^2)</th>
<th>(\Delta E_0) (eV)</th>
<th>R-factor (%)</th>
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<td>Pt – O</td>
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<td>Pt – Pt</td>
<td>7.5(2)</td>
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<td>7.3(4)</td>
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<td></td>
<td>Sn – Pt</td>
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<td>2.82(2)</td>
<td>14(6)</td>
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<td>3(2)</td>
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<tr>
<td></td>
<td>Sn – Sn</td>
<td>2(2)</td>
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<td>8(6)</td>
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<td></td>
<td>Pt – Pt</td>
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<td>2.760(1)</td>
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<td>Sn – O</td>
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<td>2.035(8)</td>
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<td>13(2)</td>
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<td></td>
<td>Sn – Sn</td>
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<td>10(6)</td>
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<tr>
<td>SnO\textsubscript{2}</td>
<td>Sn – O</td>
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<td>2.056(4)</td>
<td>3.9(5)</td>
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<td>PtSn (^1)</td>
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<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
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</table>

\(^a\) N, the degeneracy of the absorber – backscatterer scattering pair; \(^b\) R, the average distance of the pair; \(^c\) \(\sigma^2\), the mean square relative replacement of the R; \(^d\) \(\Delta E_0\), the difference with the assigned \(E_0\); \(^e\) R factor, a measure of the goodness of fit; \(^f\) Pt – Sn and Sn – Pt scattering paths are set to have the same value in R and \(\sigma^2\); \(^g\) \(N(Sn–Pt)/2\) was fit as 12\(^g\)\([1-(N(Sn–O)/6)]\), assuming the CN of Sn-O is 6, and the CN of Sn-Pt is 12. The fit without such a constraint is plotted in Figure S8 listed in Table S2, producing approximate structural values but with large uncertainty in the \(N(Sn–Pt)\) value, 4(5); \(^h\) not allowed to vary; \(^i\) obtained from Feff calculation of the crystal structure of PtSn (ICSD 105796).
From the proposed structural model of dealloyed Pt-Sn nanoparticles (Figure 3), the selective conversion of [SnIVO] to Sn0 alloyed with Pt suggests that the reduction of [SnIVO] is facilitated by the Pt surface, which was also found previously for organotin(IV) and SnO2 at higher temperatures. The promotional role of Pt is ascertained by temperature-programmed reduction using diluted H2 (Figure S11), showing that the dealloyed Pt-Sn sample requires <60 °C to trigger reduction whilst SnO2/C needs 125 °C. The promoted [SnIVO] reduction by Pt can be attributed to the highly negative formation enthalpy of Pt-Sn intermetallic compounds, -55.3 kJ mol⁻¹ for Pt2Sn82. Note that the reduction of [SnIVO] is not complete in the room temperature experiments reported herein. The residual contribution of SnO may be due to excess clusters of [SnIVO] on Pt particles, where the Sn:Pt ratio exceeds capacity of the topmost layer to reduce all the Sn atoms (see below), and/or to [SnIVO] species located on the carbon support.

The Sn3+ atoms resulting from the [SnIVO] reduction facilitated by Pt probably stay on the nanoparticle surface rather than migrating into the Pt lattice at room temperature. Sn2+ diffusion into bulk Pt crystal was found to be unfavourable and limited to the topmost layers43, presumably due to the significant lattice expansion accompanying the transition from Pt (3.92 Å, fcc) to Pt2Sn (4.00 Å, fcc). The preparation of Pt-Sn surface alloys (multiple layers) generally requires heat treatments to incorporate deposited excessive Sn layers into Pt crystals (>400 K under vacuum)43. The preferential location of Sn on Pt surface is also supported by the configuration of Sn atoms to the structural parameters are described as the ‘shell’ (Figure 3). The R and σ* values of Sn–O and Sn–Sn are also assumed to be transferable between data measured in the two atmospheres. As the fitting result shown in Figure S17 and the obtained structural parameters listed in Table 2, the improved fitting model yields a good fit that produces an R-factor of 0.38% and improved accuracy in the obtained structural parameters and only uses 28 variables out of ~54 independent points.

Using the improved fitting model, structural parameters specifically of the surface Sn atoms were obtained. Compared with the conventional fitting model above, an even shorter bond length for the “shell” Sn–Pt was found, 2.72 ± 0.02 Å, which is expected because a small amount of Sn–Pt from the core (with longer R) was separated in the fitting model. Assuming the Sn atoms of tin oxide species are saturated with 6 oxygen atoms (unreduced SnO2) in both atmospheres, the amount of the freshly formed surface Sn atoms (Sn[Sn-surface]%6) is equal to [N(Sn–O)6 – N(Sn–O)6]/6, and the CN of the shell Sn–Pt is then equal to [N(Sn–Pt)shell/Sn[Sn-surface]%6, 5.4 ± 3.3. 

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Figure 3 Schematic illustration of the structural model of the dealloyed Pt-Sn in air (left) and under H2 (right). In air the dealloyed Pt-Sn nanoparticles have an amorphous mixed oxide layer on the surface, and a metallic Pt core with small amount of alloyed Sn. When in H2, the surface oxide layer is reduced into a metallic Pt-Sn shell, and the reduction is assumed to have no effect on the metallic core and excess or separate [SnIVO] species.
To further explore the relationship between the CN and R for the surface Sn atoms, two control samples were prepared, in which the tin oxide phases were deposited on to a commercial Pt/C rather than mixing Pt and Sn precursors at the beginning of the synthesis; (i) SnO₂-Pt/C, in which disordered [Sn₃O₄] was deposited on a commercial Pt/C catalyst (with naturally formed surface oxide layers) by hydrolysis of SnO₂, and (ii) Snad-Pt/C, in which Sn ad-atoms were deposited on the same Pt/C catalyst using a surface organometallic chemistry (SOMC) method where the Sn atoms are selectively deposited on freshly reduced Pt surface³¹. XAS analysis in air and in H₂ was conducted on SnO₂-Pt/C as for the dealloyed Pt-Sn sample (Supplementary note 1), and the Snad-Pt/C data can be found in Figure S18–S20 and Table S5. Only Sn K edge data were collected for these two samples, because the Pt-Sn signal from the Pt edge data would be diluted by the dominant Pt atoms in the interior.

Shortened R(Sn-Pt) values were found for both control samples; 2.768 ± 0.007 Å for SnO₂-Pt/C and 2.690 ± 0.007 Å for Snad-Pt/C, and the corresponding CN values are 8.8 ± 1.7 and 4.5 ± 0.4, respectively. Such a shortened Sn-Pt bond distance can also be found on Sn/Pt(111)⁴⁹, ⁵⁰ and Sn/Pt(100)⁵¹ surface

Table 2 Structural parameters obtained from the 4 dataset fit of the dealloyed Pt-Sn samples. The fit uses 28 variables out of ~54 independent points. Plots of the data and fits are shown in Figure S17

<table>
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<tr>
<th>Data set</th>
<th>Scattering path</th>
<th>N</th>
<th>R (Å)</th>
<th>σ² (×10⁻⁴ Å⁴)</th>
<th>ΔE₂ (eV)</th>
<th>R-factor (%)</th>
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<tr>
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<td>Pt – O</td>
<td>0.84(8)</td>
<td>1.998(4)</td>
<td>5(1)</td>
<td>7.3(2)</td>
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<td>Pt – Pt</td>
<td>7.4(2)*</td>
<td>2.757(1)*</td>
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<td>Sn – Pt</td>
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<td>2.821(1)**</td>
<td>14(4)**</td>
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<td></td>
<td>Sn – Sn (2nd shell)</td>
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<td>3.25(2)**</td>
<td>9(4)**</td>
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<td>Pt – Pt (core)</td>
<td>7.4(2)*</td>
<td>2.757(1)*</td>
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<td>Sn – Sn (2nd shell)</td>
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<td>3.25(2)**</td>
<td>9(4)**</td>
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*Pt – Pt (core), Pt – Sn (core) and Sn – Pt (core) of the H₂ data and the corresponding ones of the air data are set to be equal in values of N, ΔR and σ²;
**Sn – O and Sn – Sn (2nd shell) are set to be equal in values of R and σ²;
***For data measured in the same atmosphere and probing the core or the shell, Pt – Sn and Sn – Pt are set to be equal in values of R and σ².

Figure 4: Comparison of the dealloyed Pt-Sn, the partly alloyed Pt-Sn and the alloyed Pt-Sn in terms of the decrease of (A) Sn K-edge whiteline intensity, CN(Sn–O) and (B) R(Sn–Pt) when being exposed to H₂. The average CN(Sn–O) and R(Sn–Pt) values are labelled on the top of columns, along with that calculated from Pt₅Sn crystal (ICSD 105796) using Feff6.
two surface alloys, where the CN(Sn-Pt) is 9 and 8, respectively. On these two surface alloys the surface Sn atoms were found to protrude ~0.2 Å above the surface using scattering techniques, corresponding to a $R$(Sn-Pt) of ~2.78 Å$^{52,53}$. Comparison of these two surface alloys with SnO$_2$-Pt/C reveals that they have similar $R$ and CN values, in agreement with the results presented here obtained by EXAFS fitting and suggesting that the $R$(Sn-Pt) has a similar coordination-dependence for both single crystals and nanoparticles.

To summarise, the $R$(Sn-Pt) values of the surface Sn are plotted as a function of CN(Sn-Pt) in Figure 5, which includes the dealloyed Pt-Sn, Sn$_{100}$-Pt/C and SnO$_2$-Pt/C, Sn/Pt(111)$^{52,53}$ and Sn/Pt(100)$^{52}$, and a reference Pt$_3$Sn crystal (CN = 12, $R = 2.829$ Å). The correlation is almost linear. For monometallic metals, the Goldschmidt correction was used to convert atomic radii of the metal to the value that they would have with 12-fold coordination, and as per the correction, atomic radii contract by 3%, 4% and 12% if the CN is reduced from 12 to 8, 6 and 4, respectively.$^{54}$ Sun$^{55,56}$ formulates the correction into a CN-dependent bond-contraction coefficient (eq.1),

$$C(z) = R(z)/R(12) = 2(1+\exp[(12-z)/(8z)])^{-1} \text{ (eq.1)}$$

where $z$ is the CN. The equation was also found to agree with experimental data for Au nanoparticles$^{55,57}$. For the present Sn-on-Pt system, the data points fall on the function only when the CN is 29, but the $R$ with CN = 4 to 6 are clearly higher than those predicted by the function (Figure 5). This mismatch is presumably due to the nature of the Sn-Pt bond. Sn is a p-block metal and the orbitals involved in forming Sn-Pt bond should be different from Pt with other transition metals. Unlike other Pt-based alloys forming solid solution alloys, Pt$_3$Sn is an intermetallic compound with highly ordered atomic arrangement in which the Pt atoms in the corner-sites of fcc structure are substituted by Sn. Sn 5p orbitals are found to hybridize with Pt 5d orbitals and participate in forming bulk Pt$_3$Sn$^{58}$ and Pt-Sn surface alloys$^{58,59}$, rather than s-orbitals mainly involved in Pt$^{60,61}$. Thus, the directionality of the Sn 5p orbitals may cause poor overlapping with the available orbitals of the Pt surface and lead to weaker bond strength than would be for transition metals interacting via their s-orbitals. The extent of overlap decreases with lowering CN, consistent with the trend of the difference between the data collected and the theory.

**Conclusions**

In this work, XAS measurements in H$_2$ at room temperature were carried out to ascertain the bond length contraction on the surface of Pt-Sn bimetallic nanoparticles. Dealloyed Pt-Sn nanoparticles, where most Sn atoms are segregated to the surface, show an average bond length of Sn-Pt ~0.09 Å shorter than the bulk value. The bond contraction is found to decrease as the surface-to-bulk Sn ratio decreases (or as the extent of alloying increases), supporting the main contribution of surface contraction to the shortened bond length. To extract the structural information specifically of the surface from the average EXAFS results, an improved fitting model combining the data measured in H$_2$ and in air was devised, yielding a good fit with a Sn-Pt bond length on the surface ($2.72 \pm 0.02$ Å) and a corresponding coordination number ($5.4 \pm 3.3$). Two control samples without Sn in the bulk were also studied in the same fashion, and the results support the surface contraction and provide data points for coordination-dependent bond length contraction. Plotting the measured $R$ of Sn-Pt against the corresponding CN values reveals that $R$ is proportional to the CN for the Pt-Sn bimetallic system, which is different from the established theory in monometallic system when the CN is <9. The origin of the mismatch is attributed to the directionality of Sn 5p orbitals, which causes poor overlap with the available orbital on the Pt surface.

**Conflicts of interest**

There are no conflicts to declare.

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