

# Room temperature reaction of oxygen with gold: an in situ ambient-pressure X-ray photoelectron spectroscopy investigation

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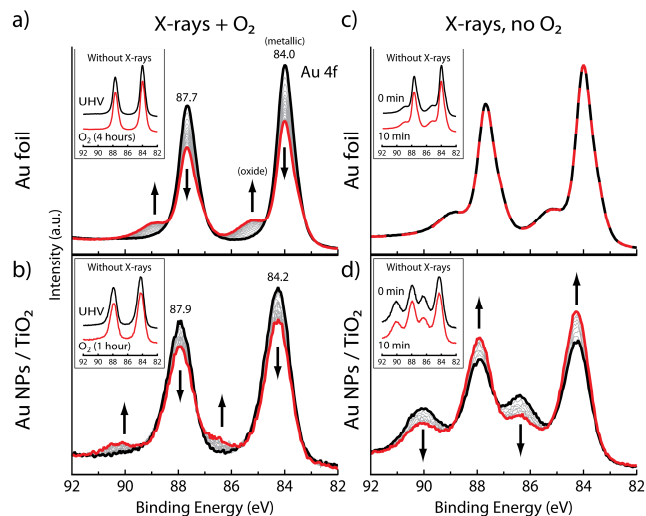
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Gold is commonly regarded as the most inert element.<sup>1</sup> However, the discovery of the exceptional catalytic properties of gold nanoparticles (NPs) for low temperature CO oxidation<sup>2</sup> initiated great interest due to its promising applications and spawned a large number of studies devoted to the understanding of the reaction mechanism.<sup>3-6</sup> Nevertheless, no consistent and conclusive picture has arisen.<sup>7-13</sup>

One of the most important and controversial issues is the activation mechanism of O<sub>2</sub> on Au.<sup>9,14-19</sup> For instance, based on the experimental observation that a bilayer Au structure, which completely wets the oxide support, exhibits extraordinary catalytic activity, Goodman et al. proposed that Au can be directly involved in the activation of O<sub>2</sub>.<sup>9</sup> In contrast, more recently, Behm et al. found that the amount of active oxygen species on the Au/TiO<sub>2</sub> surface has a linear relationship with the number of perimeter sites at the interface between the oxide support and the Au NPs, indicating that the support-Au interface plays a dominating role in the oxygen activation.<sup>19</sup> Furthermore, based on theoretical calculations, under-coordinated Au atoms were proposed to have the capability to adsorb and even dissociate O<sub>2</sub>.<sup>14</sup> Using high-intensity *in situ* X-ray absorption near-edge structure (XANES), van Bokhoven and co-workers observed an increased white line intensity at the Au L<sub>3</sub> edge for Au NPs supported on Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> substrates during treatment in O<sub>2</sub>, indicating that Au NPs can be oxidized by molecular oxygen.<sup>17,18</sup> However, Liu et al. calculated that the dissociation barrier is larger than 2 eV on non-supported Au and even at the Au/TiO<sub>2</sub> interface the dissociation barrier is still 0.52 eV,<sup>15</sup> which means that O<sub>2</sub> has a very weak interaction with Au, and thus spontaneous dissociation of molecular oxygen on the Au surface is not energetically favorable.

In order to reconcile these controversial observations and proposals we investigated the reactivity of O<sub>2</sub> with bulk Au foil and Au NPs supported on TiO<sub>2</sub>(110) surface using *in situ* Ambient Pressure X-ray Photoelectron Spectroscopy (AP-XPS) at O<sub>2</sub> pressures of up to 1 Torr.<sup>20,21</sup> Our data demonstrate that molecular oxygen does not have a strong interaction with Au surfaces at room temperature. However, we observed that molecular oxygen can be activated on both types of samples by X-ray irradiation to produce oxidic Au. We further investigated and compared the stability of oxidized Au on both model systems.



**Figure 1.** Time evolution of the XPS spectra of Au 4f under X-ray irradiation at room temperature. (a) Au foil and (b) Au NPs on TiO<sub>2</sub> support in the presence of 1 Torr O<sub>2</sub>. (c) Oxidized Au foil and (d) oxidized Au NPs on TiO<sub>2</sub> support in UHV. The peaks on the higher energy binding side of the metallic 4f<sub>7/2</sub> and 4f<sub>5/2</sub> peaks are due to oxidized gold. The bold black and red curves correspond to the first and the last spectrum, respectively. The arrows indicate the direction of the intensity changes. The insets show the Au 4f spectra from the test experiments under similar condition, but without X-ray irradiation for the specified time.

The experiments were performed at beam line 11.0.2 of the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory.<sup>20,21</sup> This system consists of a preparation chamber and an AP-XPS analysis chamber with base pressure of 3×10<sup>-10</sup> Torr. The Au foil and the TiO<sub>2</sub>(110) single crystal samples were cleaned by several cycles of Ar<sup>+</sup> sputtering and annealing. Au NPs were obtained by thermal evaporation of Au onto the TiO<sub>2</sub>(110) surface at 320 K, following a procedure described in the literature.<sup>22</sup> The amount of deposited Au was calibrated by the ratio between Au 4f and Ti 2p peaks. O<sub>2</sub> gas was dosed through a leak valve. A photon energy of 690 eV was used to acquire all the spectra. The binding energy scale was calibrated by using the metallic Au 4f<sub>7/2</sub> (binding energy 84.0 eV) peak and the Fermi

edge of Au foil as references. The photon flux density was approximately  $4 \times 10^{12}$  photons  $\text{mm}^{-2}\text{s}^{-1}$ .

The insets in Figures 1a and 1b show the Au 4f spectra obtained from the gold foil and from a 0.3 ML (monolayer) of Au on  $\text{TiO}_2$  under UHV and under 1 Torr of  $\text{O}_2$ , respectively. In comparison with bulk Au foil (84.0 eV), the Au 4f<sub>7/2</sub> peak of the submonolayer deposit shifts to a higher binding energy (84.2 eV), due to a combination of initial and final state effects.<sup>23,24</sup> After exposure to  $\text{O}_2$  at 1 Torr for several hours in the absence of X-rays, both peak position and width remain the same. These results demonstrate that  $\text{O}_2$  does not have a strong interaction with Au, both in bulk form and in the form of NPs, under the above conditions. This observation is consistent with the known inertness of Au, which originates from the filled d-band structure.<sup>1</sup>

However, we observed that under X-ray irradiation in the presence of oxygen gas, the Au surfaces could be oxidized. Figures 1a and 1b show the time evolution of the Au 4f region under irradiation of X-rays in the presence of 1 Torr of  $\text{O}_2$  over 15 minutes. On the foil the intensity of the metallic Au 4f peaks (Au 4f<sub>7/2</sub> 84.0 eV and Au 4f<sub>5/2</sub> 87.7 eV) decreases with time, while at the same time two additional peaks appear, which are shifted by 1.3 eV to higher binding energies relative to the metallic Au 4f peaks. Previous studies have reported similar peak shifts for oxidized Au surfaces prepared using different oxidation methods.<sup>25-28</sup> On the Au NPs formed by evaporation on the  $\text{TiO}_2$  crystal, two additional peaks develop also at the higher binding energy side that can be attributed to oxide as well. It is noteworthy to mention that both the oxidation rate and the chemical shift of the oxide peaks depend strongly on the size of NPs,<sup>28-30</sup> which is still under further investigation.

X-ray induced formation of chemisorbed oxygen species have been reported previously.<sup>31,32</sup> However, these measurements were carried out under ultrahigh vacuum at temperatures below 30 K, where chemisorbed oxygen is produced from physisorbed molecular oxygen. Therefore, both the experiment conditions and the activation process are dramatically different from the ambient conditions in this communication.

The stability of the oxidic Au species formed in this way was subsequently investigated also under X-ray irradiation. We found that the two samples show different behaviors. While the oxidic Au in the NPs on  $\text{TiO}_2(110)$  could be readily reduced under x-ray irradiation, the oxidic Au film formed at the surface of the foil was resistant to X-ray irradiation. This is shown in Figs. 1c and 1d, where the spectra were recorded sequentially during 10 minutes. The difference in reduction behavior lends support to the oxygen spillover model proposed by Ono and Cuenya,<sup>33</sup> based on the well-known facile reducibility of the  $\text{TiO}_2$  support. Under X-ray irradiation, oxygen vacancies can be generated on the  $\text{TiO}_2$  surface.<sup>34</sup> For the NP sample oxygen can spill from the oxidized Au NP to the reducible  $\text{TiO}_2$  substrate, while this reduction channel is not available for bulk gold. The different reduction behavior makes it difficult to compare the oxidation rate of the two samples during X-ray induced oxidation because for Au NPs the oxidation and reduction processes induced by X-rays take place simultaneously. To exclude any effect related to the UHV condition alone, we have investigated the stability of the oxidic species under UHV without X-ray irradiation. As shown in the insets of Figs. 1c and 1d, both samples are stable after 10 minutes under UHV in the absence of the X-ray beam.

In summary, using AP-XPS we have demonstrated that molecular oxygen does not oxidize Au at room temperature, either in the form of supported NPs on  $\text{TiO}_2(110)$  or in bulk (foil) form at pressures of up to 1 Torr. These observations indicate that the

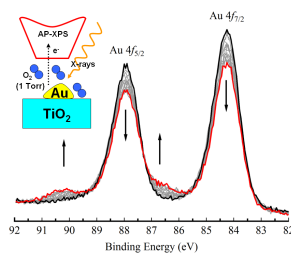
proposed gold-only activation mechanism of  $\text{O}_2$  is unlikely under these reaction conditions.<sup>8,13,15,16,19</sup> With the help of X-ray irradiation, however, both surfaces can be effectively oxidized under 1 Torr of  $\text{O}_2$ . Therefore, our observations demonstrate that X-rays play a critical dual role during *in situ* measurements and that extreme care must be taken to carry out experiments and interpret spectra, especially when using intense synchrotron radiation.

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## REFERENCES

- (1) Hammer, B.; Nørskov, J. K. *Nature* **1995**, *376*, 238.
- (2) Haruta, M.; Kobayashi, T.; Yamada, N. *Chem. Lett.* **1987**, *2*, 405.
- (3) Haruta, M. *Catal. Today* **1997**, *36*, 153.
- (4) Daniel, M. C.; Astruc, D. *Chem. Rev.* **2004**, *104*, 293.
- (5) Hashmi, A. S. K.; Hutchings, G. J. *Angew. Chem., Int. Ed.* **2006**, *45*, 7896.
- (6) Kung, M. C.; Davis, R. J.; Kung, H. H. *J. Phys. Chem. C* **2007**, *111*, 11767.
- (7) Valden, M.; Lai, X.; Goodman, D. W. *Science* **1998**, *281*, 1647.
- (8) Schubert, M. M.; S. Hackenberg, van Veen, A. C.; Muhler, M.; Plzak, V.; Behm, R. J. *J. Catal.* **2001**, *197*, 113.
- (9) Chen, M. S.; Goodman, D. W. *Science* **2004**, *306*, 252.
- (10) Lemire, C.; Meyer, R.; Shaikhutdinov, S.; Freund, H. J. *Angew. Chem., Int. Ed.* **2004**, *43*, 118.
- (11) Yoon, B.; Hakkinen, H.; Landman, U.; Worz, A. S.; Antonietti, J. M.; Abbet, S.; Judai, K.; Heiz, U. *Science* **2005**, *307*, 403.
- (12) Herzog, A. A.; Kiely, C. J.; Carley, A. F.; Landon, P.; Hutchings, G. J. *Science* **2008**, *321*, 1331.
- (13) Matthey, D.; Wang, J. G.; Wendt, S.; Matthesen, J.; Schaub, R.; Lægsgaard, E.; Hammer, B.; Besenbacher, F. *Science* **2007**, *315*, 1692.
- (14) Lopez, N.; Nørskov, J. K. *J. Am. Chem. Soc.* **2002**, *124*, 11262.
- (15) Liu, Z. P.; Gong, X. Q.; Kohanoff, J.; Sanchez, C.; Hu, P. *Phys. Rev. Lett.* **2003**, *91*, 266102.
- (16) Hernández, N. C.; Sanz, J. F.; Rodriguez, J. A. *J. Am. Chem. Soc.* **2006**, *128*, 15600.
- (17) van Bokhoven, J. A.; Louis, C.; Miller, J. T.; Tromp, M.; Safonova, O. V.; Glatzel, P. *Angew. Chem., Int. Ed.* **2006**, *45*, 4651.
- (18) Weiher, N.; Beesley, A. M.; Tsapatsaris, N.; Delannoy, L.; Louis, C.; van Bokhoven, J. A.; Schroeder, S. L. M. *J. Am. Chem. Soc.* **2007**, *129*, 2240.
- (19) Kotobuki, M.; Leppelt, R.; Hansgen, D. A.; Widmann, D.; Behm, R. J. *J. Catal.* **2009**, *264*, 67.
- (20) Ogletree, D. F.; Bluhm, H.; Hebenstreit, E. D.; Salmeron, M. *Nucl. Instrum. Meth. A* **2009**, *601*, 151.
- (21) Salmeron, M.; Schlogl, R. *Surf. Sci. Rep.* **2008**, *63*, 169.
- (22) Lai, X.; St Clair, T. P.; Valden, M.; Goodman, D. W. *Prog. Surf. Sci.* **1998**, *59*, 25.
- (23) Mason, M. G. *Phys. Rev. B* **1983**, *27*, 748.
- (24) Wertheim, G. K.; DiCenzo, S. B.; Youngquist, S. E. *Phys. Rev. Lett.* **1983**, *51*, 2310.
- (25) Pirezux, J. J.; Liehr, M.; Thiry, P. A.; Delrue, J. P.; Caudano, R. *Surf. Sci.* **1984**, *141*, 221.
- (26) Canning, N. D. S.; Outka, D.; Madix, R. J. *Surf. Sci.* **1984**, *141*, 240.
- (27) King, D. E. *J. Vac. Sci. Technol. A* **1995**, *13*, 1247.
- (28) Boyen, H. G.; Kastle, G.; Weigl, F.; Koslowski, B.; Dietrich, C.; Ziemann, P.; Spatz, J. P.; Reithmuller, S.; Hartmann, C.; Moller, M.; Schmid, G.; Garnier, M. G.; Oelhafen, P. *Science* **2002**, *297*, 1533.
- (29) Cuenya, B. R.; Baeck, S. H.; Jaramillo, T. F.; McFarland, E. W. *J. Am. Chem. Soc.* **2003**, *125*, 12928.
- (30) Lim, D. C.; Lopez-Salido, I.; Dietsche, R.; Bubek, M.; Kim, Y. D. *Angew. Chem., Int. Ed.* **2006**, *45*, 2413.
- (31) Gottfried, J. M.; Schmidt, K. J.; Schroeder, S. L. M.; Christmann, K. *Surf. Sci.* **2002**, *511*, 65.
- (32) Kim, J.; Dohnálek, Z.; Kay, B. D. *J. Am. Chem. Soc.* **2005**, *127*, 14592.
- (33) Ono, L. K.; Cuenya, B. R. *J. Phys. Chem. C* **2008**, *112*, 4676.
- (34) Locatelli, A.; Pabisiak, T.; Pavlovska, A.; Mentess, T. O.; Abelle, L.; Kiejna, A.; Bauer, E., *J. Phys.: Condens. Matter* **2007**, *19*, 82202.

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The interaction of O<sub>2</sub> with gold foil and gold nanoparticles grown by thermal deposition on TiO<sub>2</sub>(110) was studied by *in situ* Ambient Pressure X-ray Photoelectron Spectroscopy (AP-XPS) at room temperature. No spontaneous dissociation of O<sub>2</sub> was observed either on Au foil or on Au nanoparticles up to 1 Torr of O<sub>2</sub>. X-ray irradiation, however, is very effective in promoting gold oxidation on both surfaces in the presence of O<sub>2</sub>. Our results help reconcile recent conflicting experimental observations regarding the activation of molecular oxygen, which is a crucial issue in Au catalyzed oxidation reactions.