Determination of the structure and geometry of N-heterocyclic carbenes on Au(111) using high-resolution spectroscopy†

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N-heterocyclic carbenes (NHCs) bind very strongly to transition metals due to their unique electronic structure featuring a divalent carbon atom with a lone pair in a highly directional sp2-hybridized orbital. As such, they can be assembled into monolayers on metal surfaces that have enhanced stability compared to their thiol-based counterparts. The utility of NHCs to form such robust self-assembled monolayers (SAMs) was only recently recognized and many fundamental questions remain. Here we investigate the structure and geometry of a series of NHCs on Au(111) using high-resolution X-ray photoelectron spectroscopy and density functional theory calculations. We find that the N-substituents on the NHC ring strongly affect the molecule–metal interaction and steer the orientation of molecules in the surface layer. In contrast to previous reports, our experimental and theoretical results provide unequivocal evidence that NHCs with N-methyl substituents bind to undercoordinated adatoms to form flat-lying complexes. In these SAMs, the donor–acceptor interaction between the NHC lone pair and the undercoordinated Au adatom is primarily responsible for the strong bonding of the molecules to the surface. NHCs with bulkier N-substituents prevent the formation of such complexes by forcing the molecules into an upright orientation. Our work provides unique insights into the bonding and geometry of NHC monolayers; more generally, it charts a clear path to manipulating the interaction between NHCs and metal surfaces using traditional coordination chemistry synthetic strategies.

Introduction

N-heterocyclic carbenes (NHCs) are exceptionally strong donor ligands capable of binding to virtually any transition metal. They are receiving increasing interest for their ability to form functional self-assembled monolayers (SAMs) on metal surfaces.1–8 Johnson, Crudden and their respective coworkers have demonstrated that NHC-based SAMs exhibit remarkable thermal and chemical stability that go well beyond thiol-based SAMs on Au,1–7 opening the door to novel applications in selective heterogeneous catalysis,6,10 nanotechnology11 and sensing.2 Moreover, the strength and directionality of NHC–metal bonds, by now well-established in coordination chemistry, offer exciting new possibilities for passivating and/or manipulating the work function of metal surfaces.12 While a substantial body of work has been devoted to NHCs since their discovery,13–21 this research has thus far mainly focused on the design of homogeneous catalysts. By contrast, many fundamental questions regarding the structure of NHC SAMs and their electronic coupling with metal surfaces remain unanswered.1,7,8,22 Recently, some unique insights have been provided through the application of NHCs as linker groups in molecular-scale electronics.21,24,29,32

To date, most models of NHC-bound SAMs on metal surfaces postulate that the molecules adopt an upright geometry, with the heterocyclic system perpendicular to the surface.7,8,23,25–28 In this orientation, a donor–acceptor interaction from the carbene lone pair to a surface atom is the primary contribution to the NHC–metal bond. In contrast, Baddeley, Papageorgiou, and their respective co-workers recently reported that some NHCs can form
flat-lying mononuclear complexes \((\text{NHC})_2\text{M} \ (\text{M} = \text{Cu}, \text{Ag}, \text{Au})\) on surfaces, where the coordinated metal site is pulled out of the surface plane.\(^{2,3}\) Such adatoms are key structural components in SAMs of thiol molecules on Au(111),\(^{31}\) and provide a clear experimental signature of surface reorganization induced by strong molecule–surface interactions. With the exception of a single report utilizing high resolution electron energy loss spectroscopy (HREELS),\(^{32}\) the conflicting conclusions regarding the structure of NHC SAMs may be attributed to the use of scanning tunneling microscope (STM) imaging or low resolution X-ray photoelectron spectroscopy (LR-XPS) to probe these systems.\(^{33}\) Such methods do not provide the chemical sensitivity required to determine the precise orientation of NHCs in SAMs, the nature of their bonding to the surface, or the unambiguous detection of any associated Au adatoms. As a result, the role of N-substituents in influencing NHC SAM structure remains ill-defined.

In this work, we use synchrotron radiation to perform high-resolution X-ray photoelectron spectroscopy (HR-XPS) and near-edge X-ray absorption fine-structure spectroscopy (NEXAFS), and combine these measurements with density functional theory (DFT) calculations to establish a detailed picture of the geometry and bonding of a series of NHCs assembled on Au(111) in ultra-high vacuum (UHV). HR-XPS is highly sensitive to the chemical composition of the NHC layer and detects small changes to core-level electron binding energies that result from NHC composition of the NHC layer and detects small changes to core-level electron binding energies that result from NHC–Au interactions, providing unique measurements of surface coverage and surface adatom density. NEXAFS allows us to unequivocally determine the orientation of the molecules relative to the surface by probing their unoccupied electronic states. Such information is key to understanding the relationship between the NHC molecular structure and their adsorption geometry. It can be obtained clearly through spectroscopic measurements. In contrast, surface imaging techniques only focus on small areas of the surface and they cannot resolve precisely the orientation of molecules bound to the surface. By rationalizing our experimental results using DFT calculations, we quantify the impact of the NHC structure and conformation on the strength of the molecule–Au interaction. Importantly, we show that through changes in the substituents on the N atoms, we can alter the steric environment around the carbene C atom, which strongly affects the surface tilt angle and adsorption behavior of the molecules. This study complements and extends previous important efforts to characterize these systems. It further shows how thermal annealing in combination with careful selection of N-substituents can modulate the structure of NHCs on Au(111) surfaces.

Results and discussion

Three NHCs with different steric properties are investigated: 1,3-dimethylimidazol-2-ylidene (NHC\(^{\text{Me}}\)), 1,3-diisopropylbenzimidazol-2-ylidene (\(^{\text{b-NHC}}\text{\text{Pr}}\))\(^{\text{b-NHC}}\text{\text{Pr}}\), and 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene (NHC\(^{\text{dipp}}\)). Details for the syntheses of the NHC precursors are found in the ESL. Monolayers were prepared in UHV via thermal decomposition/sublimation of NHC–CO\(_2\) precursors,\(^{34}\) as illustrated in Fig. 1 and described in the ESL. Briefly here, the precursors are placed in a Pyrex cell and connected to the pre-chamber through a leak valve. This cell is evacuated, heated to \(\sim 70^\circ\text{C}\), and the carbene is introduced as a vapor into a pre-chamber containing a clean Au(111) crystal kept between \(-20\) and \(-30^\circ\text{C}\) for \(\sim 5\text{ min}\) while maintaining a partial molecular pressure of \(10^{-7}\) mbar. After deposition we confirm that the molecules deposited on the substrate have lost their CO\(_2\) moieties, ostensibly through thermal decomposition, by measuring the O 1s spectrum of the layer using XPS.\(^{35}\)

To determine the orientation of the NHC relative to the Au (111) surface normal (defined as the tilt angle \(\theta\) in Fig. 1), we first present NEXAFS linear dichroism results for each molecule.\(^{33}\) Fig. 2a shows the NEXAFS spectra collected at the N K-edge with the electric field of the incident photons perpendicular (p-polarization) and parallel (s-polarization) to the surface for NHC\(^{\text{Me}},\) \(^{\text{b-NHC}}\text{\text{Pr}},\) NHC\(^{\text{dipp}}\) monolayers. The key result is that the dependence of the NEXAFS spectra on the photon polarization (dichroism) varies with the carbene N-substituents.\(^{36}\) The lowest energy NEXAFS resonance at \(\sim 401\) eV arises from the N 1s \(\rightarrow\) \(\pi^*\)-LUMO (lowest unoccupied molecular orbital) transition. It is strongly enhanced with p-polarized photons for NHC\(^{\text{Me}},\) moderately enhanced for \(^{\text{b-NHC}}\text{\text{Pr}},\) and virtually absent for NHC\(^{\text{dipp}},\) the opposite trend is observed for s-polarized photons. Since the \(\pi^*\)-LUMO is delocalized over the whole imidazole ring for all three molecules, we can use the relative intensities of the \(\sim 401\) eV NEXAFS p-polarized and s-polarized peaks to determine the average tilt angle \(\theta\) for each carbene monolayer.\(^{33}\) We find that NHC\(^{\text{Me}}\) is almost flat (\(\theta \sim 72^\circ\)), \(^{\text{b-NHC}}\text{\text{Pr}}\) has an intermediate tilt.

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Fig. 1  Schematic showing the molecular structure of the NHC precursors, the thermal decomposition/sublimation deposition approach to create the NHC monolayers, and the NEXAFS dichroism measurement. Free NHC molecules are generated in the gas phase upon heating.
We first consider two simple adsorption models for all three carbenes and use DFT calculations to evaluate their structure and bonding energy. We consider a single NHC molecule adsorbed either on a pristine Au(111) surface or an Au adatom sitting on a hollow site of the Au(111) surface. We will show later that this is not the structure that is consistent with our data for NHCMe. Total energy and geometry optimization calculations, detailed in the ESI† are performed using Quantum ESPRESSO® with an exchange and correlation functional that accounts for van der Waals interactions.³⁶,³⁷ A 4-layer Au(111) slab comprising 3 × 3, 4 × 3, and 5 × 5 surface unit cells is used to model surface-adsorbed NHCMe, ²⁸NHCIPr and NHCdipp, respectively. The adsorption energy is defined as the difference between the energy of the combined system and the sum of the energies for each component separately. It is negative for bound systems.

The adsorption energy of NHCMe in a constrained flat-lying geometry on an Au(111) slab is small (−0.91 eV). The carbene lone pair lies parallel to the Au slab and does not form a strong σ-bond to an Au atom (Fig. S3†). Removing the constraint on the tilt angle in this model results in NHCMe adopting a binding geometry nearly normal to the Au(111) surface (θ ~ 15°). This geometrical change is accompanied by a 0.58 eV increase of the adsorption energy of the molecule (~1.49 eV; Fig. S4†). However, these results are at odds with the NEXAFS data indicating that θ ~ 72° for NHCMe.

A significantly different outcome is obtained when the NHCs are relaxed on top of an Au adatom, as shown in Fig. 2b. The adsorption energy for the NHCs at different tilt angles is calculated by constraining the geometry of the NHC ring relative to the surface normal. In its most stable conformation (Fig. 2b and c), NHCMe has a tilt angle θ ~ 75°, in excellent agreement with the NEXAFS data. The corresponding adsorption energy of −2.49 eV is 1 eV larger than when NHCMe is bound to a flat Au(111) surface. The maximum adsorption energy for ²⁸NHCIPr is −2.85 eV, corresponding to an optimized tilt angle θ ~ 50°. The adsorption energy for ²⁸NHCIPr, however, is only weakly dependent on θ, a consequence of the competition between steric repulsion imparted by the bulkier side substituents and the van der Waals interaction of the benzene ring towards the Au surface. The weak dichroism in the NEXAFS spectrum of ²⁸NHCIPr (Fig. 2a) agrees well with the theoretical results. The shallow energy minimum implies that there is no strong driving force to orient the molecule in a preferential geometry. Moreover, the computed lowest energy θ for ²⁸NHCIPr is close to the theoretical angle at which no dichroism is expected (θ ~ 55°). Due to its bulkier N-substituents, NHCdipp can only bind vertically, irrespective of the presence of an adatom (Fig. S5†). The adsorption energies for NHCdipp bound to the Au(111) surface and to an Au adatom are −2.69 eV and −4.11 eV, respectively.

For all three NHCs, the adsorption energy is larger when the molecule binds to an Au adatom. This is the result of the metal s- and d-orbitals being more accessible in the adatom resulting in a stronger donor–acceptor bond. This is reflected in the shorter NHC–Au bond length when the molecule is modeled on an Au adatom (see Table S1†). However, among the three NHCs, NHCdipp stands out. The calculated adsorption energy for the adatom-bound model is significantly larger than the
corresponding values for the other two NHCs. We attribute this difference to the van der Waals interactions of the dipp groups with the Au surface. The difference in adsorption energy between the pristine surface-bound and adatom-bound models is also significantly larger for the NHC\textsuperscript{dipp} system than for the other two NHCs. This can be explained by steric effects between the bulky dipp substituents and the surface, which significantly lengthen the NHC–Au bond (2.15 Å) and distort the molecule when NHC\textsuperscript{dipp} is bound to a pristine Au(111) surface. By contrast, when NHC\textsuperscript{dipp} is bound to an Au adatom, the dipp groups are further away from the surface, the carbenic carbon can get closer to the Au adatom (NHC–Au\textsuperscript{ad} bond length = 2.02 Å), and the molecule can relax to a less strained conformation. This is most easily seen looking at the orientation of the dipp groups. They are almost parallel to the surface in the perfect slab model (Fig. S5) and close to the unstrained geometry in the adatom model (i.e. the C\textsuperscript{NHC}–N\textsuperscript{NHC}–C\textsuperscript{dipp} angle is ~124°; Fig. 2c).

The DFT calculations presented above suggest that NHCs bind significantly more strongly to an Au adatom than to a perfect Au(111) surface. XPS measurements can detect the presence of such adatoms on the surface. Fig. 3a presents the N 1s core level XPS spectra of NHC\textsuperscript{Me}, NHC\textsuperscript{Pr}, and NHC\textsuperscript{dipp} monolayers. A single N 1s peak is observed in the NHC\textsuperscript{Me} and NHC\textsuperscript{dipp} spectra, consistent with only one type of N-containing species on the surface. The spectrum of NHC\textsuperscript{Pr} shows two peaks. The first and more intense main peak is very close in energy to that of NHC\textsuperscript{dipp}. It is attributed to surface-bound NHC\textsuperscript{Pr}. The second, lower-energy peak is attributed to incipient second-layer growth and/or a small amount of undissociated NHC\textsuperscript{Pr}, CO adsorbs on the surface. Note that the NHC\textsuperscript{Me} N 1s peak (401.2 eV) is at a significantly higher binding energy than the corresponding peaks for the NHC\textsuperscript{Pr} and NHC\textsuperscript{dipp} monolayers (~400.5 eV). The correlation between this shift and the positions of the NEXAFS N 1s → \pi*-LUMO resonance (Fig. 2a) for these monolayers indicates that the latter is related to the N 1s core binding energy (an initial state effect). Such a shift to higher binding energy results from charge depletion at the N in the NHC\textsuperscript{Me} monolayer due to interaction of its \pi-electron system with the Au surface. This is consistent with the orientation of the molecule as determined by NEXAFS.

Fig. 3b compares the XPS spectra of the Au core level 4f spin-orbit doublet for a clean Au(111) surface and an NHC\textsuperscript{Me} monolayer grown on the same Au(111) surface.\textsuperscript{22} The NHC\textsuperscript{Me} monolayer spectrum features a doublet of satellite peaks at higher binding energies. Fits of the Au 4f\textsubscript{7/2} peak indicate that the new set of peaks is shifted by +1.1 eV with respect to the Au bulk component (Fig. S6a). Two contributions can explain the difference in the binding energy of the Au 4f peak: (1) a chemical shift; or (2) a screening shift that both result for an Au atom that is lifted significantly from the surface. Comparing the area under each peak, we find that 1/6 of the surface is covered by adatoms (Fig. S6af).

To explore the origin of these satellite peaks, we consider two possible adsorption scenarios for NHC\textsuperscript{Me}: (1) the adsorption of a single NHC\textsuperscript{Me} on an Au adatom (NHC\textsuperscript{Me}–Au\textsuperscript{ad}), and (2) the formation of a flat-lying bis(NHC) complex with an Au adatom (NHC\textsuperscript{Me}–Au\textsuperscript{ad}–NHC\textsuperscript{Me}). We calculate the binding energy shift for the Au adatom 4f core level relative to the bulk (\Delta BE) using the transition state model,\textsuperscript{39,40} of the excited system and the projector augmented-wave method implemented in the Vienna Ab initio Simulation Package (VASP).\textsuperscript{41,42} Fig. 3c presents the computed structure for the fully relaxed NHC\textsuperscript{Me}–Au\textsuperscript{ad}–NHC\textsuperscript{Me} complex adsorbed on a 5 × 4 unit cell. For the complex, \Delta BE = 0.91 eV, in good agreement with the experimental value (\Delta BE = 1.1 eV). By contrast, the computed binding energy shift for NHC\textsuperscript{Me}–Au\textsuperscript{ad} (\Delta BE = 0.16 eV) is much smaller, suggesting that the satellite peaks in Fig. 3b come from NHC\textsuperscript{Me}–Au\textsuperscript{ad}–NHC\textsuperscript{Me} complexes on the surface. The formation of this bis(NHC) complex pulls the Au adatom away from the surface by more than 1 Å (Au\textsuperscript{ad}–Au\textsuperscript{surf} distance is 2.06 and 3.09 Å for NHC\textsuperscript{Me}–Au\textsuperscript{ad} and NHC\textsuperscript{Me}–Au\textsuperscript{ad}–NHC\textsuperscript{Me}, respectively). The change in the electron binding energy of the Au adatom, due to chemical shift and screening effects, is similar to what has been observed in thiol-based monolayers.\textsuperscript{28}

As a comparison, the Au 4f XPS spectrum of the NHC\textsuperscript{dipp} monolayer shows no satellite peaks at higher binding energy. The bulky dipp groups prevent the formation of such bis(NHC) complexes (Fig. S6b). A careful analysis of the STM images presented in a recent study\textsuperscript{38} of NHC\textsuperscript{Me} monolayers on Au(111) further corroborate our conclusion that the molecules indeed form flat-lying NHC\textsuperscript{Me}–Au\textsuperscript{ad}–NHC\textsuperscript{Me} complexes as opposed to NHC\textsuperscript{Me}–Au\textsuperscript{ad} species oriented normal to the surface, as originally proposed. To illustrate this point, Fig. S7f compares an
The behavior of \( ^{14}\text{NHC}^{\text{Pr}} \) differs from that of \( ^{14}\text{NHC}^{\text{Me}} \) and \( ^{14}\text{NHC}^{\text{dipp}} \). This suggests a thermally activated process for the formation of the flat-lying bis(NHC) complexes. Fig. 4a compares the N 1s XPS spectrum of a \( ^{14}\text{NHC}^{\text{Pr}} \) monolayer deposited at \(-20^\circ\text{C}\) with that of the monolayer annealed to \(90^\circ\text{C}\). The low-temperature monolayer shows a broad peak at \(-400.5\) eV, indicating the formation of a mostly disordered surface structure (Fig. 2a). Remarkably, the XPS peak shape and energy change significantly upon thermal annealing. The high temperature N 1s XPS peak is sharp and shifted to a higher binding energy \([-401.5\) eV]. This spectrum is similar to that observed for the \( ^{14}\text{NHC}^{\text{Me}}\text{Au}_{\text{ad}}^{\text{Me}}\text{NHC}_{\text{Me}} \) complexes (Fig. 3a). The striking reorganization of the molecular layer is also captured in the NEXAFS dichroism collected at the N K-edge (Fig. 4b). The N 1s \( \rightarrow \pi^*\text{-LUMO} \) resonance is greatly enhanced in p-polarized light, pointing to a nearly flat geometry for the annealed monolayer.

These spectroscopic changes make the adsorption behavior of \( ^{14}\text{NHC}^{\text{Pr}} \) at high temperature similar to that of \( ^{14}\text{NHC}^{\text{Me}} \). This prompted us to investigate theoretically the possibility that \( ^{14}\text{NHC}^{\text{Pr}} \) forms flat-lying bis(NHC) complexes, provided sufficient energy is available. Similar to its \( ^{14}\text{NHC}^{\text{Me}} \) analogue, the modeled structure of the \( ^{14}\text{NHC}^{\text{Pr}}\text{Au}_{\text{ad}}^{\text{Pr}}\text{NHC}^{\text{Pr}} \) complex on an \( \text{Au}_{\text{111}} \) slab (Fig. 4c) shows that the Au adatom is pulled away from the surface by \(-1\) Å (Table S1†). While this should in principle also alter the Au 4f XPS spectra, we do not observe Au satellite peaks in Fig. S6b†. The lower surface density of \( ^{14}\text{NHC}^{\text{Pr}} \) accounts for this result. Using the intensity of the N 1s XPS peak, we estimate that the \( ^{14}\text{NHC}^{\text{Pr}} \) surface density at \(90^\circ\text{C}\) is \(-10\) times lower than that of \( ^{14}\text{NHC}^{\text{Me}} \) at \(-20^\circ\text{C}\). At this implied density of Au adatoms, the shifted Au 4f XPS satellite would be undetectable. Two effects combine to explain the lower surface density: (1) the footprint of the flat-lying benzannulated \( ^{14}\text{NHC}^{\text{Pr}} \) is larger than that of \( ^{14}\text{NHC}^{\text{Me}} \); and (2) the elevated temperature for the measurement leads to a further decrease in the packing density.

**Conclusions**

The strong carbene–Au interaction offers exciting opportunities as an alternative to the traditional thiol–Au bond, which suffers from limited chemical, electrochemical and thermal stability. By combining high-resolution X-ray photoelectron spectroscopy and computational modeling, this work reveals how adsorption energy, molecular orientation and metal surface structure are closely interconnected in a series of NHC monolayers. We find that NHCs bind significantly more strongly to an Au adatom than to a flat Au(111) surface. We show that with sufficient time and thermal energy, the molecule is capable of reorganizing the underlying gold surface structure. The orientation of the NHC on the surface is determined by the N-substituents. The smallest group – methyl – favors a planar geometry in which the NHC ring is parallel to the surface and organized into \( ^{14}\text{NHC}^{\text{Me}}\text{Au}_{\text{ad}}^{\text{Me}}\text{NHC}_{\text{Me}} \) complexes. Bulkier groups force the molecule into a more vertical orientation and prevent the formation of such flat-lying complexes. By thermally annealing the monolayer, we show it is possible to modulate the structure of surface-bound NHCs. Specifically, conversion from a single, vertically oriented NHC moiety to bis(NHC) complexes has been observed for \( ^{14}\text{NHC}^{\text{Pr}} \). While the initial orientation of NHCs on the surface appears to have little effect on the high thermal stability of NHCs SAMs, we expect that the geometry and electronic structure of the surface-bound carbenes will ultimately prove critical in controlling their (electro)chemical stability, reactivity and functionality, through steric hindrance of reactive sites as well as the extent of intermolecular and molecule–surface interactions.

**Conflicts of interest**

There are no conflicts to declare.

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