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Adsorption of ammonia on multilayer iron phthalocyanine

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The adsorption of ammonia on multilayers of well-ordered, flat-lying iron phthalocyanine (FePc) molecules on a Au(111) support was investigated by x-ray photoelectron spectroscopy. We find that the electron-donating ammonia molecules coordinate to the metal centers of iron phthalocyanine. The coordination of ammonia induces changes of the electronic structure of the iron phthalocyanine layer, which, in particular, lead to a modification of the FePc valence electron spin.

I. INTRODUCTION

Phthalocyanines, as shown in Fig. 1, are planar aromatic compounds, which consist of four isoindole units linked together by nitrogen atoms and which are characterized by an electron cloud delocalized over the alternating carbon and nitrogen atoms.¹ In its center, the phthalocyanine molecule may hold an ion from a large variety of different metal elements and the compound is then termed a metal phthalocyanine.² From a technological point-of-view, metal phthalocyanines have been considered for applications in organic light-emitting diodes,³–⁵ organic thin film transistors,⁶, ⁷ solar cells,⁷, ⁸ gas sensors,⁹–¹⁷ and catalytic applications.¹⁸–²¹ Of fundamental importance to all these applications is the electronic structure of the various metal phthalocyanine compounds, which conveys highly interesting optical, chemical, and physical properties to the molecules. More specifically, the iron phthalocyanine (FePc) compound has an open valence d shell, which results in a number of energetically close-lying electronic states. Their energy distribution can be modified in a number of ways, e.g., by attachment of side groups to the phthalocyanine macrocycle,²² single-molecule manipulation,²³ change of support,²⁴ exchange of the metal center²⁵–²⁸ or, as pursued here, by adsorption of molecular ligands. Specific ligands can be used to tailor the electronic properties of the compound, which also implies that the spin state and thus the magnetic properties of the phthalocyanine can be controlled.

The present study focuses on the influence of adsorption of ammonia (NH₃) on the spin state of the FePc molecule. Using x-ray photoelectron spectroscopy we show that the formation of a dative bond between ammonia and the phthalocyanine iron center leads to a quenching of the spin, which we interpret in terms of a reorganization of the electronic state upon ammonia adsorption. The experimental results are supported by density functional theory (DFT) calculations of the spin magnetic moment, which is shown to drop from ~2 μₓ for the free molecule to less than 0.3 μₓ.

II. METHODS

The experimental work was carried out at the spectroscopy end station of beam line I311 (Ref. 29) of the Swedish national synchrotron radiation facility MAX-lab in Lund. The end station with separate preparation and analysis chambers is equipped with a SCIENTA SES200 electron energy analyzer. The base pressure in the preparation chamber is in the high 10⁻¹¹ mbar and in the analysis chamber in the mid 10⁻¹¹ mbar range. The Au(111) single crystal was cleaned by repeated cycles of argon ion sputtering (energy 1 keV) and annealing. For annealing a current was passed through the tungsten wire, with which the crystal was mounted to the helium cryostat until the temperature reached 770 K. The sample was kept at this temperature for 10 min. The FePc molecules, purchased from Sigma-Aldrich with a purity of 90%, were thoroughly degassed for several days at temperatures slightly lower than the evaporation temperature. Before sublimation from a resistively heated tantalum pocket the powder was further degassed by heating to the evaporation temperature of 650 to 670 K for approximately 3–4 h. During sublimation the Au(111) substrate was kept at room temperature. After multilayer deposition, the sample was cooled down to ~20 K using liquid helium.

The N 1s XAS experiments were performed in Auger yield mode using the linearly polarized synchrotron light of beam line I311. Several light incidence angles were considered: 0°, 20°, 40°, 55°, and 70° incidence with respect to the surface normal. The photon energy scale was calibrated by recording Au 4f photoemission spectra excited by first and second order light at relevant photon energies. The intensity of the x-ray absorption spectra was beam line transmission-corrected by dividing the spectra by the energy-dependent photon flux, which was recorded by measuring the photoinduced current on a photodiode placed between the...
monochromator and sample. Further, a constant background determined at the low-energy side of the spectra was subtracted and the spectra were then normalized to the height of the step edge determined at around 25 eV above the adsorption edge.\(^{30}\)

All x-ray photoelectron experiments were carried out in normal emission geometry. The C 1s, N 1s, and Fe 2p x-ray photoelectron spectra were recorded using photon energies of 385, 525, and 820 eV. To avoid beam damage the sample was continuously scanned during the measurement at a carefully adjusted speed. The overall instrumental resolution was 140 meV in the case of the C 1s, 180 meV for the N 1s, and 280 meV for the Fe 2p photoemission line. All spectra were calibrated with respect to the Au 4f level of the sample at 83.96 eV (the multilayer thickness was chosen such that some Au 4f substrate signal was still visible). In essence, this way of calibration corresponds to calibrating to the substrate Fermi level. Since the FePc multilayer is characterized primarily by dispersion-type interactions the most appropriate energy reference would instead be the vacuum level,\(^{31}\) the position of which we, however, could not determine at beam line I311 due to limitations of the experimental equipment. Finally, a polynomial-type background was subtracted from the Fe 2p and N 1s photoemission spectra, and from the C 1s spectra a Shirley-type background was subtracted.

For the least-square fit analysis performed on the N 1s and Fe 2p photoelectron spectra, a convolution of a Doniach–Šunjić and Gaussian line shapes was used for each component. For the symmetric peaks, where the Doniach–Šunjić asymmetry parameter is zero, the Doniach–Šunjić line shape and N 1s photoelectron spectra were recorded using photon energies of 385, 525, and 820 eV. To avoid beam damage the sample was continuously scanned during the measurement at a carefully adjusted speed. The overall instrumental resolution was 140 meV in the case of the C 1s, 180 meV for the N 1s, and 280 meV for the Fe 2p photoemission line. All spectra were calibrated with respect to the Au 4f level of the sample at 83.96 eV (the multilayer thickness was chosen such that some Au 4f substrate signal was still visible). In essence, this way of calibration corresponds to calibrating to the substrate Fermi level. Since the FePc multilayer is characterized primarily by dispersion-type interactions the most appropriate energy reference would instead be the vacuum level,\(^{31}\) the position of which we, however, could not determine at beam line I311 due to limitations of the experimental equipment. Finally, a polynomial-type background was subtracted from the Fe 2p and N 1s photoemission spectra, and from the C 1s spectra a Shirley-type background was subtracted.

III. RESULTS

Well-ordered multilayers of flat-lying FePc molecules were prepared by the procedure described above. The x-ray absorption spectra obtained on these multilayers (Fig. 2) show maximum intensity of the \(\pi^+\) resonances (resonances below \(\sim 405\) eV) in grazing photon incidence. Their intensities decrease when going to less grazing incidence angles, and at normal incidence the intensity is quenched. The opposite angular behavior is observed for the \(\sigma^*\) shape resonances [resonances above \(\sim 405\) eV and double peak feature at 399 eV (Ref. 32)]. The intensity variation of the XAS resonances with light incidence angle allows the exact determination of the molecular tilt angle with respect to the surface.\(^{33}\) The inset in Fig. 2 displays the intensity variation of the lowest \(\pi^+\) resonance (LUMO) at around 398 eV, which is expected to change as\(^{33}\)

\[
AP \left( \cos^2 (90^\circ - \theta) \cos^2 \alpha + \frac{1}{2} \sin^2 (90^\circ - \theta) \sin^2 \alpha \right) + A \left( 1 - P \right) \frac{1}{2} \sin^2 \alpha,
\]

where \(A\) is an amplitude, \(P = 0.97\) is the degree of polarization of the beam line, \(\theta\) is the light incidence angle, and \(\alpha\) is the inclination of the normal of the indole molecular plane with respect to the surface normal. Fitting the data in the inset of Fig. 2 reveals that the normal of the molecular plane is oriented along the surface normal (\(\alpha = 0^\circ\)), proving a perfectly flat, ordered geometry of the multilayer FePc adsorbates.

![FIG. 1. Molecular structure of iron phthalocyanine.](image1)

![FIG. 2. Angle-resolved N 1s x-ray absorption spectra measured on a multilayer of FePc on Au(111); the inset shows the variation of the \(\pi^+\) LUMO resonance intensity as a function of light incidence angle with respect to the surface normal. The angular dependence proves a tilt angle of 0° of the LUMO with respect to the surface normal, showing thus a perfectly flat geometry of the multilayer FePc adsorbates.](image2)
The bond between the FePc iron ion and the NH$_3$ adsorbate is expected to be a coordinate bond involving the lone pair orbital on the nitrogen atom and empty valence states on the FePc molecule. This coordinate bond is a relatively weak chemisorptive interaction. The relative weakness of the bond is reflected by the fact that the main component of the Fe 2p line at 708 eV is not shifted with respect to that measured on the multilayer even at saturation. The constant binding energy also indicates that the lone pair electrons are still highly localized on the NH$_3$ molecule. The decrease in FWHM of the Fe 2p$_{3/2}$ line is very large—the FWHM is 3.7 eV before and 1.05 eV after adsorption of NH$_3$. This is larger than what would be expected for changes in the electronic structure and morphology of the FePc film. Instead, we will argue in the following that the narrowing of the Fe 2p photoemission line proves the formation of a low spin compound.

Basically, the broadening of the Fe 2p$_{3/2}$ line shape is, to a large part, a consequence of a Zeeman-like splitting of the two $m_j$ components (3/2, 1/2, −1/2, −3/2) in the magnetic field of the valence spin. $m_j$ is the quantum number related to the $z$-component of the total angular momentum of the core hole. The higher the valence spin, the larger the split between the $m_j$ components, and in consequence the broader the spectrum. The changes in the FWHM of the Fe 2p$_{3/2}$ photoemission line can thus be used as a measure for changes in the valence spin magnetic moment. The narrowing of the signal at saturation offers a clear indication of a significant decrease in the separation between the Fe 2p$_{3/2}$ $m_j$ components and thus in valence spin. This experimental interpretation is also supported by theoretical work. The ligand field created by the NH$_3$ molecules leads to a reorganization of the Fe 3d levels, which results in the pairing of the spins of the 6d-electrons. We have observed similar effects of quenching or reducing the spin state on the phthalocyanine metal center in the presence of different ligands in a previous study.

In detail, from our own and from previously published work, it is known that, in the absence of any additional ligands, the energetic distribution of the iron 3d orbitals of FePc is characterized by the order $3d_{x^2−y^2} ≫ 3d_{z^2} ≈ 3d_{xy} ≈ 3d_{xz}, 3d_{yz}$. Energetically, it is not favorable to place electrons inside the $3d_{x^2−y^2}$ states, and, thus, the application of Hund’s rule implies that two of the six electrons will remain unpaired. In view of the geometric constraints, the ammonia lone pair is expected to interact primarily with the iron $3d_{z^2}$ orbital, leading to an upward energy shift. The $3d_{z^2}$ orbital becomes depopulated after NH$_3$ adsorption and instead the six $d$ electrons completely fill the $3d_{x^2}, 3d_{xz},$ and $3d_{yz}$ orbitals. All spins are paired and the overall spin is quenched.

In Fig. 3 a least-square fit of the Fe 2p$_{3/2}$ spectrum at saturation dose is shown. Table I shows the fit parameters. The spectrum contains a main peak at 708.06 eV with a FWHM of 1.02 eV and a broad satellite feature at 710.38 eV. The relatively low FWHM of the main peak matches well with the previous results of ours for low spin compounds formed by adsorption of NH$_3$ on monolayers of FePc on Au(111). The lowering of the spin magnetic moment upon ammonia adsorption is also predicted by calculations: it is found to…
be $-0.27 \mu_B$ after NH$_3$ adsorption, compared to $2.02 \mu_B$ for free FePc.

Further information about the adsorption of NH$_3$ on FePc can be deduced from the evolution of the N 1$s$ photoemission peaks with increasing NH$_3$ dose (cf. Fig. 4 for the spectra and Table II for some representative peak parameters). The N 1$s$ photoemission signal from the FePc multilayer contains two features, a main peak (P1) at 398.57 eV and a low intensity shake-up satellite (P4) at 400.46 eV. A new component, labeled P3, appears when dosing the smallest amount (0.2 L) of NH$_3$. At this dose P3 has a binding energy of 399.85 eV. Upon an increase of the dose to 0.4 L P3 shifts to 399.75 eV and then remains constant in binding energy at higher ammonia doses (to within the uncertainty). Its area relative to that of the FePc N 1$s$ signal increases up to the saturation dose [cf. Fig. 5(a)]. From that dose onward the P3 peak parameters remain unchanged, as do those of the Fe 2$p_{3/2}$ line. This shows clearly that the P3 peak is due to NH$_3$ molecules bound to the Fe ions (Fe–NH$_3$ bonds). At saturation, the relative area of the P3 peak with respect to the FePc peak (P1) is 0.244, which from the stoichiometry of the FePc compound (eight nitrogen atoms) suggests that there are two ammonia molecules bound to each Fe center. This is in agreement with the fact that the valence band structure of the iron atom allows the formation of sixfold coordinated complexes, and it also agrees with the finding of diffusion of ammonia into the multilayer. In addition, DFT calculations performed on the gas phase FePc found an adsorption energy of $-0.44$ eV for the first NH$_3$ molecule, while for the second molecule the adsorption energy is $-1.1$ eV [see Fig. 6 for the structure of the FePc(NH$_3$)$_2$ complex], showing that indeed the formation of sixfold coordinated FePc(NH$_3$)$_2$ complexes is likely to take place.

In addition to P3 a new component P2 appears at the saturation dose at 399.41 eV. We assign it to additional NH$_3$ molecules adsorbed on FePc on other sites than the iron

<table>
<thead>
<tr>
<th>Dose (L)</th>
<th>Peak parameter</th>
<th>N 1$s$ peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1 (FePc)</td>
<td>P2 (NH$_3$)</td>
</tr>
<tr>
<td>0 L (FePc multilayer)</td>
<td>BE 398.57</td>
<td>400.46</td>
</tr>
<tr>
<td></td>
<td>FWHM 0.85</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Rel. area 1.00</td>
<td>0.02</td>
</tr>
<tr>
<td>0.2 L</td>
<td>BE 398.57</td>
<td>399.85</td>
</tr>
<tr>
<td></td>
<td>FWHM 0.85</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>Rel. area 1.00</td>
<td>0.11</td>
</tr>
<tr>
<td>0.4 L</td>
<td>BE 398.57</td>
<td>399.75</td>
</tr>
<tr>
<td></td>
<td>FWHM 0.88</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Rel. area 1.00</td>
<td>0.18</td>
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<tr>
<td>0.8 L</td>
<td>BE 398.56</td>
<td>399.41</td>
</tr>
<tr>
<td></td>
<td>FWHM 0.88</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>Rel. area 1.00</td>
<td>0.15</td>
</tr>
<tr>
<td>1.6 L</td>
<td>BE 398.58</td>
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<tr>
<td></td>
<td>FWHM 0.88</td>
<td>0.82</td>
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<tr>
<td></td>
<td>Rel. area 1.00</td>
<td>0.43</td>
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<tr>
<td>2 L</td>
<td>BE 398.62</td>
<td>399.39</td>
</tr>
<tr>
<td></td>
<td>FWHM 0.88</td>
<td>1.17</td>
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<tr>
<td></td>
<td>Rel. area 1.00</td>
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</tr>
<tr>
<td>3.5 L</td>
<td>BE 398.62</td>
<td>399.44</td>
</tr>
<tr>
<td></td>
<td>FWHM 0.88</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>Rel. area 1.00</td>
<td>8.4</td>
</tr>
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</table>

FIG. 4. Experimental data and fits of the N 1$s$ x-ray photoelectron spectra before and after adsorption of NH$_3$ on multilayer FePc. The bottom spectrum is the spectrum of a clean FePc multilayer, characterized by the main peak (P1) and a shake-up satellite (P4). Ammonia adsorption results in additional peak components, P3 due to Fe–NH$_3$ bond formation and P2 due to NH$_3$ species adsorbed elsewhere on the macrocycle (Pc–NH$_3$ interactions). The spectra are normalized with respect to the height of the main peak.
(Pc–NH₃ interactions) as well as, at higher doses, NH₃ multilayer molecules. Since P2 is observed already at a dose of 0.8 L, it seems likely that the true saturation dose is somewhat lower. This would imply that all iron sites are occupied before adsorption occurs at any other site. This makes a very interesting difference to what we have observed for NH₃ adsorption on monolayers of FePc on Au(111) (Ref. 41); there simultaneous occupation of different sites is observed even for doses far below the saturation dose.

The notion that after saturation of the iron ions a first NH₃ layer is completed on top of the FePc film which then develops into a multilayer is supported by a consideration of the absolute intensities of the C 1s and N 1s spectra (not shown). Both the C 1s spectra and P1 and P3 components of the N 1s spectra start to be attenuated at a dose of 0.8 L, while the N 1s P2 component continues to grow [cf. Fig. 5(b)]. This also allows us to relate NH₃ dose and coverage: at around 0.8 L dose the first NH₃ layer is filled, i.e., a monolayer coverage is reached, not counting the ammonia molecules, though, which have diffused into the FePc film. The exact binding sites of this monolayer, other than the iron site, cannot be assigned more specifically, but we note that the binding energy and width of the P1 component of the N 1s spectra, i.e., of the component related to the FePc macrocycle, do not change (cf. Table II) and, likewise, that the C 1s spectra (not shown) remain the same for all doses. Hence, on the FePc macrocycle the ammonia molecules only physisorb. Since the C 1s and N 1s are attenuated in the same way at saturation dose, we also conclude that the physisorption is not specific to a particular site.

One interesting aspect is a comparison between the present case of NH₃ adsorption on multilayer FePc/Au(111) and the adsorption of NH₃ on monolayer FePc/Au(111), reported by us previously. 41 Figure 7 shows the characteristic Fe 2pᵢ/₂ photoelectron spectra for mono- and multilayers of FePc on Au(111), as well as the corresponding spectra at saturation after NH₃ adsorption. For the Fe 2pᵢ/₂ photoemission line of monolayer FePc we found that, in addition to multiplet splitting effects, the line is broadened additionally by the interaction between the FePc adsorbates and the Au(111) substrate. The same holds after adsorption of NH₃. The interaction with the substrate is visible mainly through the low-binding energy shoulder at around 707 eV. The complete disappearance of this shoulder in the Fe 2pᵢ/₂ line of the multilayer FePc, both prior and after NH₃ adsorption nicely illustrates that no substrate influence is visible in the multilayer Fe 2p spectra. This basically shows that the relatively large FWHM of the Fe 2p multilayer line is mainly given by the unpaired spins in the valence band. The narrowing of the Fe 2p spectra after NH₃ adsorption is an indicator of the spin quench of the FePc molecule. Ammonia coordination to the Fe site produces similar effects on the spin state of both mono- and multilayer FePc.

The N 1s spectra at iron saturation also reveal some interesting differences between the adsorption behavior of NH₃ on multi- and monolayer of FePc on Au(111) (Fig. 8). First,
the adsorption on monolayer FePc results in a single peak at 400.01 eV for both the NH$_3$ species bound to iron and those adsorbed on the macrocycle (labeled Fe–NH$_3$ and Pc–NH$_3$ in Fig. 8). In contrast, the adsorption of NH$_3$ on the FePc multilayer results in two distinct peaks separated by around 0.35 eV (at 399.41 and 399.76 eV). The NH$_3$/monolayer adsorption also results in an additional peak due to Au(111)–NH$_3$ interactions. Second, as already discussed above, we find that NH$_3$ adsorption on FePc monolayers results in both the Fe–NH$_3$ and Pc–NH$_3$ species being present already at the initial doses of NH$_3$, while in the multilayer adsorption the Pc–NH$_3$ component appears only after all the iron sites are occupied. This shows that the Au(111) surface plays an important role in determining the ammonia adsorption behavior on FePc, possibly by lowering the adsorption energy for certain sites or by changing the diffusion behavior of the ammonia molecules.

IV. CONCLUSIONS

Adsorption of the electron donor species ammonia on multilayers of iron phthalocyanine supported by a Au(111) surface leads to significant changes of the electronic structure of the FePc molecular network. Most important, dative Fe–NH$_3$ bonds are formed, resulting in the formation of sixfold coordinated complexes. The formation of Fe–NH$_3$ bonds has a significant impact on the magnetic properties of the FePc molecule. The evolution of the Fe 2p photoemission spectra shape shows a transition from an open shell structure characteristic for the 3d valence band of the FePc to a closed shell, low-spin FePc(NH$_3$)$_2$ complex. The Fe–NH$_3$ interaction is rather weak, it does not result in any binding energy shift of the Fe 2p core levels. First all iron sites are occupied by ammonia, and only once saturation of the iron centers is reached adsorption on other sites starts to take place. This behavior is different from what we have observed in a previous study of adsorption of ammonia on monolayer FePc on Au(111), where several adsorption sites are populated already at the lowest doses of ammonia.

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