

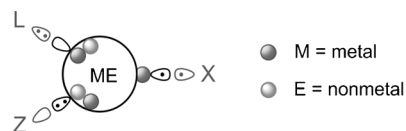
Carboxylic-Acid-Passivated Metal Oxide Nanocrystals: Ligand Exchange Characteristics of a New Binding Motif**

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Abstract: Ligand exchange is central in the processing of inorganic nanocrystals (NCs) and requires understanding of surface chemistry. Studying sterically stabilized HfO_2 and ZrO_2 NCs using ^1H solution NMR and IR spectroscopy as well as elemental analysis, this paper demonstrates the reversible exchange of initial oleic acid ligands for octylamine and self-adsorption of oleic acid at NC surfaces. Both processes are incompatible with an X-type binding motif of carboxylic acids as reported for sulfide and selenide NCs. We argue that this behavior stems from the dissociative adsorption of carboxylic acids at the oxide surface. Both proton and carboxylate moieties must be regarded as X-type ligands yielding a combined X_2 binding motif that allows for self-adsorption and exchange for L-type ligands.

Colloidal nanocrystals (NCs) are hybrid objects in which the properties of core and surface both determine the characteristics of the entire NC. The surface is often capped by (in)organic ligands which determine colloidal stability and the physical and chemical properties.^[1] As a result, NC surface chemistry, i.e., the understanding of and control over the ligand shell, has become one of the central themes in NC research.

The covalent bond classification (CBC)^[2] provides an apt framework to describe NC-ligand binding.^[1a,3] Ligands are defined as L-, X-, or Z-type depending on the number of electrons that the neutral ligand contributes to the NC-ligand bond (2, 1, or 0, respectively). This classification is unambiguous^[4] and allows to label distinct NC–ligand model systems (Scheme 1). L-type ligands such as amines and phosphines are neutral donors of a free electron pair. In apolar solvents, they coordinate to surface metal ions of stoichiometric NCs to yield overall charge-neutral objects.^[5] Z-type ligands are neutral electron-pair acceptors (e.g., metal carboxylates) that bind to the surface anions of stoichiometric NCs.^[1a] In NC surface chemistry, X-type ligands are presented as negatively



Scheme 1. The covalent bond classification (CBC) considers L-type ligands as Lewis bases, Z-type ligands as Lewis acids, and X-type ligands as radicals.

charged ligands (RCOO^- , OH^- , Cl^-) that bind to excess surface cations of nonstoichiometric NCs.^[1a,6] Although this concept is correct, it is a too restrictive description as we argue in this paper. According to the original CBC, ligands must be classified in their neutral form. X-type ligands are thus formally regarded as radicals (Scheme 1).

Obviously, desorption or adsorption of L- and Z-type ligands involves the separation or combination of two neutral, closed-shell moieties. In contrast, self-desorption of X-type ligands implies the formation of either radicals or charged species. The former process is generally unfeasible and the latter is thermodynamically unfavorable in apolar media due to the low dielectric screening. For the same reason, it would be impossible to exchange X-type ligands for L-type ligands. Anionic X-type ligands can only be traded for other anionic X-type ligands by the transfer of a proton or trimethylsilyl group.^[3,6a,c,7]

In contrast to CdSe NCs,^[6a] the surface of ZnO , TiO_2 , ZrO_2 , and HfO_2 NCs can adsorb protons.^[8] In case of fatty-acid-capped ZrO_2 and HfO_2 NCs, we recently showed that both carboxylate and proton bind to the metal oxide NC surface.^[8d] Here, we analyze possible ligand exchange reactions enabled by the presence of this internal proton source, in which we focus on exchange and self-adsorption of oleic acid (HOAc) on HfO_2 and ZrO_2 NCs, benchmarked against oleate-capped CdSe NCs. Our findings indicate that the dissociated carboxylic acid can be described as an X_2 ligand, i.e., a combination of a cationic X-type ligand (H^+) and an anionic X-type ligand (RCOO^-). This new binding motif results in exchange characteristics comparable to those of L-type ligands.

HfO_2 , ZrO_2 , and CdSe NCs were synthesized according to established procedures and HOAc was employed as ligand.^[9] Although HOAc can populate three different states—chemisorbed to the NC, physisorbed in the ligand shell, and free in solution,^[6a] the ^1H NMR spectrum of a purified HfO_2 NC dispersion features only the broadened signals of chemisorbed HOAc (Figure 1A), i.e., no free or physisorbed acid is present in the sample. Upon addition of octylamine (Am), the alkene resonance changes and a new signal appears at

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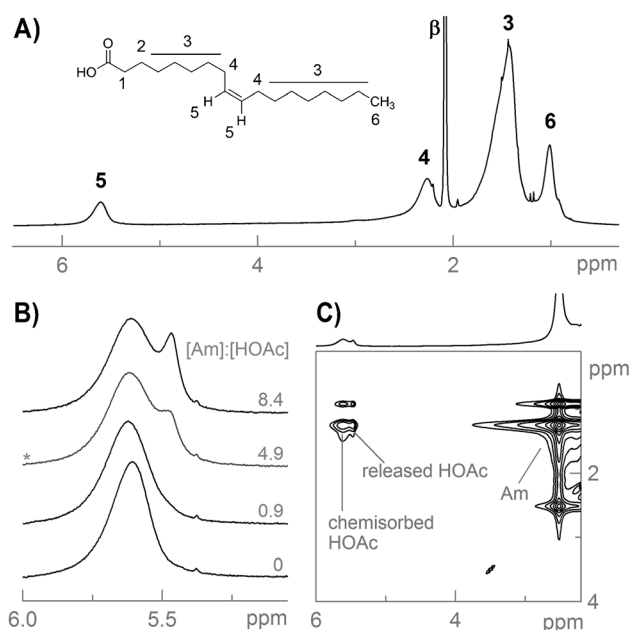


Figure 1. A) Bound HOAc (3–6) and toluene (β) are noted in the ¹H NMR spectrum of a HfO₂ NCs dispersion in [D₈]toluene, [HOAc] = 10.69 mol L⁻¹. B) Upon addition of Am the alkene resonance splits in two parts, bound and free acid. C) 2D NOESY spectrum of HfO₂ NCs + 8.4 equiv of Am.

a slightly lower chemical shift (Figure 1B). This signal increases and sharpens with increasing Am concentration while still featuring the negative nOe cross-peaks that characterize bound states (Figure 1C). We thus interpret it as a mixed-state resonance that exhibits a population-averaged chemical shift and line width resulting from the fast exchange between physisorbed and free HOAc.

Regarding the amine, we focus on its α-CH₂ resonance at 2.3 ppm because it is separated from the aliphatic signals of HOAc. Only a single resonance without fine structure is observed, which clearly leads to negative nOe cross-peaks (Figure 1C). From these two features we infer that Am is in fast exchange between a bound and a free state and only a time average is detected.^[10] The above results suggest that HOAc is displaced by Am.

As reported by Anderson et al. the addition of amines to oleate-capped CdSe NCs releases coordinated Cd(OAc)₂.^[1a] Although these authors did not analyze subtle changes in the alkene resonance—probably due to the higher amine concentration—this raises the question as to whether our results with HfO₂ could be explained by a release of Hf(OAc)₄ instead of HOAc. We therefore added similar amounts of Am to a CdSe NC dispersion, upon which again a sharper alkene resonance appeared (Figure 2A). Because this signal features negative nOe cross peaks (Figure S1), we again attribute it to a mixed-state resonance with, however, slightly different characteristics. The fraction of mixed state—the released species—is much larger for CdSe than for HfO₂, as determined by deconvolution of the alkene resonance (Figure 2B), indicating a more effective ligand exchange for CdSe NCs. Furthermore, a comparison of the according spectra in Figure 1B and 2A (marked with an asterisk), both having

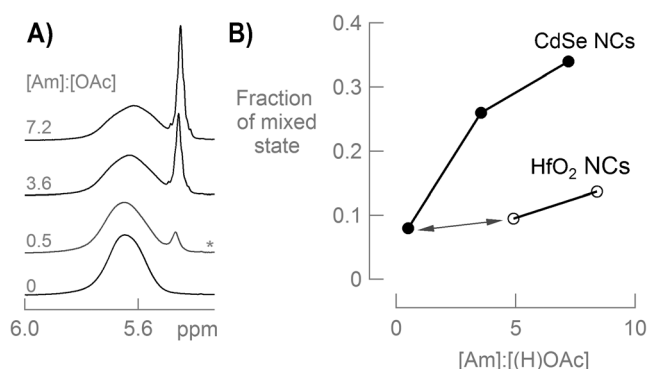


Figure 2. A) A new alkene resonance appears upon addition of Am to a CdSe NC dispersion in [D₈]toluene. B) Am releases a higher fraction of original ligand at CdSe NCs than at HfO₂ NCs.

a more or less equal amount of released alkene (Figure 2B), shows that the mixed resonance of CdSe NCs appears at lower chemical shifts and is more narrow. We conclude that the free state is more predominant in case of Cd(OAc)₂ release. Indeed, even a first hint of fine structure is observed for the mixed resonances in Figure 2A, innate to free molecules. Since Cd(OAc)₂ can be coordinated in solution by excess Am, it will less populate the physisorbed state due to steric hindrance. This behavior is not observed in the titration of HfO₂ NCs, indicating that the released species is not Hf(OAc)₄.

To confirm the nature of the released species we combined IR, NMR, and X-ray fluorescence (XRF) analysis. Upon addition of Am to HfO₂ NCs, the expected carboxylic acid band at 1720 cm⁻¹ is absent in the IR spectrum (Figure 3). However, released HOAc could be deprotonated

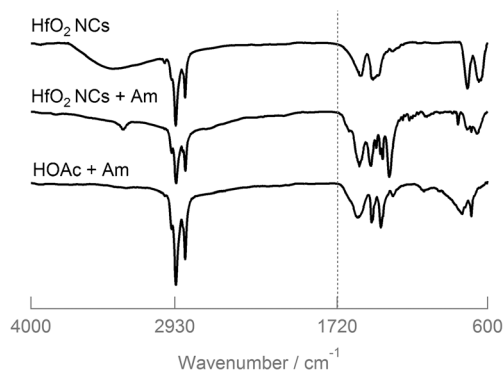


Figure 3. Carboxylic acid bands (1720 cm⁻¹) are neither observed in the FTIR spectrum upon addition of Am to HOAc capped HfO₂ NCs nor in a mixture of HOAc and Am.

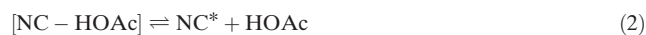
by the excess of Am and form an ion pair. Indeed, the shape and position of the carboxylate peak (1570 cm⁻¹) of Am-treated NCs is essentially the same as for a mixture of HOAc and Am. However, IR does not allow to differentiate between the ion pair and Hf(OAc)₄. Therefore, we precipitated the Am-treated NCs with methanol. After centrifugation, the supernatant was dried under vacuum and the resulting oil was

dissolved in deuterated methanol and measured by NMR and XRF. An alkene resonance with fine structure was observed in the ^1H NMR spectrum (Figure S2) indicating free species. The intensity of the resonance was comparable to the mixed-state resonance in the titration experiment, confirming that we were able to quantitatively separate the NCs from the released species. In addition, no hafnium was detected by XRF analysis (Figure S3) so we finally conclude that the displaced species is HOAc and not $\text{Hf}(\text{OAc})_4$.

Clearly, the exchange reaction is in an equilibrium. In addition, the NOESY spectrum (Figure 1C) proves that Am has a bound state and IR analysis showed that released HOAc forms an ion pair with Am. Therefore we write this exchange equilibrium as follows:



The reaction formally comprises three equilibria; oleic acid desorption (2), octylamine adsorption (3), and ion pair formation (4).



We calculated a reaction quotient of $(2.0 \pm 0.6) \times 10^{-5}$ for the exchange reaction (1), confirming that carboxylic acids bind stronger to the NC surface than amines (for the calculation see the Supporting Information, SI). Importantly, the reaction quotient is only independent of amine concentration if equilibrium (4) is included (Figure 4A). This stresses the central role of the ion-pair formation in the exchange reaction.

Even clearer is the equilibrium's temperature dependence. We find that with increasing temperature equilibrium (1) is shifted to the left, i.e., less HOAc is removed from the surface by Am (Figure 4B). The exchange is therefore reversible and exothermic. If the exchange was regarded as a combination of only (2) and (3), it would be endothermic because amines bind weaker than carboxylic acids. However, reaction (4) is apparently sufficiently exothermic to render the whole exchange exothermic. Hence the identification of (4) as the main driving force of (1). The same temperature dependence is observed for CdSe (Figure 4B). In that case, the driving force for exchange is most likely the exothermic coordination of octylamine to $\text{Cd}(\text{OAc})_2$,^[1a] rendering the overall reaction exothermic. This means that at high temperatures—typical for NC syntheses—the adsorption of amines is negligible compared to the binding of metal carboxylates or carboxylic acids.

Autodesorption of HOAc (2) does not take place without external driving force. Even when the temperature was raised to 130 °C, no free HOAc was observed in the NMR spectrum. However, we could demonstrate the reverse, autoadsorption, by gradually adding excess HOAc to a HfO_2 NC suspension which was purified five times with acetone (Figure 5). The concentration of bound ligand increased by 17 % (at 0.4 equiv HOAc excess). HOAc is thus capable of spontaneous

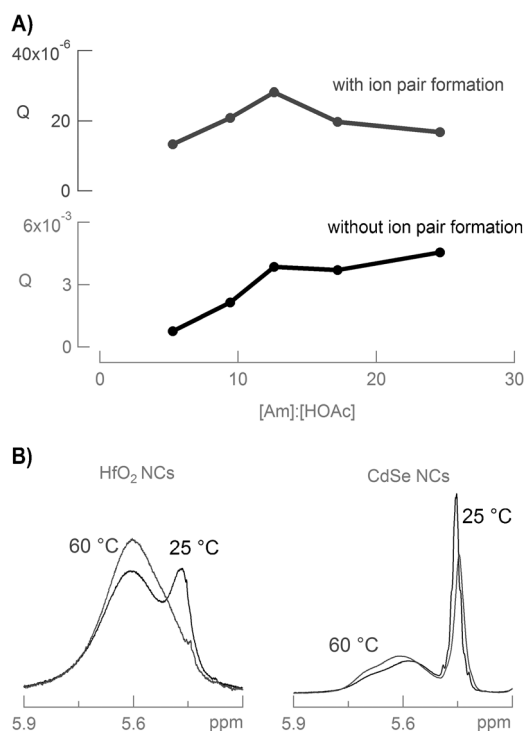


Figure 4. A) The exchange reaction quotient in function of amine concentration. B) Temperature dependence of the alkene resonance after titration with Am.

dissociation on the oxide surface at 25 °C. The free adsorption sites probably emerged from extensive purification. Indeed, dynamic light scattering (DLS) measurements (Figure S4) confirm that aggregates are formed during the purification, indicating ligand stripping. In contrast, HOAc does not display such binding behavior toward CdSe NCs.^[6a]

Scheme 2 summarizes the ligand exchange processes we observed at HfO_2 NCs. First, there is the exchange of carboxylic acids for amines, typical L-type ligands. Note that the driving force is the acid–base ion pair formation. Second, self-adsorption of HOAc on the HfO_2 surface was recognized. These reactions can be rationalized within the concepts offered by the CBC. An X-type ligand is a radical, which can either take an electron (anionic X-type, RCOO^-) or donate its own electron (cationic X-type, H^+) upon formation of an ionic NC–ligand bond. Hence, dissociative adsorption of carboxylic acids brings two X-type moieties on the NC

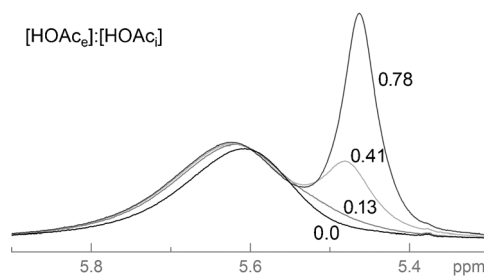
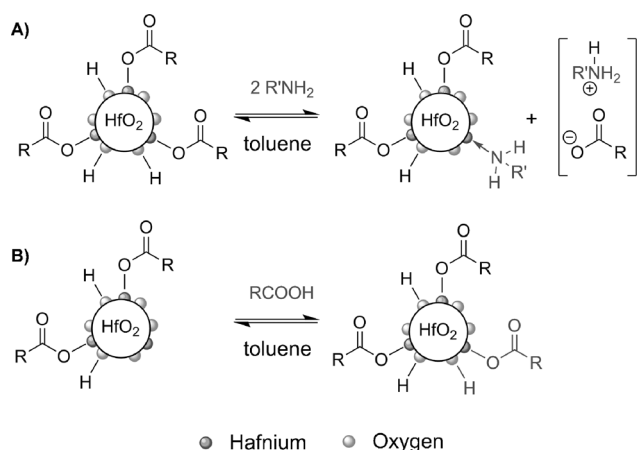


Figure 5. Change of the alkene resonance upon progressive addition of excess oleic acid, $[\text{HOAc}_e]$.



Scheme 2. A) L-type alkylamines displace X₂-type carboxylic acid. B) Autoadsorption of carboxylic acids at the HfO₂ NC surface.

surface, proton and carboxylate. Opposite to a single X-type ligand, this overall charge-neutral X₂ motif can be exchanged for L-type ligands, either by direct release of X₂ or by the formation of complexes such as the ion pair observed here.

To generalize these findings, we repeated the Am titration with ZrO₂ NCs capped with HOAc. Importantly, the ZrO₂ NCs were synthesized with a different precursor, leading to a crystal structure and initial surface chemistry different from the HfO₂ NCs.^[9c] Nevertheless, we observe the release of HOAc acid upon titration with Am (Figure S5), a result indicating that our model may apply to metal oxide NCs in general. Indeed, the ability to hold protons on the surface depends on the basicity of the anion rather than on the nature of the metal although the latter's influence cannot be fully excluded.

In conclusion, we have shown that octylamine releases oleic acid from HfO₂ and ZrO₂ NCs while cadmium oleate is released from CdSe NCs. The ligand exchange reaction is rendered exothermic and thus impeded at high temperature by the formation of an acid/base pair in case of oxides or a metal complex in case of CdSe. Finally, oleic acid features self-adsorption at the oxide but not at the CdSe NC surface. We argue that the exchange characteristics of carboxylic acids bound to metal oxide NCs result from their dissociative adsorption. The NC surface thus contains equal amounts of anionic and cationic X-type ligands, a binding motif we label as X₂. Importantly, the X₂-type binding brings about a new class of NC–ligand systems—stoichiometric NCs with overall neutral X₂ ligands—in addition to cation-rich NCs with anionic X-type ligands and stoichiometric NCs with neutral Z- or L-type ligands. Our work indicates that this new NC–

ligand class will be most relevant to understand the surface chemistry of metal oxide NCs in general.

Keywords: CdSe · ligand exchange · nanoparticles · NMR spectroscopy · surface chemistry

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- [1] a) N. C. Anderson, M. P. Hendricks, J. J. Choi, J. S. Owen, *J. Am. Chem. Soc.* **2013**, *135*, 18536–18548; b) S. W. Boettcher, N. C. Strandwitz, M. Schierhorn, N. Lock, M. C. Lonergan, G. D. Stucky, *Nat. Mater.* **2007**, *6*, 592–596; c) A. E. Nel, L. Madler, D. Velegol, T. Xia, E. M. V. Hoek, P. Somasundaran, F. Klaessig, V. Castranova, M. Thompson, *Nat. Mater.* **2009**, *8*, 543–557; d) J. Huang, W. Y. Liu, D. S. Dolzhnikov, L. Protesescu, M. V. Kovalenko, B. Koo, S. Chattopadhyay, E. V. Shchenchenko, D. V. Talapin, *ACS Nano* **2014**, *8*, 9388–9402.
- [2] M. L. H. Green, *J. Organomet. Chem.* **1995**, *500*, 127–148.
- [3] J. S. Owen, J. Park, P. E. Trudeau, A. P. Alivisatos, *J. Am. Chem. Soc.* **2008**, *130*, 12279–12280.
- [4] M. L. H. Green, G. Parkin, *J. Chem. Educ.* **2014**, *91*, 807–816.
- [5] R. Dierick, F. Van den Broeck, K. De Nolf, Q. Zhao, A. Vantomme, J. C. Martins, Z. Hens, *Chem. Mater.* **2014**, *26*, 5950–5957.
- [6] a) B. Fritzinger, R. K. Capek, K. Lambert, J. C. Martins, Z. Hens, *J. Am. Chem. Soc.* **2010**, *132*, 10195–10201; b) A. Cros-Gagneux, F. Delpech, C. Nayral, A. Cornejo, Y. Coppel, B. Chaudret, *J. Am. Chem. Soc.* **2010**, *132*, 18147–18157; c) A. J. Morris-Cohen, M. T. Frederick, G. D. Lilly, E. A. McArthur, E. A. Weiss, *J. Phys. Chem. Lett.* **2010**, *1*, 1078–1081; d) D. Zhrebetskyy, M. Scheele, Y. J. Zhang, N. Bronstein, C. Thompson, D. Britt, M. Salmeron, P. Alivisatos, L. W. Wang, *Science* **2014**, *344*, 1380–1384.
- [7] a) A. Hassinen, I. Moreels, K. De Nolf, P. F. Smet, J. C. Martins, Z. Hens, *J. Am. Chem. Soc.* **2012**, *134*, 20705–20712; b) M. A. Caldwell, A. E. Albers, S. C. Levy, T. E. Pick, B. E. Cohen, B. A. Helms, D. J. Milliron, *Chem. Commun.* **2011**, *47*, 556–558; c) N. C. Anderson, J. S. Owen, *Chem. Mater.* **2013**, *25*, 69–76.
- [8] a) C. N. Valdez, A. M. Schimpf, D. R. Gamelin, J. M. Mayer, *ACS Nano* **2014**, *8*, 9463–9470; b) C. N. Valdez, M. Braten, A. Soria, D. R. Gamelin, J. M. Mayer, *J. Am. Chem. Soc.* **2013**, *135*, 8492–8495; c) J. N. Schrauben, R. Hayoun, C. N. Valdez, M. Braten, L. Fridley, J. M. Mayer, *Science* **2012**, *336*, 1298–1301; d) J. De Roo, F. Van den Broeck, K. De Keukeleere, J. C. Martins, I. Van Driessche, Z. Hens, *J. Am. Chem. Soc.* **2014**, *136*, 9650–9657.
- [9] a) J. De Roo, K. De Keukeleere, J. Feys, P. Lommens, Z. Hens, I. Van Driessche, *J. Nanopart. Res.* **2013**, *15*, 1778; b) J. Jasieniak, C. Bullen, J. van Embden, P. Mulvaney, *J. Phys. Chem. B* **2005**, *109*, 20665–20668; c) K. De Keukeleere, J. De Roo, P. Lommens, J. C. Martins, P. Van Der Voort, I. Van Driessche, *Inorg. Chem.* **2015**, DOI: 10.1021/acs.inorgchem.5b00046.
- [10] Z. Hens, J. C. Martins, *Chem. Mater.* **2013**, *25*, 1211–1221.

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