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Studying the Thermodynamics of Surface Reactions on Nanoparticles by Electrostatic Titrations

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Nanoparticles coated with mixed self-assembled monolayers[1] (*m*-SAM NPs) have been studied extensively as components of new types of (bio)sensors,[2] as building blocks of NP suprastructures,[3] and in the context of nanoscale phase-separation phenomena.[4] Since many of these applications rely on the ability to adjust and control *m*-SAM's composition, various spectroscopic methods[5] have been used to elucidate both the kinetics[6] and the thermodynamics[7] of mixed monolayer formation; these methods, however, sometimes lack generality[5a] and are often limited by line broadening/signal overlap effects (cf. Supporting Information). Here, we show that for NPs covered with binary SAMs containing at least one charged (or ionizable) component, the relative equilibrium constants and the difference in the free energies of absorption of the *m*-SAM's components can be obtained in a straightforward way by titrating the *m*-SAM NPs with oppositely charged nanoparticle "standards". Our approach is based on the recent discovery that mixtures of oppositely charged NPs of various sizes (3−11 nm) and relative charges always precipitate sharply at the point of overall electroneutrality.[8,9] This unique nanoscale property allows (i) for the determination of surface compositions of the *m*-SAM NPs from the positions of precipitation points, χ^P and (ii) for relating the values of χ^P to the pertinent thermodynamic quantities.

We investigated the formation of mixed SAMs of 11-mercaptoundecanoic acid ($HS(CH_2)_{10}COOH$; MUA) and 11-mercaptoundecanol ($HS(CH_2)_{11}OH$; MUO) on gold nanoparticles[8] of average diameter of 5.5 nm and dispersity $\sigma = 9\%$ (Figure 1a). We chose this model system because it cannot easily be studied by other instrumental methods (e.g., NMR or XPS) due to pronounced line broadening and/or overlap of signals from COOH and OH groups (for further discussion, see Supporting Information). In addition, although it has recently been shown that both of these thiols are capable of favorable hydrogen bonding in the SAMs they form, and that the free energies of their absorption onto gold are ∼12 kT lower than those of the corresponding (nonfunctionalized) alkane thiols,[10] it was not possible to determine the energetic difference of H-bonding in MUA versus MUO SAMs.

To study competitive MUO/MUA adsorption, Au NPs stabilized with dodecylamine (DDA) were first soaked for 15 h in toluene/dichloromethane (50 mL/15 mL) mixtures of various relative concentrations of the two thiols, $\alpha = c_{sol}^{MUO}/c_{sol}^{MUA} = 0, 2, 4, 8, 16, 32$ (Figure 1a). For all values of α, the concentration of gold NPs (2 mM in terms of gold atoms) and the total concentration of thiols (8 mM) were kept constant, with the thiols used in large excess with respect to the number of adsorption sites on NPs (>40 times). After soaking, the unbound thiols were removed by washing with dichloromethane. The NPs were then dissolved in water, and the pH of all solutions was adjusted to 11 to deprotonate the carboxylic groups. The resulting 2 mM solutions of Au NPs covered with mixed MUO/MUA SAMs were then titrated (Figure 1b,c) with small (0.05−0.1 equiv) aliquots of 2 mM solutions of equally sized Au NPs covered with positively charged *N*,*N*,*N*-trimethyl(11-mercaptoundecyl)ammonium chloride ($HS(CH_2)_{11}N(CH_3)_3{}^+Cl^-$; TMA).[11]

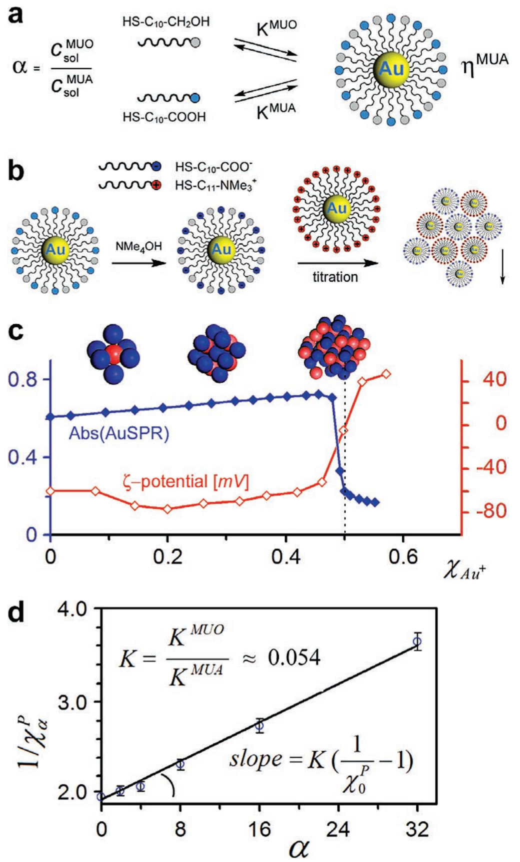

Figure 1. (a) Structures of the thiols and their competitive absorption onto NPs. (b) Scheme of the titration of Au NPs coated with a mixed MUO/MUA SAM against oppositely charged AuTMA nanoparticles. (c) Typical titration involving NPs bearing charges of equal magnitudes and opposite polarities (here, 5.5 nm Au MUA with 5.5 nm Au TMA). Blue curve gives the intensity of the Au SPR band at $\lambda_{max} = 520-550$ nm as the function of the mole fraction of AuTMAs added; red curve has the value of the ζ-potential. Dashed vertical line gives the theoretically expected precipitation point. Schemes illustrate the structures that form at various stages of the titration: from small, stable core-and-shell complexes to large, precipitating electroneutral aggregates. (d) Dependence of the inverse of the precipitation points, $1/\chi_\alpha^P$, on the ratio of the concentrations, α, of MUO/MUA thiols in solution. The line is the least-square fit to data and its slope is proportional to the ratio of absorption equilibrium constants. The standard errors are within 1−3%.

During the titration, the NPs initially remained in solution and the values of the ζ-potential did not change.[8a] This behavior was due to the formation of aggregates surrounded by shells composed

10.1021/ja068329t CCC: $37.00

mostly of the like-charged, excess NPs (here, MUO/MUA NPs).[8c] Since the shells had a net electric charge, they stabilized the solution phase by solvation and mutual electrostatic repulsions. When, however, the charges of the NPs were compensated, these favorable effects were no longer operative, and the neutral aggregates precipitated rapidly. Importantly, because the negative charge on the NPs was proportional to the amount of adsorbed and deprotonated MUA, the measured precipitation points, χ_{α}^{P}, gave the molar fractions of both types of thiols, η, in the adsorbed *m*-SAMs.

To determine equilibrium constants from the titration points, we first note that (i) DDA capping ligands are bound to the surface of gold NP weakly and their replacement with thiols occurs rapidly, within a few minutes[12] and (ii) because the thiols were used in large excess with respect to NPs, the adsorbed and free thiols of both types could exchange[7a] to ultimately give a nearly equilibrated ratio of MUO/MUA on NP surfaces.

For each of the thiols, the equilibrium constant for absorption onto Au NPs is given by $K^{T} = c_{Au}^{T}/(c_{sol}^{T}c_{Au})$, where $T =$ MUO or MUA, c_{Au}^{T} is the concentration of thiol adsorbed onto AuNPs, c_{sol}^{T} stands for concentration of free thiol in solution, and c_{Au} is the concentration of the adsorption sites on the surface of Au NPs. Because the mole fraction of MUA thiol on the surface can be written as $\eta^{MUA} = 1/[1 + \alpha(K^{MUO}/K^{MUA})]$, the positions of precipitation points for different values of α are related by $\chi_{\alpha}^{P} = \chi_{0}^{P}\eta^{MUA}/(1 + \chi_{0}^{P}\eta^{MUA} - \chi_{0}^{P})$, where χ_{0}^{P} is the precipitation point of Au NPs soaked in pure MUA ($\alpha = 0$). Therefore, the ratio of the equilibrium constants K^{MUO} and K^{MUA} can be determined from the slope of the dependence of $1/\chi_{\alpha}^{P}$ on α: $1/\chi_{\alpha}^{P} = 1/\chi_{0}^{P} + (1/\chi_{0}^{P} - 1)(K^{MUO}/K^{MUA})\alpha$ (Figure 1d).

The calculated value $K^{MUO}/K^{MUA} = 0.054$ indicates that MUA absorption is favored over that of MUO, likely because of stronger hydrogen bonding between the COOH head-groups than between the OH ones. This preference can be quantified in terms of the free energies of absorption of the two thiols using the thermodynamic relationship $\Delta G = -k_{B}T \ln K$, from which it follows that $\Delta G^{MUO} - \Delta G^{MUA} = -k_{B}T \ln(K^{MUO}/K^{MUA}) = 2.9k_{B}T$. Interestingly, this estimate agrees with the difference of hydrogen-bonding energies in methanol and in carboxylic acids.[13]

We make two further comments regarding the method and its extensions. First, material properties of the NPs (e.g., Au versus Ag), differences in their average sizes (from ~4 to 10 nm), and the concentration of NP solutions (0.2−2 mM) do not affect the results perceptibly provided that the NPs are not too polydisperse ($\sigma \leq \sim 15\%$).[8a] When the polydisperisty is increased and skewed toward smaller particles, however, the solutions become more stable, and at $\sigma \approx 40\%$ do not precipitate at all. This effect is discussed in detail in ref 8b and is due to the small particles, which screen the attractions between larger NPs, stabilize them, and prevent their aggregation/precipitation. Second, the method is suitable not only for titrations involving two types of NPs, but also NPs and charged molecules. This is illustrated in Figure 2, which shows changes in the intensity of Au SPR band during the titration of Au NPs covered with TMA with either free MUA thiol or sodium dodecylsulfate ($C_{12}H_{25}SO_3^{-}Na^{+}$; cf. Supporting Information). For both systems, precipitation occurs at the same point (and at zero ζ-potential) as for the AuMUA/AuTMA, allowing for direct estimation of the number of TMA thiols adsorbed on the surface of the NP with respect to the number of gold atoms in one NP, $n_{TMA} = n_{Au}/11.6$, which agrees with previous estimates.[14] This experiment also suggests a possibility of "reverse" experiments, in which NPs of known charge could be used to probe electrostatics of other (bio)-molecules.[15]

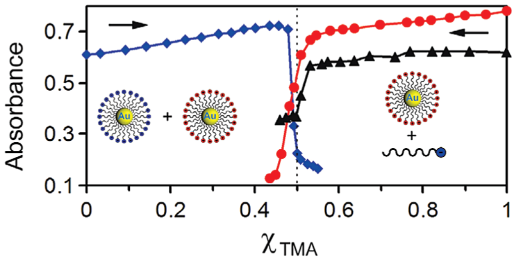

Figure 2. The curves show the intensity of the Au SPR band during (blue line) titration of negatively charged Au MUAs with positively charged Au TMA NPs; (red line) titration of a solution of AuTMAs with SDS; (black line) titration of Au TMA with MUA. Here, $\chi_{TMA} = N_{TMA}/(N_{TMA} + N_{x})$, where N_{TMA} is the number of moles of TMA adsorbed onto Au NPs, and N_{x} stands for the total number of moles of SDS or MUA in solution (i.e., either free or on the NPs). Dashed vertical line gives the theoretically expected precipitation point; arrows indicate the "direction" of titration.

In summary, titrations involving charged NPs provide a simple, accurate, and versatile method of probing charges and surface reactions on nanoparticles. We suggest the method can be further extended to systems involving interactions other than electrostatic (vdW, covalent), and in which the deviation of the observed precipitation point from the "ideal" point of electroneutrality would allow quantification of the additional interactions/effects.

Acknowledgment. This work was supported by the Pew Scholars Program in the Biomedical Sciences (to B.A.G.).

Supporting Information Available: Synthesis, NMR and XPS spectra of the *m*-SAM NPs; verification of *m*-SAM composition via NP dissolution; NP precipitation with surfactants. This material is available free of charge via the Internet at http://pubs.acs.org.

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JA068329T