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Enhanced optical sensing of anions with amide-functionalized gold nanoparticles

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A gold nanoparticle surface-modified with amide ligands shows enhanced optical sensing of anions: the detection limit is increased by about three orders of magnitude higher than that originally expected from the anion binding ability of neutral amide ligands.

Gold and silver nanoparticles have been of increasing interest in applications to biological and chemical nanosensors. In recent years, optical[1–3] and electrochemical[4,5] nanoprobes have been developed by modifying the surface of metal nanoparticles with various functional molecules. Gold nanoprobes capable of optically sensing biological macromolecules such as polynucleotides have been extensively studied.[1] However, there are few nanoparticle-type optical probes for biologically important ions and molecules. As gold nanoparticles have tremendously high molar absorptivity in the visible region,[6] they must have considerable potential for optical detection of ions and molecules as well as macromolecules. Here we report that an amide-functionalized gold nanoparticle **1** can optically sense anions with significantly high sensitivity.[7,8]

The amide-functionalized gold nanoparticle **1** (Fig. 1) was synthesized by ligand exchange of alkanethiolate-protected gold nanoparticles[9] without structural changes in the gold core. The exchange reactions of hexanetiolate-protected gold nanoparticles[10] with *n*-BuNHCO($C_{10}H_{20}$)SH in CH_2Cl_2 for 24 h were carried out for a 1 : 1 mole ratio of *n*-BuNHCO($C_{10}H_{20}$)SH to C_6H_{13}S–Au. After purification *via* sequential precipitation, gold nanoparticles **1** were characterized by elemental analysis, powder X-ray diffraction (XRD), and UV-vis spectroscopies. The mean diameter of the gold core determined by XRD was 4.0 ± 0.5 nm. Assuming a truncated octahedral shape[11] the core of **1** is predicted to contain 2406 Au atoms. Given the values for elemental analysis of **1** (C: 9.37%; H: 1.37%; N: 0.68%), there are 69 C_6H_{13}S–Au and 260 BuNHCO($C_{10}H_{20}$)S–Au ligands. CH_2Cl_2 solutions of **1** are wine-red characteristic of the plasmon band at 520 nm (ε = 4.65 × 10^6 M^{-1} cm^{-1}).

The anion sensing properties of **1** were investigated by UV-vis titrations with $H_2PO_4^-$, HSO_4^-, AcO^-, NO_3^-, Cl^-, Br^- and I^-. The addition of anions (as their Bu_4N^+ salts) to a solution of **1** in CH_2Cl_2 at 20 °C caused dramatic changes in the plasmon band. When 0–0.5 equiv. of anion/BuNHCO($C_{10}H_{20}$)S–Au was added to the solution of **1** ([**1**] = 2.26 × 10^{-8} M), the plasmon band decreased by 45–55% in intensity with a slight red shift in wavelength (Fig. 2(a)). When blank tests were performed on hexanethiolate-protected gold nanoparticles lacking the amide ligands, there was no significant spectral change. Under the present conditions, consequently, the spectral changes in **1** were dominantly induced by anions. The counter cation, Bu_4N^+, minimally contributes to the overall spectral change in **1**. Lazarides and Schatz reported that, upon DNA-induced nanoparticle aggregation, the decrease in extinction is attributed to the screening of nanoparticles embedded deeply within the aggregate interior.[12] The marked decrease in extinction would be due to anion-induced aggregation of **1** through hydrogen-bond formation between the anions and the interparticle amide ligands. They also showed using coupled dipole approximations that a dramatic red shift occurs in the plasmon band when the interparticle distances in the aggregates decrease to less than the average particle radius.[13] Nanoparticles **1** within the anion-induced aggregates might not be close enough to cause the color change. Further addition of anions to the solution of **1** caused an increase in extinction (Fig. 2(b)), reflecting the disaggregation of the suprananoparticles composed of **1** and anions. Fig. 3 shows UV-vis titration curves for anions in CH_2Cl_2. When excess of $H_2PO_4^-$, HSO_4^- or AcO^- was added to the solution, the UV-vis spectra were restored to the original state. In contrast, the initial extinction was not recovered even after addition of a large excess of Cl^-, Br^-, I^- or NO_3^-. There were also no time-dependent spectral changes when these solutions were kept at 20 °C for 24 h after addition of 10 equiv. of anion/BuNHCO($C_{10}H_{20}$)S–Au. The aggregates of **1** and these anions were tightly held together and were hardly disaggregated by the component anions themselves.

The association constants for anions with neutral amide ligands are generally not so high (K_a < 100 M^{-1}) even in low dielectric solvents.[14] If there are optical probes containing such

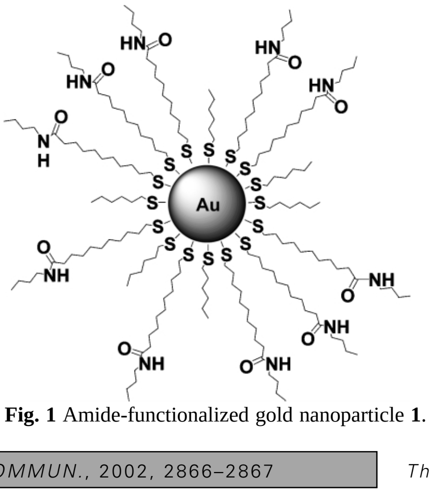

Fig. 1 Amide-functionalized gold nanoparticle **1**.

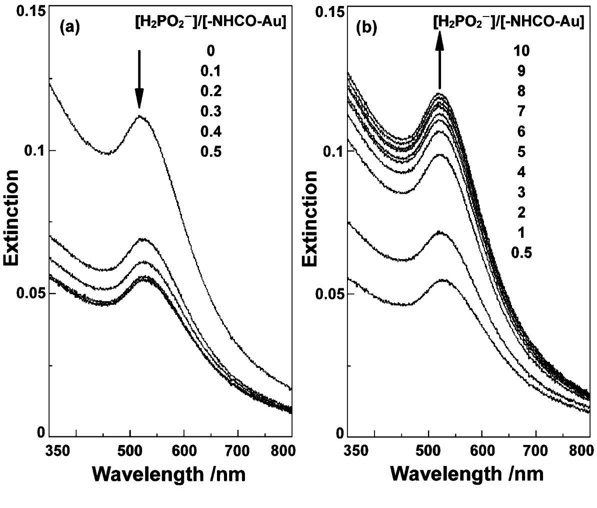

Fig. 2 Change in the UV-vis spectrum of Au nanoparticles **1** upon addition of $H_2PO_4^-$ in CH_2Cl_2 at 293 K: [**1**] = 2.26 × 10^{-8} M, [$H_2PO_4^-$] = 0–5.86 × 10^{-5} M.

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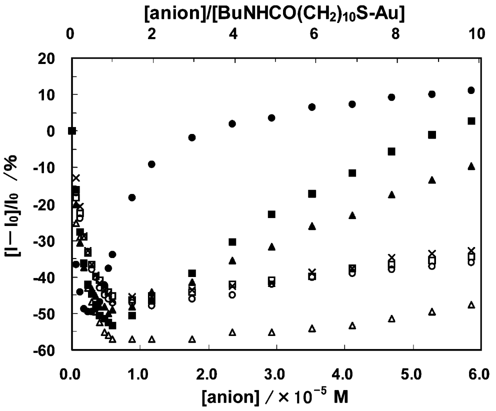

Fig. 3 UV-vis titration curves of **1** with anions in CH_2Cl_2 at 293 K: (●) $H_2PO_4^-$, (■) HSO_4^-, (▲) AcO^-, (×) NO_3^-, (○) Cl^-, (□) Br^-, (△) I^-.

amide ligands, they would be expected to have a detectable response only at $> 10^{-3}$ M concentration of anions.[15] Therefore, it is noted that the nanoparticles **1** are capable of optically sensing changes in anion concentration at a level of 10^{-6} M. The detection limit is increased about three orders of magnitude higher than originally expected. This effectiveness cannot be understood only by the cooperative action of the amide ligands assembled on the particle surface. Interparticle van der Waals attractions may play a key role, which are quite strong, in particular between metal nanoparticles, because of the large polarizability of the gold cores.[16]

In order to elucidate the fundamental features of binding selectivity, optical sensing studies between **1** and anions were further performed in CH_2Cl_2 containing DMSO as a competitive solvent. For 1% DMSO/CH_2Cl_2, the maximum decreasing ratio $\Delta I_{max} = (I_{min} - I_0)/I_0$ in extinction of **1** upon anion binding was in the following order: HSO_4^- (−48%) > $H_2PO_4^-$ (−43%) > AcO^- (−29%) > Cl^-, NO_3^- (−19%) > Br^-, I^- (−10%). As the amide ligands were randomly introduced on the surface of **1**, the binding selectivity should follow the ability of the guest anions to form hydrogen-bonds to the amide ligands rather than their structural differences. ΔI_{max} is plotted against the free energy of hydration $\Delta G°_{0,1}$ (kcal mol^{-1}) [17] in the gas phase for the anions as a measure of hydrogen-bond acceptor strength of the guest anions (Fig. 4).[18] There is a good correlation between ΔI_{max} and $\Delta G°_{0,1}$ for the anions except for HSO_4^- and $H_2PO_4^-$. The marked deviation of ΔI_{max} for these two anions cannot be explained only by their hydrogen-bond acceptor strength. The preference for HSO_4^- and $H_2PO_4^-$ over other anions indicates that the hydrogen-bond interaction of NHCO···HOX (X = S or P) significantly contributes to the anion recognition leading to nanoparticle aggregation.

In summary, amide-functionalized gold nanoparticles **1** represent novel prototype nanoprobes for the optical recognition of anions, which has distinct advantages in sensitivity. Although further improvements of the selectivity and the binding affinity are required for practical use, gold nanoparticles are particularly easy to build up their highly functionalized surface through ligand exchange reactions. The surface-functionalized gold nanoparticles are considerably potential as optical nanoprobes of biologically important ions and molecules.

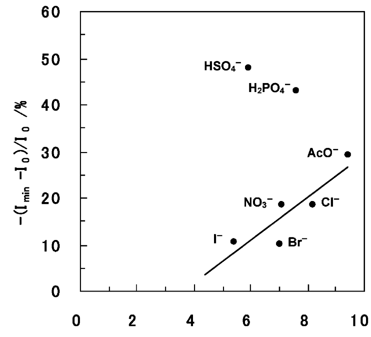

Fig. 4 Plots of anion-induced maximum decreasing ratio $(I_{min} - I_0)/I_0$ in extinction of **1** in 1% DMSO/CH_2Cl_2 *vs.* free energies $\Delta G_{0,1}$ of hydration in the gas phase for anions.

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Notes and references

1 C. A. Mirkin, R. L. Letsinger, R. C. Mucic and J. J. Storhoff, *Nature*, 1996, **382**, 607; R. Elghanian, J. J. Storhoff, R. C. Mucic, R. L. Letsinger and C. A. Mirkin, *Science*, 1997, **277**, 1078; L. M. Demers, C. A. Mirkin, R. C. Mucic, R. A. Reynolds, III, R. L. Letsinger, R. Elghanian and G. Viswanadham, *Anal. Chem.*, 2000, **72**, 5535; T. A. Taton, G. Lu and C. A. Mirkin, *J. Am. Chem. Soc.*, 2001, **123**, 5164; H. Otsuka, Y. Akiyama, Y. Nagasaki and K. Kataoka, *J. Am. Chem. Soc.*, 2001, **123**, 8226.

2 N. Nath and A. Chilkoti, *J. Am. Chem. Soc.*, 2001, **123**, 8197.

3 K. G. Thomas and P. V. Kamat, *J. Am. Chem. Soc.*, 2000, **122**, 2655.

4 A. K. Boal and V. M. Rotello, *J. Am. Chem. Soc.*, 1999, **121**, 4914.

5 A. Labande, J. Ruiz and D. Astruc, *J. Am. Chem. Soc.*, 2002, **124**, 1782.

6 The molar absorptivity for the 8- and 13-nm-diameter particles was reported to be 7.5×10^7 M^{-1} cm^{-1} at 520 nm and 4.7×10^9 M^{-1} cm^{-1} at 524 nm, respectively: R. C. Mucic, J. J. Storhoff, C. A. Mirkin and R. L. Letsinger, *J. Am. Chem. Soc.*, 1998, **120**, 12674.

7 For recent reports for colorimetric anion sensors, see: P. A. Gale, L. J. Twyman, C. I. Handlin and J. L. Sessler, *Chem. Commun.*, 1999, 1851; J. J. Lavigne and E. V. Anslyn, *Angew. Chem., Int. Ed.*, 1999, **38**, 3666; H. Miyaji, W. Sato and J. L. Sessler, *Angew. Chem., Int. Ed.*, 2000, **39**, 1777; S. Yamaguchi, S. Akiyama and K. Tamao, *J. Am. Chem. Soc.*, 2001, **123**, 11372; H. Miyaji and J. L. Sessler, *Angew. Chem., Int. Ed.*, 2001, **40**, 154; T. Mizuno, W.-H. Wei, L. R. Eller and J. L. Sessler, *J. Am. Chem. Soc.*, 2002, **124**, 1134.

8 For a recent review also dealing with general anion receptors, see: P. D. Beer and P. A. Gale, *Angew. Chem., Int. Ed.*, 2001, **40**, 486.

9 M. Brust, M. Walker, D. Bethell, D. J. Schiffrin and R. Whyman, *J. Chem. Soc., Chem. Commun.*, 1994, 801.

10 M. J. Hostetler, J. E. Wingate, C.-J. Zhong, J. E. Harris, R. W. Vachet, M. R. Clark, J. D. Londono, S. J. Green, J. J. Stokes, G. D. Wignall, G. L. Glish, M. D. Porter, N. D. Evans and R. W. Murray, *Langmuir*, 1998, **14**, 17.

11 R. L. Whetten, J. T. Khoury, M. M. Alvarez, S. Murthy, I. Vezmar, Z. L. Wang, P. W. Stephens, C. L. Cleveland, W. D. Luedtke and U. Landman, *Adv. Mater.*, 1996, **8**, 428.

12 A. A. Lazarides and G. C. Schatz, *J. Phys. Chem. B*, 2000, **104**, 460; J. J. Storhoff, A. A. Lazarides, R. C. Mucic, C. A. Mirkin, R. L. Letsinger and G. C. Schatz, *J. Am. Chem. Soc.*, 2000, **122**, 4640.

13 A. A. Lazarides and G. C. Schatz, *J. Chem. Phys.*, 2000, **112**, 2987.

14 P. D. Beer, A. R. Graydon, A. O. M. Johnson and D. K. Smith, *Inorg. Chem.*, 1997, **36**, 2112; J. E. Kingston, L. Ashford, P. D. Beer and M. G. B. Drew, *J. Chem. Soc., Dalton Trans.*, 1999, 251; P. D. Beer, P. K. Hopkins and J. D. McKinney, *Chem. Commun.*, 1999, 1253.

15 The maximum optical response generally occurs near the dissociation constant (K_d) of the probes. We assumed that optical probes have a detectable response in the concentration range from approximately 0. 1 × K_d to 10 × K_d. The lower limit of the detection was estimated to be 0.001 M by 0. 1 × K_d (= K_a^{-1}): R. P. Haugland, *Handbook of Fluorescent Probes and Research Chemicals*, Molecular Probes, Eugene, 6th edn., 1996.

16 D. Bargeman and F. Van Voorst Vader, *J. Electroanal. Chem.*, 1972, **37**, 45.

17 M. Arshadi, R. Yamdagni and P. Kebarle, *J. Phys. Chem.*, 1970, **74**, 1475; A. T. Blades, J. S. Klassen and P. Kebarle, *J. Am. Chem. Soc.*, 1995, **117**, 10563.

18 The pK_a values of acids (HX) in aqueous solution are often used as a measure of the hydrogen-bond acceptor strength of the corresponding anions (X^-). The differences in solvation of HX and X^- are well known to influence pK_a values and in certain cases reverse acidity order in solution. For the present system, consequently, the $\Delta G°_{n-1,n}$ for $X^-(H_2O)_{n-1} + H_2O \rightarrow X^-(H_2O)_{n-1}$ in the gas phase is a much better measure of the hydrogen-bond acceptor strength than the pK_a in water: P. Buhlmann, S. Nishizawa, K. P. Xiao and Y. Umezawa, *Tetrahedron*, 1997, **53**, 1647.