

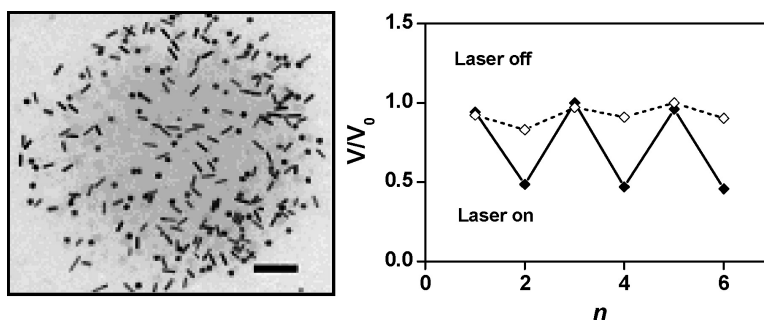
Communication

Hybrid Microgels Photoresponsive in the Near-Infrared Spectral Range

Ivan Gorelikov, Lora M. Field, and Eugenia Kumacheva

J. Am. Chem. Soc., **2004**, 126 (49), 15938-15939 • DOI: 10.1021/ja0448869 • Publication Date (Web): 16 November 2004

Downloaded from <http://pubs.acs.org> on April 5, 2009



More About This Article

Additional resources and features associated with this article are available within the HTML version:

- Supporting Information
- Links to the 18 articles that cite this article, as of the time of this article download
- Access to high resolution figures
- Links to articles and content related to this article
- Copyright permission to reproduce figures and/or text from this article

[View the Full Text HTML](#)



ACS Publications
 High quality. High impact.

Hybrid Microgels Photoresponsive in the Near-Infrared Spectral Range

Ivan Gorelikov, Lora M. Field, and Eugenia Kumacheva*

Department of Chemistry, University of Toronto, 80 St. George Street, Toronto, Ontario M6S 3H6, Canada

Received August 24, 2004; E-mail: ekumache@alchemy.chem.utoronto.ca

Photothermally modulated volume transitions in polymer hydrogels have promising applications in materials science^{1–3} and in drug delivery.⁴ To induce such transitions, photosensitive moieties (dyes^{1,5–7} or metal nanoparticles^{2–4}) are embedded in a thermally reversible polymer matrix and irradiated at their resonance wavelengths. Conversion of the light energy to heat through nonradiative relaxation causes hydrogel heating and, for polymers with a lower critical solution temperature (LCST), results in their volume phase transition (deswelling). For applications of thermoresponsive gels as drug delivery carriers, it is vital that the photosensitive species strongly absorb in the “water window” spectral range, that is, at $800 \text{ nm} < \lambda < 1200 \text{ nm}$.⁸ To our knowledge, the only feasible approach to achieving a strong photothermally triggered volume transition in the desired spectral range has been demonstrated by Halas and West,⁴ who employed a new class of optically active nanoparticles: SiO₂ particles coated with thin gold shells. The relation between the diameter of the SiO₂ core and the Au shell thickness was varied to shift the surface plasmon of gold to the spectral range from 700 to 1050 nm.⁹ Following the incorporation of such particles in a bulk hydrogel with a LCST and irradiation at $\lambda = 1064 \text{ nm}$, the hydrogel shrank and released the drug.⁴

Here we report a new approach to achieving photothermally modulated volume transitions in submicrometer hydrogel particles (microgels) in the near-IR spectral range. We employed hybrid microgels comprised of a temperature-responsive copolymer and gold nanorods (NRs) designed to absorb near-IR light. The advantage of microgels is their small size, a relatively fast volume response to variation in temperature,¹⁰ and the possibility to use them as drug delivery systems.¹¹ The unique feature of gold NRs is that the wavelength of their longitudinal surface plasmon can be accurately controlled by altering their aspect ratio.¹² We irradiated the hybrid microgels with $\lambda = 810 \text{ nm}$ and observed a strong photothermally induced decrease in microgel volume.

Poly(*N*-isopropylacrylamide-*acrylic acid*) [poly(NIPAM-AA)] microgels with a hydrodynamic diameter of ca. 500 nm (pH = 4.0, $T = 25 \text{ }^\circ\text{C}$) were synthesized using surfactant-free polymerization.¹³ The microgels were then dialyzed against deionized water (Millipore MilliQ water with Spectra/Por 4 dialysis membrane) for one week, diluted to 1.5 mg/mL with a potassium biphthalate buffer (pH = 4.0), centrifuged at 10 000 rpm at 4 $^\circ\text{C}$, and redispersed in pH 4 buffer.

The gold NRs were obtained following the method of El-Sayed.¹² We synthesized 3-nm-size seed Au nanoparticles stabilized with cetyltrimethylammonium bromide (CTAB). Nanorods were obtained by adding nanoparticle seeds to the growth solution: an aqueous mixture of CTAB and benzyldimethylhexadecylammonium chloride (BDAC), AgNO₃, HAuCl₄, and L-ascorbic acid.¹² We used the weight ratio BDAC/CTAB of 1:1 to produce rods with ca. 6 nm diameter. The length of the NRs was controlled by changing the concentration of seed nanoparticles added to the growth solution and by varying the concentration of ascorbic acid. Figure 1 (inset) shows the variation in absorption spectra of nanorods with increase

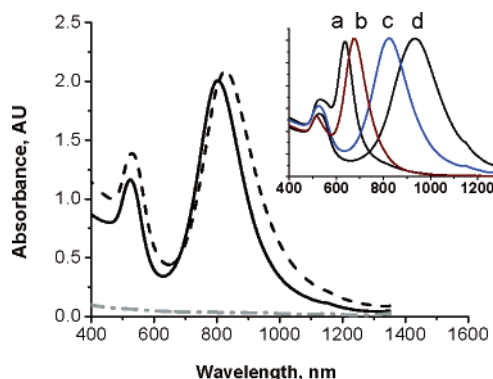


Figure 1. UV-visible-near-IR spectra of gold nanorods with aspect ratio 4.3 dispersed in an aqueous solution (—) and localized in the interior of microgels (---). (Inset) Variation in absorption spectra of gold nanorods dispersed in an aqueous solution as a function of their aspect ratio: (a) 2, (b) 2.5, (c) 4.3, and (d) 6.

of their mean aspect ratio. When the value of the aspect ratio increased from ca. 2 to 6, the position of the short-wavelength absorption peak (at 525 nm) associated with the width of the nanorods was invariant, while the wavelength of the longitudinal surface plasmon band shifted from 650 to 950 nm.

The solution of NRs and the microgel dispersion were mixed at pH = 6 to the weight ratio polymer/NRs of 2:3. We used attractive electrostatic forces to embed the positively charged Au NRs into the negatively charged poly(NIPAM-AA) microgel particles (ζ -potential = -10 mV). At pH = 6, the polymer is highly swollen due to the osmotic effect and electrostatic repulsion between the AA residues, both favoring the incorporation of the NRs into the voids of microgel. In Figure 1, the plasmon band of the NRs embedded in the microgels is centered at 824 nm; that is, it was only by 20 nm red-shifted in comparison with the band of free Au nanorods dispersed in the water solution. The red-shift presumably originated from a minor end-to-end aggregation of nanorods, causing their effective elongation. The transverse surface plasmon peak of the nanorods did not change following their incorporation into the microgel particles.

Figure 2 shows a typical TEM image of the microgels doped with Au nanorods. Individual nanorods were well-isolated in the microgel interior due to electrostatic repulsion between the positively charged nanoparticles. The NRs were evenly dispersed throughout the microgel spheres. An extremely small number of free nanorods remained in the solution.

Figure 3 shows that hybrid microgel-nanorod particles remained temperature responsive: the value of LCST for both pure (non-doped) and hybrid microgel particles was 30 $^\circ\text{C}$ at pH = 4. A small shift toward a lower LCST in comparison with that of homopolymer polyNIPAM microgels (LCST = 32 $^\circ\text{C}$)¹⁴ resulted from the relative hydrophobicity of AA at pH = 4. As shown in Figure 3a, at 25 $^\circ\text{C}$, the hybrid particles exhibited a smaller original diameter than pure (nondoped) microgels. The difference resulted from the higher

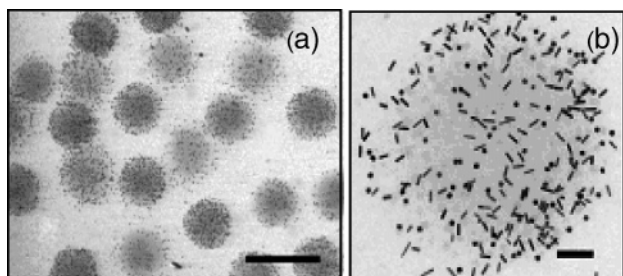


Figure 2. (a) Low- and (b) high-resolution TEM images of poly(NIPAM-AA) microgels loaded with gold nanorods. Scale bars are 1 μm and 100 nm, respectively.

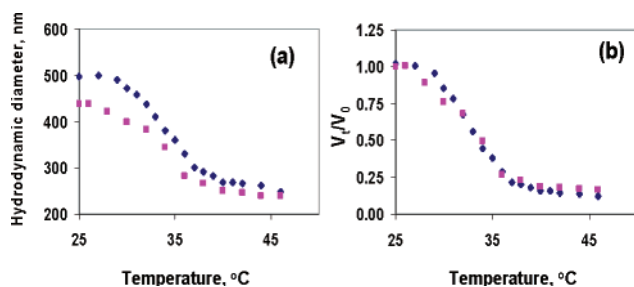


Figure 3. Variation in (a) hydrodynamic diameter and (b) deswelling ratio, V_t/V_0 , as a function of temperature of pure poly(NIPAM-AA) microgel particles (\blacklozenge) and hybrid microgels (\blacksquare) in pH = 4 buffer.

ionic strength of the hybrid system¹⁵ and the physical cross-linking of the microgel particles with the Au NRs.¹⁶ Upon heating, the hybrid microgels shrank to a slightly smaller size. Figure 3b shows the variation in deswelling ratio, V_t/V_0 , of the pure and hybrid microgel particles, where V_t and V_0 are the microgel volumes at a particular temperature and at 25 °C, respectively. At elevated temperatures, microgel particles doped with Au nanorods showed a somewhat smaller deswelling ratio than the corresponding pure microgels (that is, 84 vs 88% shrinkage, respectively). No notable difference in the time of response (less than 1 s) of pure and hybrid microgels was observed.

We further investigated the potential application of the polymer microgels doped with gold NRs with respect to their photothermally triggered volume transitions. The dispersion of hybrid microgel particles was heated to 30 °C and illuminated at $\lambda = 810$ nm (Optopower Corp. diode, CW/pulsed, 30 W CW, power ca. 0.3 W/mm²), close to the plasmon band of NRs ($\lambda = 804$ nm). The variation in microgel size was monitored at 632.8 nm using a photon correlation spectroscopy setup (Zetasizer 3000HS, Malvern Instruments), modified to accommodate the pump laser. Following irradiation of hybrid microgels, we observed a rapid particle size change. Figure 4 demonstrates the reduction in volume of the hybrid microgels doped with Au nanorods of $53 \pm 1.4\%$ (that is, about two-thirds of the volume reduction induced by heating of hybrid microgels to 46 °C (Figure 3b)). Using the results of steady-state swelling experiments, we estimate the temperature of the microgel particles to be 34 °C (the temperature of the bulk dispersion measured with a thermocouple remained at 30 °C). By contrast, in the control experiment upon illumination of the dispersion of pure microgel particles at $\lambda = 810$ nm, they shrank by only $10 \pm 1.4\%$. We conclude that a strong change in the volume of hybrid microgels resulted from the local heating of polymer particles, following conversion of light energy to heat by the Au nanorods.

The *laser on* and *laser off* cycles were repeated several times. The photothermally induced deswelling–swelling transitions in hybrid microgels were reproducible within 4.2%. Such reproduc-

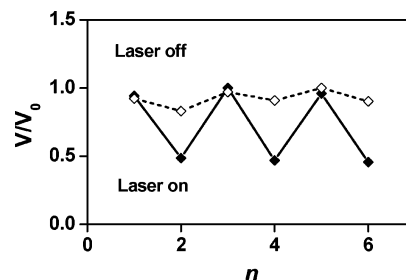


Figure 4. Variation in volume of pure (\diamond) and hybrid (\blacklozenge) poly(NIPAM-AA) microgels plotted as a function of the number of *laser on* and *laser off* events n . Both microgel systems were irradiated at $\lambda = 810$ nm. The original dimensions of pure and hybrid microgels are as in Figure 3. pH = 4.

ibility indicated that no notable loss of NRs by poly(NIPAM-AA) microgel particles occurred during polymer volume phase transitions.

In conclusion, we have demonstrated a new excellent example of materials with structural hierarchy: polymer microgel particles doped with gold nanorods. We used the variation of the longitudinal surface plasmon of the nanorods with their aspect ratio to tune absorption of the hybrid microgels into the near-IR spectral range. Upon irradiation at $\lambda = 810$ nm, the particles carrying Au nanorods shrank by ca. 53%. These photothermally responsive microgels can be used to carry and release small molecules (e.g., drugs). Further modification of the composite material reported herein will aim at the synthesis of microgel particles with dimensions below 100 nm, which are photothermally responsive at biological temperatures and pH.

Acknowledgment. The authors gratefully acknowledge financial support from the NanoIP program (NSERC Canada). The authors thank Dr. Yu for his assistance in assembly of the experimental setup.

Supporting Information Available: Synthesis, characterization, and experimental details of irradiation experiments. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References

- (1) Nayak, S.; Lyon, L. A. L. *Chem. Mater.* **2004**, *16*, 2623–2627.
- (2) (a) Wang, C.; Flynn, N. T.; Langer, R. *Adv. Mater.* **2004**, *16*, 1074–1079. (b) Zhu, M. Q.; Wang, L. Q.; Exarhos, G. J.; Li, A. D. Q. *J. Am. Chem. Soc.* **2004**, *126*, 2656–2657.
- (3) (a) Jones, C. D.; Serpe, M. J.; Schroeder, L.; Lyon, L. A. *J. Am. Chem. Soc.* **2003**, *125*, 5292–5293. (b) Jones, C. D.; Lyon, L. A. *J. Am. Chem. Soc.* **2003**, *125*, 460–465.
- (4) Sershen, S. R.; Westcott, S. L.; Halas, N. J.; West, J. L. *J. Biomed. Mater. Res.* **2000**, *51*, 293–298.
- (5) Suzuki, A.; Tanaka, T. *Nature* **1990**, *346*, 345–347.
- (6) Kamenjicki, M.; Lednev, I. K.; Mikhonin, A.; Kesavamoorthy, R.; Asher, S. A. *Adv. Funct. Mater.* **2003**, *13*, 774–780.
- (7) Kungwachakun, D.; Irie, M. *Macromol. Chem. Rapid Commun.* **1988**, *9*, 243–246.
- (8) Simpson, C. R.; Kohl, M.; Essenpreis, M.; Cope, M. *Phys. Med. Biol.* **1998**, *43*, 2465–2478.
- (9) (a) Oldenburg, S. L.; Hale, G. D.; Jackson, J. B.; Halas, N. J. *Appl. Phys. Lett.* **1999**, *75*, 1063–1065. (b) Oldenburg, S. L.; Jackson, J. B.; Westcott, S. L.; Halas, N. J. *Appl. Phys. Lett.* **1999**, *75*, 2897–2899.
- (10) Pelton, R. *Adv. Colloid Interface Sci.* **2000**, *85*, 1–33.
- (11) Murthy, N.; Xu, M.; Schuck, S.; Kunisawa, J.; Shastri, N.; Fréchet, J. M. J. *Proc. Natl. Acad. Sci. U.S.A.* **2003**, *100*, 4995–5000.
- (12) Nikoobakht, B.; El-Sayed, M. A. *Chem. Mater.* **2003**, *15*, 1957–1962.
- (13) Snowden, M. J.; Chowdhry, B. Z.; Vincent, B.; Morris, G. E. *J. Chem. Soc., Faraday Trans.* **1996**, *92*, 5013–5016.
- (14) Schild, H. G. *Prog. Polym. Sci.* **1992**, *17*, 163–249.
- (15) Jones, C. D.; Lyon, L. A. *Macromolecules* **2003**, *36*, 1988–1993.
- (16) Huang, J.; Wu, X. Y. *J. Polym. Sci. Part A: Polym. Chem.* **1999**, *37*, 2667–2676.

JA0448869