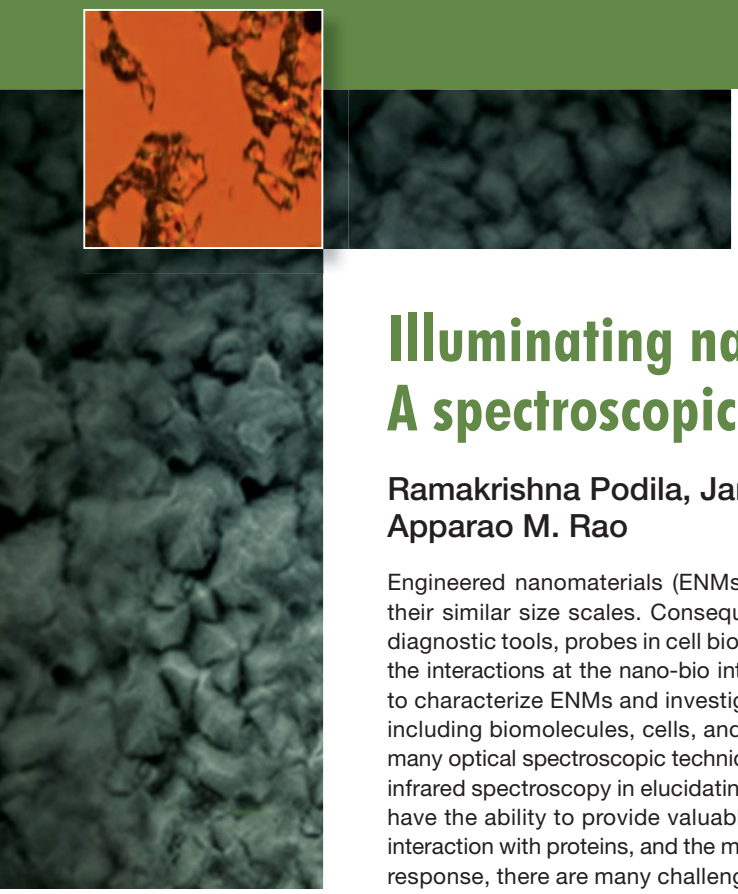


Illuminating nano-bio interactions: A spectroscopic perspective

Ramakrishna Podila, Jared M. Brown, Anne Kahru, and Apparao M. Rao

Engineered nanomaterials (ENMs) strongly interact with biomolecules and cells due to their similar size scales. Consequently, ENMs are beginning to emerge as new medical diagnostic tools, probes in cell biology, and delivery vehicles, compelling us to understand the interactions at the nano-bio interface. Optical spectroscopic tools are excellent probes to characterize ENMs and investigate their interactions with complex biological systems, including biomolecules, cells, and even whole animals alike. Here, we discuss the role of many optical spectroscopic techniques such as fluorescence, Raman, surface plasmon, and infrared spectroscopy in elucidating nano-bio interactions. While these spectroscopic tools have the ability to provide valuable information on ENM distribution in biosystems, ENM interaction with proteins, and the mechanisms by which ENMs elicit an adverse physiological response, there are many challenges that remain to be addressed to improve their scope, resolution, and throughput.

Introduction

Engineered nanomaterials (ENMs) provide much-needed breakthroughs for resolving some longstanding challenges in drug delivery and personalized medicine. They exhibit pronounced interactions with biomolecules and the ability to efficiently cross many physiological barriers due to their small size, which may also cause undesired side effects (also see the Wick et al., Hemmer et al., and Bhattacharya et al. articles in this issue).[1–5] Spectroscopic tools can be used to determine the underlying biophysical mechanisms and the nature of nano-bio interactions at the cellular, subcellular, and protein levels, which cannot be gleaned from traditional toxicological studies. For example, some ENMs release metal ions through dissolution at varying rates in different media, including blood.[6–11] As discussed in this article, these metal ions can adversely affect the proper functioning of biomolecules and cells through an "action-at-a-distance" mechanism. Spectroscopic tools can clearly identify the net bioavailable metal ion content and help establish relationships between ion-release from ENM and ENM-induced toxicity. As outlined in **Figure 1**, this article discusses how various spectroscopic tools (e.g., Raman, photoluminescence, infrared, and surface plasmon) can probe the intrinsic properties of ENMs (e.g., crystallinity and electronic states) and biomolecules (e.g., protein structure) and provide a comprehensive understanding of ENM transport within organisms (e.g., via biodistribution) and new perspectives of biological interactions (e.g., loss of protein structure upon adsorption on ENM) at the nanoscale.

Fluorescence imaging of ENM biodistribution

The ultimate prerequisite for a harmful effect from any toxicant is exposure. Therefore, tools allowing the visualization of the nanoparticles (NPs) *in vivo* are crucial for risk evaluation. On the other hand, the growing utilization of ENMs in potential clinical applications ranging from diagnosis to therapeutic treatment of diseases necessitates a need for understanding their *in vivo* transport, biodistribution, and long-term fate in the organism.[12] ENMs are known to exhibit a higher uptake by monocytes and macrophages of the mononuclear phagocyte system (a part of the immune system containing phagocytic cells) upon injection into animals, which prevents their rapid clearance through excretion and impairs therapeutic or diagnostic targeting.[2,12]

Indeed, the clearance mechanisms for most ENMs remain unresolved due to the existing difficulties in *in vivo* tracking and monitoring of the ENMs. Fluorescence spectroscopy is one of the important tools in assessing the biological interaction

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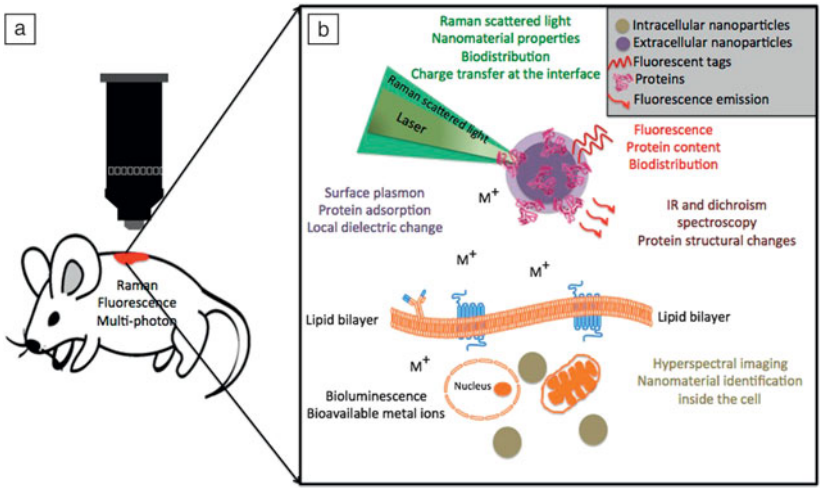


Figure 1. A spectroscopic perspective of the nano-bio interface: (a) Spectroscopic tools provide facile monitoring of *in vivo* engineered nanomaterial (ENM) distribution. While Raman spectroscopy provides information on the surface (~8 μm), near-infrared fluorescence and 3-photon absorption spectroscopies can probe tissues as deep as mm to cm. (b) Inside the organism, ENMs interact with biomolecules and cells in multiple ways. For instance, extracellular nanoparticles (shown in purple) can form a protein corona (depicted by the halo) that could be probed by redshifts in the ENM surface plasmon peak. Indeed, the changes in surface plasmon peak could be used in hyperspectral imaging to identify intracelleular ENM. The interaction between protein and ENM occurs through charge transfer, as inferred from Raman spectroscopy, and can result in loss of protein structure evidenced by infrared (IR) and circular dichroism spectroscopy. ENMs may also leach away metal ions (M+) and interact with cells without being internalized through the "action-at-a-distance" mechanism. The amount of bioavailable (i.e., entering the living cells) metal ions and the resulting adverse biological response can be measured using recombinant luminescent biosensors.

of ENMs. Oxide NPs such as SiO_2, TiO_2, CeO_2, ZnO, and graphene oxide (GO) are often conjugated with visible or near-infrared (NIR) fluorophores to help track their transport *in vivo*.[12–14] In this regard, fluorescence imaging studies on carbon nanotubes (CNTs) and GO in mice with a U-138 glioblastoma (brain tumor) intracranial xenograft (a surgical graft from a foreign tissue) using Alexa Fluor 647 fluorescent dye are noteworthy since they revealed that the hydroxyl and quinone groups on GO result in a decreased agglomeration relative to CNTs in the tumor due to the polar nature of the hydroxyl/quinone functional groups.[14] While fluorescence imaging of ENMs is useful for *in vivo* tracking over short periods of time (a few hours to a few days), many challenges such as inherent modification of the ENM physicochemical properties following the addition of fluorophore, photobleaching, fluorescent quenching, and fluorophore dissociation from ENMs continue to plague this method. Nonetheless, spectroscopic tools that identify ENMs directly through their intrinsic properties are emerging and could provide an accurate assessment of ENM biodistribution at short (few hours) and long-time scales (many months).[12]

Raman spectroscopic investigation of the ENM physiological response

Raman spectroscopy provides a spectral fingerprint of ENMs and is based on the principle of inelastic scattering of light by ENMs. When a monochromatic beam of photons (e.g., a laser beam) interacts with atomic vibrations (phonons) in an ENM, it experiences a distinctive shift in its energy known as the Raman shift. The energy and intensity of Raman shifts are uniquely determined by the crystal structure of the ENM. Furthermore, a strong coupling between incident photons, and electronic and phonon energy levels in some ENMs (e.g., CNTs) can result in resonant Raman shifts that are several thousand-fold more intense relative to those in bulk.[15] Thus, Raman scattering serves as an ideal tool to study the biodistribution of ENMs over long-time scales.[12,16–18] As an example, we discuss the use of Raman spectroscopy in elucidating the biodistribution and immune response of CeO_2 NPs.[18]

The risk of CeO_2 NP exposure is significant since they are widely used in many applications, including solar cells and as fuel additives. Instillation of CeO_2 NPs in the lungs of mice was shown to activate mast cells, which play an important role in allergic immune responses, tissue repair, and the maintenance of homeostasis.[18] Such activation in mice induces pulmonary inflammation, an altered vascular tissue response, and an increase in infarct size within the left ventricle of the heart using a model of myocardial ischemia/reperfusion injury that mimics an episode of myocardial infarction, commonly known as a heart attack. Mice deficient in mast cells had a null effect to CeO_2 instillation, confirming that ENMs' physiological effects are mediated, in part, by mast-cell activation. In these studies, the biodistribution of CeO_2 was characterized by micro-Raman spectroscopy of sectioned mouse tissue (**Figure 2**). The crystal structure of CeO_2 consists of a simple cubic O sublattice with Ce ions occupying alternate cube centers. This cubic structure results in a unique Raman signature consisting of a dominant peak at 462 cm^{-1} (Figure 2b inset) with a typical line width of ~20–30 cm^{-1}. This peak results from the vibrational motion (breathing mode) of O atoms around the Ce cations and can be used to assess the biodistribution of CeO_2. Consistent with the previously described mast cell mediated response, Wingard et al. observed the 462 cm^{-1} Raman peak exclusively in mouse tissue, confirming the uptake of nanostructured CeO_2.[18] An important aspect of Raman spectroscopy is that it can facilitate depth profiling (through confocal Raman spectroscopy) for detecting CeO_2 NPs embedded deep inside the tissue sections (thickness ~8–10 μm below the surface), unlike electron microscopy.

Biophysical phenomena at the nanoscale

ENMs in any physiological medium become inadvertently fouled or coated with proteins and lipids, leading to the formation of a

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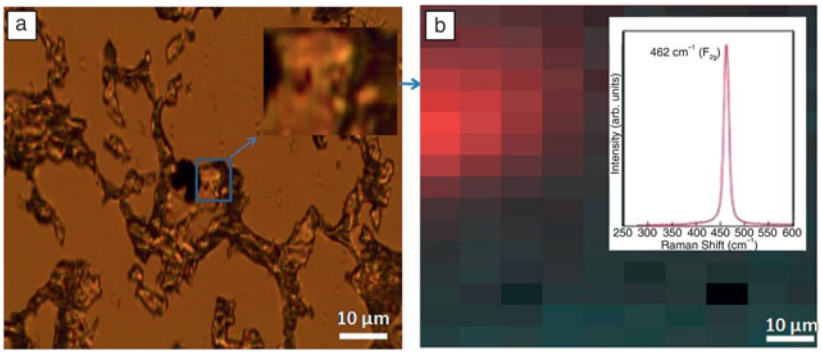


Figure 2. Raman spectroscopy of CeO_2 nanoparticles in mouse lung tissue. (a) An optical image of a mouse lung section where CeO_2 was directly instilled into the lung through oropharyngeal aspiration. The inset image (10 × 10 µm) clearly shows black colored CeO_2 at the surface of the lung tissue. (b) The corresponding Raman map of the mouse lung section shown in the inset of (a). The red colored region is a map of the characteristic Raman peak (shown in the inset ~triply degenerate (F_{2g}) mode at 462 cm^{-1}) for CeO_2 nanoparticles. The data are taken from Reference 18.

"biocorona" (*cf.* Figure 1) (also see the Bhattacharya et al. article in this issue).[2,19–21] Although it is known that proteins adsorbed on ENM exhibit significant structural changes, the underlying biophysical mechanisms of the ENM-protein interactions are not yet fully understood. It is plausible that a difference in electronegativity between the protein and ENM may induce a charge transfer, which may ensue in hydrogen bond breakage and, ultimately, lead to protein unfolding and a dysfunctional protein. More importantly, the presence of the biocorona influences metal dissolution, reactive oxygen species (ROS) production, and overall ENM interaction with cells to mitigate ENM-induced toxicity. Many groups have suggested that ROS and reactive nitrogen species (RNS) produced in the presence of ENMs are primarily responsible for most of the toxic damage to cells.[22]

While most metal oxide compounds exhibit relatively clean bandgaps (with no electronic states within the gap) in the bulk form, a limited periodicity of crystal planes in metal oxide ENMs in one or more dimensions results in new electronic or surface states within the bandgap. These surface states are often electronically active and allow charge transfer between O_2 and the ENM, resulting in an increased production of superoxide anions and OH radicals. TiO_2 and Al_2O_3 NPs (<50 nm in diameter) exhibit more toxic response per unit mass than their bulk counterparts due to the presence of surface or mid-gap states.[23–25] As explained in the proceeding sections, spectroscopic tools (Raman, photoluminescence, and hyperspectral imaging) can illuminate the fundamental mechanisms involved in biocorona formation, assess changes in ENM interaction, and provide facile ways to quantify the net bioavailable metal ions.

Formation of ENM-biocorona

As mentioned earlier, CNTs are known to exhibit strong Raman features due to resonance effects. Notably, the symmetric peak shape and peak frequency arising from the planar vibrations of carbon atoms in a CNT (G band) are highly sensitive to charge transfer (see **Figure 3**a). Indeed, the peak develops an asymmetric shape (viz., Breit-Wigner-Fano shape[19]) due to charge transfer between CNTs and adsorbed species. The G band peak frequency upshifts (downshifts) when any acceptor (donor) species interacts with CNTs via hole (electron) transfer, while the peak shape-asymmetry factor ($1/q$) deviates from 0 (>0 for acceptor and <0 for donor species).[19] Using micro-Raman spectroscopy studies, Podila et al. observed that the aromatic amino acids present in the proteins (e.g., bovine serum albumin or BSA) could interact with the unhybridized p_z orbitals of the single-walled CNTs (SWNTs) by providing a weak acceptor level in the SWNT electronic density of states to allow partial electron transfer from the SWNT to BSA.[19] Such an electron transfer is clearly reflected in the asymmetric line shape and an upshift of the G band peak frequency found in the Raman spectrum of protein coated SWNTs (Figure 3a). It is worth noting that the introduction of a relatively weak acceptor level (from proteins) could still affect the Raman spectrum of the CNTs, since the latter possess sharp and discrete energy states. As discussed next, the spectroscopic evidence for the interaction between ENM and proteins go hand-in-hand, with changes in ENM uptake, immune response, and cytotoxicity as deduced from *in vitro* studies.

Spectroscopic understanding of *in vitro* responses to ENM

Indeed, the formation of an oxide layer on many metal NPs (e.g., AgO on Ag NPs) introduces new surface states that result in an increased ENM interaction with proteins,[26] leading to (1) a change in the dielectric environment surrounding the ENM upon protein or biocorona formation and a subsequent shift in the surface plasmon resonance (SPR) absorption of ENMs, and (2) quenching of the photoluminescence of aromatic amino acids in adsorbed proteins (particularly in the case of wide bandgap metal oxide ENMs). Previously, it was demonstrated that the shift in SPR (resulting from biocorona formation) is highest for bare Ag NPs with an oxidized surface (AgO), relative to citric acid or polymer-stabilized Ag NPs (Figure 3b, d–f). More importantly, the presence of a biocorona (particularly, human serum albumin or HSA corona) possibly reduces the cytotoxic effects of Ag NPs by inhibiting their rapid dissolution and release of toxic Ag^+ ions. Inductively coupled plasma mass spectrometry (ICP-MS) measurements *in vitro* (see Figure 3c) showed that the presence of a biocorona on Ag NPs significantly decreased their uptake, cytotoxicity, and inflammatory response in cells that represent barriers to nanoparticle uptake in the vasculature and pulmonary systems

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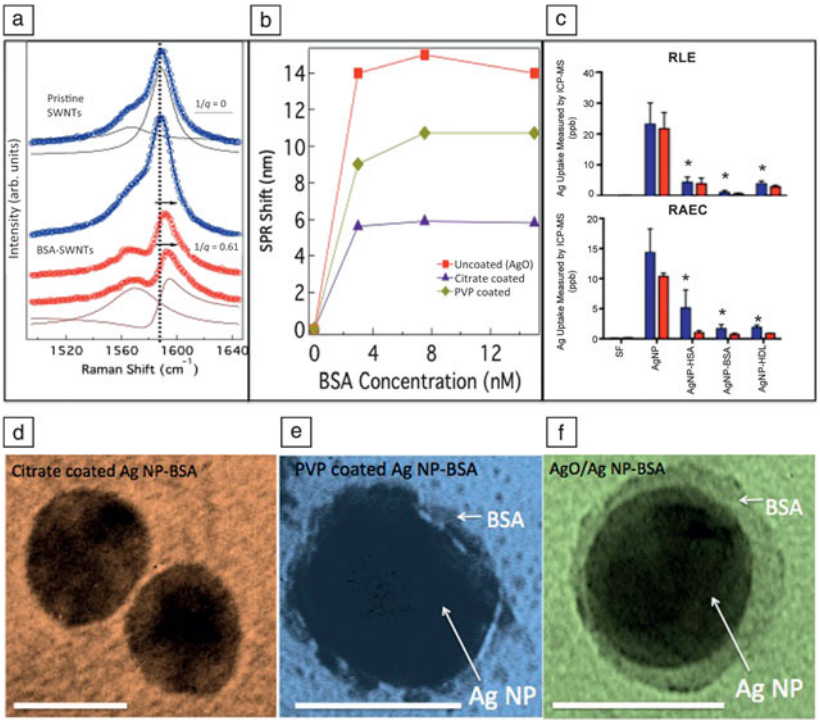


Figure 3. (a) Raman spectra of pristine and bovine serum albumin (BSA)-coated single-wall nanotubes (SWNTs). Pristine SWNTs clearly exhibit a symmetric line shape ($1/q = 0$, where $1/q$ is the peak shape-asymmetry factor), while the BSA-coated SWNT spectrum is not only upshifted (as shown by the black arrows) but also shows an asymmetric line shape due to charge transfer. Note that the solid black (red) lines below the top-most (bottom) spectrum indicate the deconvoluted peaks obtained from the peak fits.[19] (b) The surface plasmon resonance (SPR) shift for a BSA coating on Ag nanoparticles (NPs) occurs due to a change in the local dielectric environment. The presence of AgO on bare Ag NPs results in a thicker protein corona layer and the highest SPR shift.[26] (c) Rat lung epithelial cell (RLE) and rat aortic endothelial cells (RAECs) were pretreated with serum-free (SF) media and subsequently exposed to Ag NPs with or without protein corona (HSA, BSA, and HDL-high density lipoprotein). Cells were then washed and assessed by inductively coupled plasma mass spectrometry (ICP-MS) to quantify Ag NP uptake. The presence of scavenger-receptor B1 inhibitor (red bars) reduced the uptake of Ag NPs, suggesting scavenger receptor B1 mediates the uptake of Ag NPs in both cell types and the corresponding inflammatory activation and cytotoxicity.[21] (d–f) Transmission electron micrographs show a maximum protein coating for AgO/Ag NPs concurring with SPR spectroscopy results shown in (b) (scale bar: 20 nm).[26] Note: PVP, polyvinylpyrolidone; HSA, human serum albumin.

(e.g., rat aortic endothelial cells [RAEC] and rat lung epithelial [RLE] cells).

Furthermore, hyperspectral analysis[27] revealed that SPR spectra from Ag NPs with biocorona undergo a blueshift (unlike pristine Ag NPs that do not show any shift) upon cellular internalization, suggesting an intracellular loss of the biocorona that, in turn, may plausibly lead to elevated toxic effects via increased dissolution. A combination of SPR spectroscopy, hyperspectral imaging, ICP-MS, and more traditional *in vitro* cytotoxicity and inflammation assays conclusively suggest that (1) bare Ag NPs (without any capping agents) exhibit the highest protein coating or biocorona due to the presence of an AgO layer, (2) biocorona on Ag NPs reduces Ag^+ leaching and thus toxicity, (3) biocorona formation decreases the uptake and hence cytotoxicity of Ag NPs, and (4) the protein coating on Ag NPs is lost upon internalization, possibly due to changes in pH and the local intracellular microenvironment.[21,26]

The dynamic nature of biocorona formation leads to a complex physiological response to ENM, which warrants a complete thermodynamic understanding of ENM-protein binding and interactions.[28] In this regard, isothermal titration calorimetry (ITC) is an important tool that can yield useful binding information, such as the enthalpy, stoichiometry, and binding constants. However, ITC experiments are expensive and time-consuming and need extremely stable suspensions with very accurately defined concentrations. In the case of metal oxide NPs, the need for ITC could be obviated by using NP-induced fluorescence quenching of proteins. Fluorescence quenching of proteins in metal oxide NPs occurs due to an energy transfer (FRET, fluorescence resonance energy transfer) arising from a significant overlap between bandgap absorption of many metal oxides (e.g., 3.37 eV in ZnO) with the emission of aromatic amino acids in proteins (e.g., 3.5 eV in BSA). Thus, one can deduce the binding constant (K) of some proteins on metal oxide ENMs using the traditional fluorophore-quencher binding mechanisms (**Figure 4**a) instead of ITC.[29]

Biochemical toxicity of metal oxide nanomaterials

Although the toxic effects of metallic NPs reported for mammalian cells *in vitro* can be linked to oxidative stress,[30] for a comprehensive understanding of biochemical toxicity of metal oxide ENMs, the release of (toxic) metal ions should be taken into account, which can be achieved using novel spectroscopic tools. Indeed, Brunner et al.[31] showed that the solubility of oxide NPs strongly influences their cytotoxicity. Through *in vitro* studies, CuO, ZnO, and Ag NPs have been shown to release metal ions (Cu^{2+}, Zn^{2+}, and Ag^{+})[32] that can increase oxidative stress and possibly cause cell apoptosis (i.e., programmed cell death).[30]

Traditionally, the metal ion content in natural or biological matrices is determined using ICP-MS after the digestion of samples with strong acids. While ICP-MS exhibits high sensitivity (parts per trillion) in metal detection, it does not allow a clear distinction between bioavailable (potentially hazardous) and non-available (potentially non-hazardous) fractions of metals to living organisms. Use of bioluminescent metal-specific recombinant bacteria is an excellent spectroscopic tool for assessing the true bioavailable content of metal

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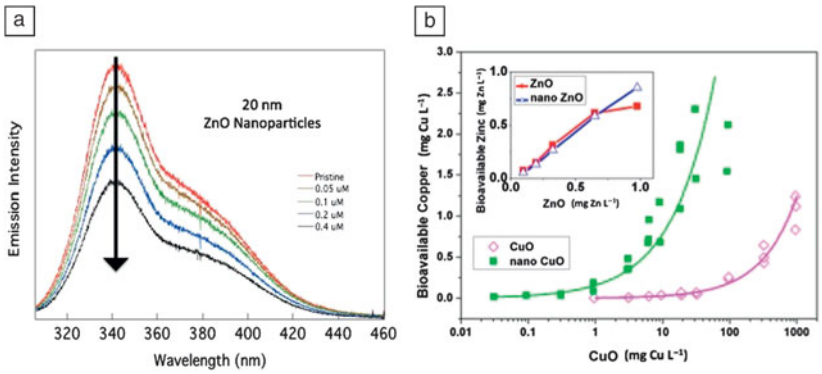


Figure 4. (a) Photoluminescence spectra of tryptophan and tyrosine residues of bovine serum albumin (BSA: 3 g/dL) display quenching (i.e., decrease in emission intensity as shown by the black arrow) with increasing ZnO nanoparticle concentration. Such spectra could be used in conjunction with fluorophore-quencher binding mechanisms to obtain binding constant and stoichiometry similar to isothermal titration calorimetry.[29] (b) Concentration of bioavailable Cu^{2+} in aqueous suspensions of nano CuO and bulk CuO as measured by luminescence of recombinant *Escherichia coli* MC1061 Cu-sensor. The inset shows concentration of bioavailable Zn^{2+} in aqueous suspensions of nano ZnO and bulk ZnO as measured using bioluminescence of recombinant *Escherichia coli* MC1061 Zn-sensor. The data originate from Reference 34. The bioavailable concentration of nano CuO is contrastingly different from the bulk, unlike the case of ZnO.

ions. In these metal-specific bacterial sensors, the expression of a reporter gene (e.g., encoding luciferase) is controlled by a genetic regulatory unit (or receptor), which specifically responds to a particular bioavailable metal ion.[33] For example, *znt*A and *znt*R genes introduced by genetic manipulations into *Escherichia coli* (a host bacterium) transform the bacterium into a living Zn-sensor that recognizes bioavailable Zn^{2+} ions and subsequently controls the expression of luciferase—a reporter protein. Thus, the amount of bioavailable Zn^{2+} that has entered the bacterial cell could be quantified. Kahru and co-workers have used recombinant bacterial sensors to determine the influence of nanosizing on the bioavailability of metal ions in CuO and ZnO NPs.[34] Interestingly, the bioavailable content of Zn^{2+} ions did not significantly differ between bulk and nanosized ZnO, while there was a stark contrast between Cu^{2+} release from CuO NPs relative to its bulk form (Figure 4b). Such observations could be attributed to an increased surface area at the nanoscale and a positive reduction potential for Cu (Cu/Cu^{2+}: 0.34 V) in contrast to Zn (Zn/Zn^{2+}: –0.76 V). Coherent with the data on bioavailable fraction, the toxicity of CuO NPs in bacteria *Vibrio fischeri* and water fleas *Daphnia magna* was 48–52 times higher than that of the bulk formulation. On the other hand, the toxicity of bulk and nanosized ZnO was comparable.[34] These observations reaffirm the hypothesis that ENMs can exhibit an "action-at-a-distance" (*cf.* Figure 1) toxic response without necessarily entering the cells. The release of metal ions may also cause the toxicity through increased generation of cellular ROS.

Conclusion

Spectroscopic tools are blazing a trail on the frontiers of the nascent field of nanotoxicology. While traditional spectroscopy techniques such as Raman, infrared, and photoluminescence are useful for studying biodistribution and engineered nanomaterial (ENM)-protein interactions, new generation surface plasmon resonance and recombinant biosensors have the ability to quantitatively identify the biophysical and biochemical mechanisms of ENM toxicity. However, many limitations such as low penetration depth and photobleaching for mapping *in vivo* biodistribution still persist. With the advent of new techniques (e.g., multi-photon absorption for increasing penetration depth and bleaching time[35]), the role of spectroscopic tools in the elucidation of nanotoxicity will grow to be more important.

Acknowledgments

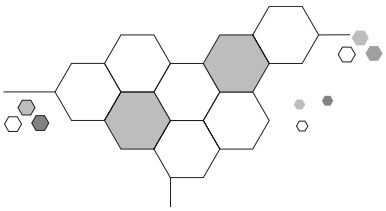
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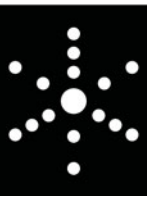
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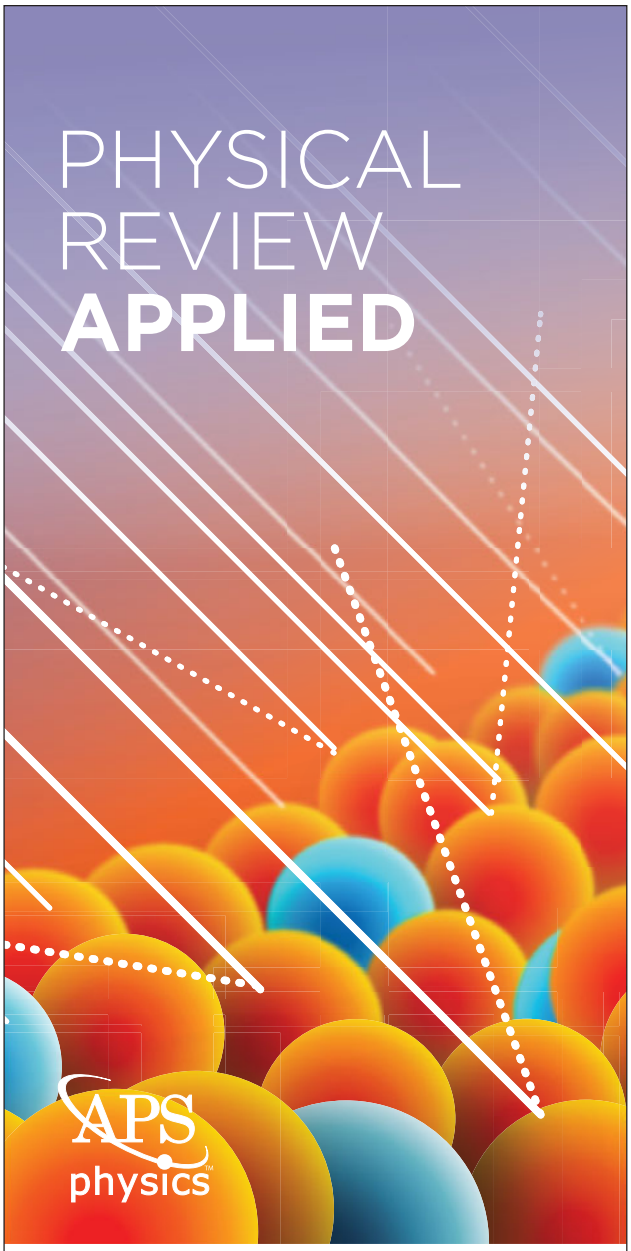


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Materials Research Society®

University Chapters

The Materials Research Society® (MRS) University Chapter Program is a passionate and talented network of students from universities around the world. Supported by the Materials Research Society Foundation, the program fosters an environment for collaboration and open exchange of ideas across all scientific disciplines, spanning campuses and continents. These students represent the next generation of materials research and are preparing to carry the torch forward, advancing materials and improving the quality of life.

You'll find starting an MRS University Chapter is a fun and exceptionally valuable experience. Working through your Chapter—hosting events, creating special projects and connecting with experts from around the world—will prepare you for future professional and leadership roles in the materials community. Your Chapter can also play a vital role in bringing science to a broader audience. Now more than ever, the goal is to successfully bring research out of the laboratory and into the classroom and to the general public … to show how materials have changed our history and continue to shape our future.

MRS continues to explore new ways to effectively foster growth of virtual global materials communities, using emerging technologies that are smart, fresh and innovative … and that includes our University Chapters. With social media, MRS OnDemand® and two-way live streaming, we're already tapping into today's technologies to engage Chapters unable to attend our Meetings, but with the promise of new innovations, tools and devices, we continue to look ahead. **Help us build the Chapter of the Future!** Together we can design and develop virtual events to better collaborate, educate, participate and fascinate—across Chapters, across disciplines, across borders.

Now's the time to use your excitement, expertise and unique scientific perspectives to forge a new path. Join this international student community.

Start an MRS University Chapter today!

MATERIALS RESEARCH SOCIETY FOUNDATION

HELP US BUILD THE FUTURE

An International Community

One of the main objectives as graduate students and future researchers is to acquire the ability to build scientific networks for enhancing our vision, mission and scientific cooperation. MRS offers multiple tools to accomplish this with annual meetings, workshops, the MRS Bulletin and useful applications such as career connections or MRS OnDemand. Our MRS Student Chapter allowed us to obtain support from the Sociedad Mexicana de Materiales (SMM) that expands our national network. The formation of MRS Cinvestav Student Chapter not only allows us to integrate and exchange ideas as materials science students at Cinvestav, but also have the opportunity to know the science beyond our borders.

Natalia Tapia, Chapter President
Centro de Investigación y de Estudios Avanzados
del Instituto Politécnico Nacional (Cinvestav-IPN)
Mexico City, MEXICO

Interdisciplinary Collaboration

The MRS Student Chapter at WSU was organized by students who recognized the need to bring together a diverse group of students who were working in materials science. The campus is spread out geographically and students pursuing PhD degrees in MSE can be advised by chemistry or physics professors who are located far from the MSE department located in the engineering buildings. There is no distinction made between students whose advisors are in different departments or colleges, and the MRS Student Chapter has been a great vehicle to promote unity within the disciplines here.

David Field, Chapter Faculty Advisor
Washington State University
Pullman, Washington, USA

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The MRS University Chapter Experience

The MRS University Chapter Program provides invaluable experiences and benefits for student members, but don't take our word for it. **Our Chapter Members Say It Best!**

Leadership Development

The Materials Research Society, along with our local Binghamton University Chapter, has positively influenced my commitment to materials science and technology. We were inspired by our advisor, Professor M. Stanley Whittingham, to start this Chapter … and motivated by his enthusiasm and our faith to bring science to the general public, we continue to hold numerous events taken from MRS, i.e. MAKING STUFF and NanoDays. As our organization grows, we keep growing our events, and have found a solid and welcoming place in our community. Apart from the target audience, our events also benefit the volunteers, who gained valuable experience both from preparation, interaction, and activities. We feel proud and grateful to be part of an MRS University Chapter.

Tianchan Jiang, Chapter President
Binghamton University
Binghamton, New York, USA

Education Outreach

Our Chapter has enabled us to establish collaborations among the scientists on campus through informal social events, in addition to providing opportunities to participate in outreach. Integrating the science outreach efforts of Vanderbilt's community into our local community is one of our primary goals. As a University Chapter, we received a grant through the Materials Research Society Foundation to bring emerging materials science and hands-on activities to disadvantaged students and teachers in rural Tennessee. Without these seed funds, our Vanderbilt program, Materials Outreach for Rural Education (MORE), would not have been possible.

Amy Ng, Chapter President
Vanderbilt/Fisk Universities
Nashville, Tennessee, USA

Professional Growth

Starting and advising an MRS University Chapter is truly a rewarding experience. One can see professional growth of students, who start feeling like members of the worldwide materials research community. I come to MRS meetings with a "team," not just a couple of my students. Exciting initiatives and project ideas generated by students are amazing. Not surprisingly, some of the most prominent materials scientists, such as Millie Dresselhaus (MIT) or Stan Whittingham (SUNY Binghamton), have been acting as Faculty Advisors for many years.

Yury Gogotsi, Chapter Faculty Advisor
Drexel University
Philadelphia, Pennsylvania, USA

Building Chapters of the Future

I had the chance to present at the 2012 MRS Fall Meeting's Sustainability Forum, while being over 9000 km away from the meeting venue. I felt as if I was actually in Boston, being able to take questions, address them and getting into discussions with the committee. Thanks to the Materials Research Society and our local MRS-KAUST University Chapter for making this possible.

Ahmed E. Mansour, Chapter Vice President
King Abdullah University of Science and Technology (KAUST)
Thuwal, SAUDI ARABIA

Chapter Support

As a graduate student, it is key to broaden your spectrum of what is taking place in the research world in real time. MRS opens up many avenues, especially when working from a University Chapter. Direct contact with MRS associates helps keep everyone abreast of conferences, Chapter opportunities and activities that otherwise may not have been as easily accessible. MRS also rewards student memberships with rebates and travel expenditures, helping promote student involvement as well as Chapter building. We were able to host a multitude of meetings and seminars as well as send students to attend MRS conferences to promote their research.

Chinedu Okoro, Chapter President
Tuskegee University
Tuskegee, Alabama, USA

FOR MORE INFORMATION

on the MRS University Chapter Program,
visit **www.mrs.org/university-chapters**

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