

Advances at the Frontiers of Photochemical Sciences

A great share of today's knowledge in the photochemical sciences has been reported in the pages of the *Journal of the American Chemical Society* by the world's leading scientists. That trend has continued as strongly as ever in the past few years. In fact, making a selection of representative articles published within the past few months has been challenging. One can see that nearly all the preceding volumes of JACS Select include a significant number of publications reporting knowledge and developments obtained with the help of photochemical and spectroscopic tools, as well as many basic contributions that have helped progress in the field. The impact of photochemistry and photophysics in the physical, biological, and medical sciences, as well as in all modern technologies, has increased in a spectacular manner over the years. A deeper understanding of the absorption, emission, and detection of light, along with knowledge on the evolution of excited states, including reactivity, energy transfer, and electron transfer, continues to provide the most versatile analytical tools to study bulk materials, living systems, metabolic processes, quantum dots, single molecules, and even matter in the interstellar space. Applications under development range from diagnostics, sub-diffraction microscopy, and phototherapy to the use of solar energy for green synthesis, water splitting, molecular photovoltaics, and the capture and reduction of CO₂. By giving a robust understanding of the interaction between light and matter, photochemistry and spectroscopy have had an impact in a large number of disciplines, and their principles have been successfully implemented in numerous applications and technologies.

Given the breadth of basic sciences and developments reported in the Journal, the collection presented in this issue of JACS Select aims to illustrate some of the most novel concepts and opportunities that are currently under development. The ultimate goal of these studies is to attain a better understanding of the rules that control the formation and fate of excited states and their application in a manner that is analogous to, and goes beyond, the ones achieved by nature with a generous solar energy supply after more than 3 billion years of evolution. Among the most interesting and challenging objectives for photochemistry today are the manipulation and design of multiphotonic processes, including the development of novel chromophores for multiphoton absorption and nonlinear optical effects; the design of supramolecular constructs that can control the fate of electronic excitation in a manner that compares with photosynthesis; the spectroscopic, photochemical, and photomechanical characterization of photo-reactions in solids; the use of visible light for the development of sustainable chemical processes; the design of molecular entities for molecular logic applications; sub-diffraction microscopy; and the development of structures that use photochemical reactions to release molecules that may function as probes, drugs, analytes, and more. The past months have also witnessed the exploration and use of plasmonic excitations alone and with the use of antennas, which suggest important

roles for electronic excitations and charge transfer as well as thermal and field effects.

Multiphotonic Processes and Multiple Excitations.

Multiphotonic processes are an important extension of the simplest photochemical paradigm, involving one photon, one absorber, one excited state, and one outcome (reaction, electron transfer, energy transfer, emission, or thermal decay). An increase in the number of events involved in each of the fundamental photochemical steps will result in greater versatility and functionality that will bring advantages in many scientific and technological fronts. For example, it has been shown that the simultaneous absorption of two or more photons with a high-intensity, low-energy beam provides the means to generate excited-state molecules under conditions where the incident light is not absorbed by molecules in the intervening medium. These non-resonant, multiphotonic excitations are orders of magnitude weaker than normal linear absorption and are ideal for applications that require three-dimensional spatial control, such as optical imaging. A notable example by **Belfield** and co-workers illustrates the development of a high-fidelity, non-toxic probe for the two-photon fluorescence intracellular imaging of lysosomes.¹ Clear advantages of the two-photon probe were demonstrated by comparison with a standard, one-photon fluorescent probe. Going beyond two-photon absorption, a recent study by **Uchida, Irie, and Miyasaka** has shown that the use of one, two, and up to three photon absorption processes by a single molecule offers some interesting possibilities.² Utilizing a photochromic dithienylethane, these authors showed that variations in the intensity of an infrared laser operating at $\lambda = 1280$ nm could be used to control the isomerization of the colorless and colored forms of the compound. The observed three-photon cyclization and two-photon cycloreversion suggest a novel strategy to control optical information by dialing the intensity of the laser with a single color of light. In fact, an alternative use of nonlinear optical effects to control optical information was shown by **Andréasson and Pischel** in their design of an all-photonic molecule-based D flip-flop.³ Instead of using non-coherent one-, two-, and three-photon absorption, these authors increased the frequency of incident light by taking advantage of second (SHG) and third harmonic generation (THG), so that they were able to excite different entities in a linear resonant manner. Common in silicon technologies, the D flip-flop circuits are used as memory cells that have two interdependent inputs (clock and data) to control whether the output should remain as it is (current) or respond to the input data (next). To accomplish this using photochemical responses and spectroscopic information, the authors used a fulgimide chromophore with isomers that absorb at the second and third harmonics of a Nd:YAG laser. In this case, the colorless state has an absorption band at $\lambda_{\text{max}} = 374$ nm and can be excited with the combined input of the fundamental (1064 nm) and the second harmonic (532 nm),

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which generates the third harmonic (355 nm) of the Nd:YAG. The THG beam causes a photoinduced electrocyclozation, such that the resulting closed form is colored with a $\lambda_{\text{max}} = 523$ nm. The latter can be effectively excited with the second harmonic (532 nm) of the Nd:YAG to produce a fluorescence signal at $\lambda_{\text{max}} = 640$ nm. The fluorescent isomer can be accumulated and depleted, depending on whether or not the two inputs (SHG and THG) are used together, while the process can be probed with the SHG input.

Another example that illustrates multiphotonic phenomena and the emergent properties of molecular aggregates was reported **Zhao and Yao** with a substituted triazine two-photon absorber.⁴ When crystalline nanowires of the chromophore were grown, the researchers were able to generate a collection of micrometer-size lasers. They showed that the efficient two-photon absorption at 750 nm resulted in a strong fluorescence emission at 475 nm that combined with a resonant cavity effect by the crystal to generate lasing action with cavity modes that depended on the dimensions of the crystals. The authors noticed that lasing action occurred with a relatively low energy threshold, suggesting potential applications for future “nanolasers”.

Second harmonic generation, or frequency doubling, is a nonlinear optical effect where photons interacting with the medium transform into photons of higher energy. While molecules suitable as media for SHG are generally polar, with electron donors and electron acceptors linked by a π -conjugated bridge, SHG materials require those molecules to adopt a polar, non-centrosymmetric arrangement. Considering that adjacent dipoles tend to cancel each other, the realization of acentric structures has been one of the greatest challenges in the construction of efficient SHG materials. To address this challenge, it has been recognized that molecules with octopolar symmetry circumvent the electrostatic interactions leading to centrosymmetric structures. The article by **Clays, Therien**, and co-workers illustrates some of the principles involved in the design of octopolar molecules for a new generation of promising SHG materials.⁵

Another interesting process involves the formation of multiple excited states from a single, high-energy, molecular excitation. This process is illustrated by singlet-state fission, a long-known but mysterious phenomenon that is beginning to be unraveled with crystals of tetracene, pentacene, and others. Singlet-state fission is a spontaneous process where a high-energy excited state shares its energy with a nearby molecule to generate two triplets. Singlet-state fission is appealing for photovoltaic applications, as two free carriers can be generated from every absorbed photon. While the factors that control the coupling of excited- and ground-state chromophores are still under investigation, **Michl** and co-workers have identified the biradicaloid 1,3-diphenylisobenzofuran chromophore as particularly promising.⁶ Their experiments revealed a $200 \pm 30\%$ triplet yield arising from singlet fission. It is worth noting that singlet fission is the opposite of triplet–triplet annihilation, which in recent years has been used for the development of photon up-conversion technologies to generate high-energy photons from low-energy and low-intensity light.

Nearly all the nonlinear effects discussed above require high-intensity light beams with high temporal coherence so that two or more photons interact with chromophores and/or a medium in a simultaneous manner. However, as illustrated by **Odobel and Hammarström** with a donor–photosensitizer–acceptor system, it is possible to engineer stepwise multiphotonic

processes that hold promise for the accumulation of charges without the use of sacrificial agents.⁷ Using nanocrystalline TiO_2 as the acceptor, the authors suggest that it may be possible to couple these processes in multielectron catalytic reactions, such as those involved in water splitting and the reduction of carbon dioxide.

Molecular and Supramolecular Constructs. Recognizing the strategies used by photobiological systems involved in photosynthesis, DNA repair, vision, circadian rhythms, bioluminescence, and others, it has been long appreciated that carefully designed molecular and supramolecular constructs can be used to influence the fate of excited states and the flow of energy from a given absorber that acts as a sensitizer or as an antenna. Examples range from small molecules capable of performing complex, predetermined functions to supramolecular aggregates and macromolecules used to determine the structure of a series of interacting chromophores, frequently setting a fluorescence resonance energy transfer (FRET) chain. The first case is nicely illustrated by the work of **Chen, Hung**, and **Chou** with a relatively simple molecule that is capable of emitting white light.⁸ Taking advantage of an adiabatic excited-state intramolecular proton transfer (ESIPT) reaction, they were able to show that broad blue emission from the excited starting material and broad red emission from the ESIPT product combined to generate white light as if there were two molecules present in the sample. More commonly, researchers have taken advantage of suitable scaffolds to organize the flow of energy by prudently placing absorbers, energy donors, and acceptors. An example by **Medintz** and co-workers describes a strategy that takes advantage of quantum dots with various chromophores attached to their surface to control not only the flow of energy but also the timing.⁹ It was shown that quantum dots can act as both donors and acceptors and that a time gate can be conveniently implemented by taking advantage of Tb(III) complexes as relay components within the multi-chromophoric assembly. A third example by **Liu** and co-workers describes the use of a self-assembled seven-helix DNA bundle to influence the location of three distinct chromophores in the structure.¹⁰ The efficient vectorial energy transfer in such artificial light-harvesting antenna suggests an excellent platform to organize arrays of chromophores with great precision. An alternative strategy that takes advantage of 3D order at the macroscopic level to control the absorption and fate of excitation is illustrated in the work of **Papanikolas, Meyer**, and **Lin** with the use of various proportions of Ru and Os polypyridyls as constituents of metal–organic frameworks.¹¹

Solid-State Photochemical Phenomena. Including some examples mentioned above, there have been a number of important and promising developments in the study of photochemical processes in solids. Among them, reports that describe the transformation of a photon's energy into mechanical work are particularly interesting. In this regard, the article by **Morimoto and Irie** reports how single-crystalline needles of a photochromic diarylethene are capable of doing a large amount of mechanical work by lifting a heavy metal ball in a reversible manner under the influence of UV and visible light illumination.¹² In another study, **Bardeen** and co-workers report how single-crystalline microribbons of 9-anthracenecarboxylic acid undergo a photoinduced [4+4] cyclodimerization that results in their twisting with simple illumination and on very short time scales.¹³ It is worth noting that one of the major challenges in the study of photochemical reactions in crystalline solids comes from the difficulties associated with the use of

ultrafast spectroscopic techniques to determine the absolute kinetics of the excited states and reactive intermediates. To that effect, our group (Garcia-Garibay, in collaboration with Guldi) has shown that sub-micrometer-size crystals suspended in water are ideal for transmission studies using pump-probe methods.¹⁴ In particular, a study with a set of crystalline benzophenones showed that triplet-state self-quenching occurs with rates that cover up to 9 orders of magnitude, depending on the structure. This observation may have a very strong impact on all aspects of materials photochemistry.

Sustainability and Photochemistry with Visible Light.

Although the importance of photochemistry in green chemistry and sustainability is well appreciated, there is a need for the development of reactions that accomplish complex transformations using sunlight, ideally using water as a solvent, or no solvent at all. While progress in this area has been steady, it is nicely illustrated in the paper by Yoon on the use of visible light and a mere 0.5% loading of a ruthenium(II) polypyridyl complex to sensitize a mismatched Diels–Alder reaction that occurs via radical cations.¹⁵ Although the photochemical reaction is essentially complete in 1 h under visible light, it fails under thermal conditions at 200 °C after 14 h.

Plasmonics. Plasmonics represents one of the most interesting fields of activity in the photochemical sciences. Recent contributions include studies addressing changes in properties as a function of their structural transition from discrete molecular entities and small clusters to nanoparticles. On one end, the report by Stampelcoskie and Scaiano describes the kinetics of formation and emission properties of silver dimers prepared by the photoinduced reduction of silver cations.¹⁶ A significant increase in size, suggesting the transition between a giant molecule and a nanoparticle, was reported by Dass with the preparation of a discrete, thiol-protected gold structure of 76.3 kDa.¹⁷ Larger than any previously prepared gold molecule and named in honor of Michael Faraday, this “Faradaurate” nanomolecule displays emergent plasmonic properties and suggests a class of structures that will be of great interest. Some of the most interesting photochemical applications of plasmonics include their use as photopolymerization agents, as illustrated by the work of Soppera.¹⁸ These and other studies offer a clear indication of the potential of plasmonic effects to influence photochemical reactivity and suggest their use in the generation of nanostructures. Another example, by Halas and co-workers, illustrates how plasmon-resonant nanoparticle complexes can be used for the light-triggered and remote release of DNA in a manner that depends on the type and shape of metallic nanostructures.¹⁹

Biological and Biomedical Applications. Several examples mentioned above fall within the category of biological applications. For example, the release of DNA from a plasmonic nanostructure may be considered an example of a new strategy to release a biologically active compound by photochemical excitation. Molecular or supramolecular entities designed with this function are commonly referred to as “photocages”, and they require efficient bond cleavage reactions to release the “caged” compound and chemical information to reach their site of action within a cell or tissue, and, when used *in vivo*, they must not be toxic. As illustrated by Nakagawa, Miyata, and co-workers with the photocontrolled release of peroxyxynitrite, photocages may involve relatively complex photochemical and thermal processes to release the desired molecule.²⁰ Another elegant application that takes advantage of changes in photochemical properties that occur when a molecule reaches

its biological target is illustrated by the work of Perez with a folate–doxorubicin disulfide-linked conjugate that acts as a cage and as a prodrug to unveil both therapeutic and diagnostic (theranostic) functions in the form of cytotoxicity and fluorescence-based cancer imaging.²¹ The development of structures for specific sensing applications to address cellular properties and functions continues to incorporate sophisticated electronic properties, as shown by Yellen et al. with a genetically encoded red fluorescent protein capable of reporting the intracellular pH of living cells in a ratiometric manner.²² On the subject of controlling the site specificity and photophysics of probe molecules in biological media, the development of fluorophores for applications in super-resolution imaging techniques has flourished in the past few years. Examples range from the development of probes for stimulated emission depletion (STED) microscopy, which demand high fluorescence intensity and extremely high chemical stability, to probes specifically designed to switch between emissive and dark states in response to photochemical or thermal stimuli to take advantage of “points accumulation for imaging in nanoscale topography” (PAINT). Articles by Tampé²³ and Hochstrasser²⁴ illustrate applications of these techniques (STED and PAINT, respectively), which provide images with resolutions as high as 40–50 nm—well beyond the diffraction limit. Important developments have been reported with other methods.

The last two articles of this collection illustrate the fact that new structures with unusual electronic properties continue to be discovered and shown to have remarkable properties. In recent years, syntheses of cyclic conjugated molecules expanding the range of aromaticity, anti-aromaticity, and non-aromaticity with closed-shell and open-shell structures have become available. Novel orbital topologies and electronic configurations are likely to unveil interesting photophysical phenomena. As an example, the report of neutral, monoradical, and biradical hexaphyrin species by Sessler, Osuka, and Kim unveils interesting one- and two-photon absorption spectra within structures that vary from 26π to 27π and 28π electrons and display formally anti-aromatic, non-aromatic, and aromatic structures.²⁵ Finally, a fascinating electron-deficient boracyclophane reported by Jäkle and co-workers represents a new type of highly emissive chromophore that is somewhat reminiscent of a porphyrin, if the latter is viewed as a pyrrolo-cyclophane, but with opposite electronics.²⁶ With six boron atoms in a conjugated macrocycle, the structure is capable of undergoing up to six reversible reduction waves.

In conclusion, the frontiers of photochemical sciences continue to expand with the inclusion of new processes, new chromophores, new materials, and new challenges. There is no doubt that photochemistry and photophysics will continue to play an increasingly important role in the basic sciences and in the development of new technologies. It will be wise for us to expect that ground-breaking contributions in photochemistry and photophysics will continue to illuminate the pages of the *Journal of the American Chemical Society*.

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REFERENCES

- (1) Wang, X.; Nguyen, D. M.; Yanez, C. O.; Rodriguez, L.; Ahn, H.-Y.; Bondar, M. V.; Belfield, K. D. *J. Am. Chem. Soc.* **2010**, *132*, 12237–12239.

(2) Mori, K.; Ishibashi, Y.; Matsuda, H.; Ito, S.; Nagasawa, Y.; Nakagawa, H.; Uchida, K.; Yokojima, S.; Nakamura, S.; Irie, M.; Miyasaka, H. *J. Am. Chem. Soc.* **2011**, *133*, 2621–2625.

(3) Remón, P.; Bälter, M.; Li, S.; Andréasson, J.; Pischel, U. *J. Am. Chem. Soc.* **2011**, *133*, 20742–20745.

(4) Zhang, C.; Zou, C.-L.; Yan, Y.; Hao, R.; Sun, F.-W.; Han, Z.-F.; Zhao, Y. S.; Yao, J. *J. Am. Chem. Soc.* **2011**, *133*, 7276–7279.

(5) Ishizuka, T.; Sinks, L. E.; Song, K.; Hung, S.-T.; Nayak, A.; Clays, K.; Therien, M. J. *J. Am. Chem. Soc.* **2011**, *133*, 2884–2896.

(6) Johnson, J. C.; Nozik, A. J.; Michl, J. *J. Am. Chem. Soc.* **2010**, *132*, 16302–16303.

(7) Karlsson, S.; Boixel, J.; Pellegrin, Y.; Blart, E.; Becker, H.-C.; Odobel, F.; Hammarström, L. *J. Am. Chem. Soc.* **2010**, *132*, 17977–17979.

(8) Tang, K.-C.; Chang, M.-J.; Lin, T.-Y.; Pan, H.-A.; Fang, T.-C.; Chen, K.-Y.; Hung, W.-Y.; Hsu, Y.-H.; Chou, P.-T. *J. Am. Chem. Soc.* **2011**, *133*, 17738–17745.

(9) Algar, W. R.; Wegner, D.; Huston, A. L.; Blanco-Canosa, J. B.; Stewart, M. H.; Armstrong, A.; Dawson, P. E.; Hildebrandt, N.; Medintz, I. L. *J. Am. Chem. Soc.* **2012**, *134*, 1876–1891.

(10) Dutta, P. K.; Varghese, R.; Nangreave, J.; Lin, S.; Yan, H.; Liu, Y. *J. Am. Chem. Soc.* **2011**, *133*, 11985–11993.

(11) Kent, C. A.; Mehl, B. P.; Ma, L.; Papanikolas, J. M.; Meyer, T. J.; Lin, W. *J. Am. Chem. Soc.* **2010**, *132*, 12767–12769.

(12) Morimoto, M.; Irie, M. *J. Am. Chem. Soc.* **2010**, *132*, 14172–14178.

(13) Zhu, L.; Al-Kaysi, R. O.; Bardeen, C. J. *J. Am. Chem. Soc.* **2011**, *133*, 12569–12575.

(14) Kuzmanich, G.; Simoncelli, S.; Gard, M. N.; Spänig, F.; Henderson, B. L.; Guldi, D. M.; Garcia-Garibay, M. A. *J. Am. Chem. Soc.* **2011**, *133*, 17296–17306.

(15) Lin, S.; Ischay, M. A.; Fry, C. G.; Yoon, T. P. *J. Am. Chem. Soc.* **2011**, *133*, 19350–19353.

(16) Stamplecoskie, K. G.; Scaiano, J. C. *J. Am. Chem. Soc.* **2011**, *133*, 3913–3920.

(17) Dass, A. *J. Am. Chem. Soc.* **2011**, *133*, 19259–19261.

(18) Deeb, C.; Ecoffet, C.; Bachelot, R.; Plain, J.; Bouhelier, A.; Soppera, O. *J. Am. Chem. Soc.* **2011**, *133*, 10535–10542.

(19) Huschka, R.; Zuloaga, J.; Knight, M. W.; Brown, L. V.; Nordlander, P.; Halas, N. J. *J. Am. Chem. Soc.* **2011**, *133*, 12247–12255.

(20) Ieda, N.; Nakagawa, H.; Peng, T.; Yang, D.; Suzuki, T.; Miyata, N. *J. Am. Chem. Soc.* **2012**, *134*, 2563–2568.

(21) Santra, S.; Kaittanis, C.; Santiesteban, O. J.; Perez, J. M. *J. Am. Chem. Soc.* **2011**, *133*, 16680–16688.

(22) Tantama, M.; Hung, Y. P.; Yellen, G. *J. Am. Chem. Soc.* **2011**, *133*, 10034–10037.

(23) Grunwald, C.; Schulze, K.; Giannone, G.; Cagnet, L.; Lounis, B.; Choquet, D.; Tampé, R. *J. Am. Chem. Soc.* **2011**, *133*, 8090–8093.

(24) Kuo, C.; Hochstrasser, R. M. *J. Am. Chem. Soc.* **2011**, *133*, 4664–4667.

(25) Ishida, M.; Shin, J.-Y.; Lim, J. M.; Lee, B. S.; Yoon, M.-C.; Koide, T.; Sessler, J. L.; Osuka, A.; Kim, D. *J. Am. Chem. Soc.* **2011**, *133*, 15533–15544.

(26) Chen, P.; Jäkle, F. *J. Am. Chem. Soc.* **2011**, *133*, 20142–20145.