The Beautiful Molecule: 30 Years of C60 and Its Derivatives

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Review—The Beautiful Molecule: 30 Years of C_{60} and Its Derivatives

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In 1996 Sir Harold W. Kroto, Robert F. Curl and Richard E. Smalley were honored with the Nobel Prize in Chemistry for the discovery of fullerenes. The advent of these new forms of carbon heralded a race to understand the physical and chemical properties. C_{60} is virtually insoluble in polar solvents but is partially soluble in benzene, toluene, and carbon disulfide. This made the processing of fullerenes for new applications fairly problematic. However, the physical and chemical properties of these cage structures may be tailored for a wide range of applications. Some of the difficulties in processing have been overcome by using novel fullerene derivatives. The functionalization of the fullerene core with different chemical moieties provided a vector toward potential applications in drug delivery, optoelectronics, electrochemistry and organic photovoltaics. In this review, we will take a closer look at the features of some of the fullerene derivatives that have reinvigorated the field of fullerene research. Water-soluble polyhydroxylated fullerenes such as fullerenol have demonstrated the potential for good electron transfer and optical transmission, while hydrophobic fullerene derivatives have shown promising avenues for catalytic applications. 2015 marked the 30th anniversary of the discovery of fullerenes, with celebrations around the world including an event by the Royal Society of Chemistry, bringing together many of Sir Harold Kroto’s former students. The event also coincided with the recent discovery of C_{60}e in space after a complex twenty-year search. It is with sadness that we, Harry’s Research Group at Florida State University, and his international collaborators, reflect on the passing of Sir Harold Kroto. His dedication to science and commitment to science communication through the VEGA Science Trust and the Global Educational Outreach for Science Engineering and Technology (GEOSET) initiative help to raise awareness of the challenges for science in the modern world. We will continue to inspire young students through outreach activities he initiated.

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Nanostructured carbon materials including fullerenes, carbon nanotubes, graphene and carbon black have the potential to be transformative in many areas from medicine to engineering. Research into carbon nanotubes is diverse in areas such as electrochemical devices, field emission, sensors and probes. Recently, carbon nanotubes have been used as additives in the thermoplastics typically used for 3D printing. Graphene is the latest material to have peaked interest in the carbon field in a similar manner to carbon nanotubes, with a range of potential applications. Graphene oxide is being explored in the production of 3D holographic images.

The famous paper in Nature, C_{60}:Buckminsterfullerene, introduced the world to the new form of carbon but the road to general acceptance at that time was difficult, even with mounting evidence in support of the discovery. The paper, now cited over 10,000 times has become the central point of reference for fullerene scientists, although it was initially difficult for the structure of C_{60} to be fully accepted. Sir Harold Kroto said that at the time when the structure was proposed, it was considered by some as bewildering and highly unconvincing. There were many papers that were published which were highly critical of the structural conjecture and experimental observations. In a fascinating turn of events, a mechanistic transformation that was published in a paper which cast doubt on the structure of C_{60} is now used to explain some of the aspects of fullerene dynamics. The acceptance of the structure of fullerenes paved the way for the acceptance of related materials such as carbon nanotubes and carbon nano-onions.

After 30 years of research into fullerenes, we take a look back at some of the key areas of research that are helping to stimulate the field. The functionalization of fullerenes has become a broad topic, and the solubility of fullerene derivatives dominates the drive for research geared toward applications. Water soluble derivatives imparts a new paradigm toward their use in medicine as antioxidants, helping to moderate the production of reactive oxygen species. Fullerenol is one example of a promising water soluble pharmaceutical additive for the treatment of oxidative stress-related disease and as biocompatible actuators. The OH-groups on fullerenol provide access to some chemical pathways and processes including catalysis, which are explored in this review. The primary areas of interest covered by this short review include antioxidant effects from a biological perspective, a brief focus on the mechanical properties and electrical properties of fullerene derivatives and the catalytic properties of some hydrophobic fullerene derivatives. The research into hydrophobic fullerene derivatives such as metallofullerenes has a tendency to focus more on fundamental chemistry and the stabilization of small fullerene cages, while other hydrophobic derivatives such as methanofullerenes have a similar remit to fullerenol regarding their potential applications in sensors and photovoltaic devices. The use of metallofullerenes as catalysts helps to promote different organic reactions: cycloadditions and Bingel reactions. The review will conclude with a reflection on the discovery of carbon nanotubes and where they may make a contribution to commercial applications.

Fullerene Derivatives: The Race to Characterize

Antioxidant behavior.—A new age of the chemistry of fullerenes and their derivatives meant a challenge and a race to characterize the properties in the hope of discovering something exotic. Fullerenes and their derivatives have an exceptional capacity for radical scavenging due to their intrinsic electronic properties and the curved conjugated...
Figure 1. The structures of carboxyfullerenes showing the paired carboxyl groups on the C60 sphere. The three-dimensional models demonstrate the polar distribution of the carboxyl groups on C3 and the equatorial distribution on D3. (Reproduced with permission from Ref. 18).

π-system.12 The quenching ability is so high that sometimes fullerenes are called ‘radical sponges’.

Fullerenes are fascinating as they can illicit two opposing biological effects, specifically antioxidant and oxidant (mediated by singlet oxygen). Pristine C60 itself is a powerful antioxidant in vivo. The intraperitoneal injection of an aqueous suspension to rats conferred protection to their liver against free-radical damage.13 The antioxidant effects were shown both in vitro and in vivo and not only for the pristine fullerene C60 but also for its low-molecular-weight derivatives (e.g., fullerene) and polymer derivatives.14 The reactive oxygen species (ROS) scavenging activity was also shown for some amino acid derivatives of C60. These included α-alanine/C60, β-alanine/C60, cysteine/C60, as well as an oxidized glutathione/C60 derivative,12,15 a covalent hybrid consisting of C60, a peptide, and a steroidal moiety.16 Other fullerenes, including endohedrals, also possess antioxidant activity.17 As mentioned earlier, the use of fullerenols can cause problems with the reproducibility of biological responses.18 The tris-adducts C3 and D3 (Figure 1) demonstrated the antioxidant and neuroprotective action of fullerene derivatives as well as the potential of fullerenes to provide cytoprotection due to their ability to scavenge reactive oxygen species.18–20

The dendritic water-soluble fullerene C60 mono-adduct I (Figure 2) exhibits the highest degree of in vitro antioxidant activity against superoxide anions as compared with trismalonate-derived anionic fullerenes, as well as cationic fullerenes of similar structure. In fact, to obtain a suitable degree of water solubility without a surfactant or co-solvent, three charges on the addends would be required.21 The article also stated that anionic derivatives have better antioxidant activity than similar cationic compounds.

Both liposoluble and water-soluble C60 derivatives can prevent radical-initiated lipid peroxidation and the breakdown of membrane integrity. For protection, the antioxidant has to reside near to the membrane interior region where lipid peroxidation chain propagation occurs. Liposoluble C60 derivatives show stronger effects than the most effective natural antioxidant, vitamin E, in the prevention of lipid peroxidation.22 Polymer compositions with fullerene derivatives form a unique group of antioxidants. Some water-soluble fullerene derivatives, including PEG, PVP, hydroxyl, isostearic acid, and γ-cyclodextrin-modified fullerenes behave as potent ROS scavengers in cell cultures and can protect human skin keratinocytes from UV irradiation and oxidative damage by tert-butyl hydroperoxide.23 The radical scavenging activity of dendrofullerene may also find applications in radioprotection in vivo.24

Antioxidant activity against lipid peroxidation in human plasma was also shown for two water-soluble sugar-pendant C60 derivatives.25 The reactivity of these compounds toward ROS is similar to those of many phenolic antioxidant compounds, although smaller than those of vitamins E and C and β-carotene. C60 and its fulleropyrrolidine derivatives, incorporated in multilamellar liposomes, exhibit high skin absorption and excellent antioxidant activity without any significant biological toxicity.26–28

Currently, there are no fullerene based commercial products that have made a significant impact, but there is a niche market for C60 as an antioxidant in cosmetics. It was used as a C60/PVP complex ‘Radical Sponge’29 and squalane-dissolved fullerene C60 ‘LipoFullerene’.30 These preparations were determined to be safe since they do not show cytotoxicity under photo-irradiation or pro-oxidant activity.31

Figure 2. The dendritic water-soluble fullerene C60 mono-adduct I. (Reproduced with permission from Ref. 21).
Metallofullerenes (MFs) have been used with many organic reactions including as: \([1+2]\) cycloadditions, \([3+2]\) cycloadditions, Prato reactions, and Diels–Alder type cycloadditions. Cui et al. documented the nature of an encapsulated metal cation for the regioslectivity and the reactivity in the Diels–Alder (DA) cycloaddition of cyclopentadiene \((\text{CpH})\) to \(\text{M}^+ @ \text{C}_{60}\) \((\text{M} = \text{Li}, \text{Na}, \text{K}, \text{Rb}, \text{and Cs})\) and \(\text{Ca}^{2+} @ \text{C}_{60}\) by density functional theory in the gas phase and solvents. It was shown that metal cations could promote the reactions of \(\text{CpH}\) and \(\text{C}_{60}\) because they decrease the activation barriers and make the reactions more exothermic and exergonic, or less endothermic and endergonic. When there were encapsulated metal cations with more positive charges, there was an enhancement in the reactivity of the 6–5 bond on \(\text{C}_{60}\), which was significant when the 6–5 adduct was the targeted product. The 6–6 bond reactions are concerted and asynchronous processes, and all the 6–5 bond reactions are concerted and asynchronous processes. Encapsulated cations change both the distortion and interaction energies, and the combined effect facilitates the DA reactions of the cation-encapsulated \(\text{C}_{60}\) molecules. It was also shown that the interactions between metal cations and \(\text{C}_{60}\) are exothermic and exergonic, with the exception of \(\text{Cs}^+\). The positions of the metal cations inside \(\text{C}_{60}\) cages for isolated \(\text{M}^+ @ \text{C}_{60}\) and \(\text{Ca}^{2+} @ \text{C}_{60}\) molecules were different, and the DA cycloaddition of \(\text{CpH}\) to \(\text{Ca}^{2+} @ \text{C}_{60}\) occurs more readily than all of the five \(\text{M}^+ @ \text{C}_{60}\). Figure 4 shows the geometric parameters \((\text{in } \text{Å})\) and the interaction energy \((\text{kcal mol}^{-1})\) in enthalpy \((\text{left})\) and Gibbs energy \((\text{right})\) of \(\text{M}^+ @ \text{C}_{60}\).

The electron properties of MFs can also be used to control catalytic activity of proteins in vivo. The work of Král evaluated the potential for the control of biological systems by using hybrid metallic nanotube ropes with proteins, embedded in biosystems, by excitation in the near infrared region. It was shown that in a double-tube rope, when one nanotube is filled with metallofullerenes and another is empty, the tubes will change their opposite equilibrium charging during irradiation, resulting in a change of the local electric field. This change can lead to the deformation of proteins attached to the tubes and modify their catalytic properties.

Metallofullerenes have been suggested as alternative catalysts with ultra-low Pt loading for use in polymer electrolyte membrane fuel cells. Traditional Pt/C electrodes have stability problems with ‘Pt coarsening’ and erosion of the carbon black support during fuel cell operation. The expense and instability of platinum/carbon black catalysts have led to a search for new alternative catalyst materials. Since \(\text{C}_{60}\) is quite stable, metallofullerenes may be used to reduce corrosion, while preserving the catalytic activity of the metal atom(s).

Fullerenes can be functionalized with hydroxyl groups to become fullerenol and may be used as a hydrogen bond catalyst. Hydrogen bond catalysis requires the use of hydroxyl groups for hydrogen bonding with reactants, with the hydrogen bond elevating the reaction rate. Since hydroxyl groups are directly attached to the fullerene cages, fullerenol benefits from the strong electron affinity of the fullerene cage as a hydrogen bond catalyst. Niu et al. studied fullerenol \(\text{Na}_2\text{C}_{60}\text{O}_4(\text{OH})_{15}\) as a candidate for a hydrogen bond catalyst, and it was shown to be a good catalyst for Henry reactions, Aldol reactions, Michael addition reactions and Friedel–Crafts reactions. It showed excellent catalytic activity and stability as a fullerenol catalyst and was easy to recycle. In Henry reactions, the \(\text{C}_{60}\) fullerenol showed high catalytic activity at room temperature, and was stable over an extended period with deactivation after 450 h, with 100% selectivity for the nitro alcohol product.

Sun et al. used the fullerenol \(\text{C}_{60}(\text{OH})_2\text{O} @ \cdot 2\text{H}_2\text{O}\) as a catalyst in the synthesis of cyclic carbonates from \(\text{CO}_2\) and epoxides. This study proposed that hydrogen bonding between the catalyst and epoxide could be a key factor in promoting the cycloaddition reaction between the epoxide and \(\text{CO}_2\). It was shown that with the use of fullerenol and the salt \(\text{KI}\), the propylene carbonate yield reached 95% within two hours due to the fullerenol providing Lewis acid sites for activating the oxygen atom in the epoxide ring through its hydroxyl groups, with \(\text{KI}\) acting as the nucleophilic group to activate the carbon in the epoxide ring.

In a further effort to highlight transition metal free molecular catalysts, Zhuo et al. studied a novel catalyst based on carbon which included a salt consisting of \(\text{C}_{60}(\text{OH})_2\) fullerenol anions electrodeposited onto a glassy carbon electrode coated with Nafion in an aqueous solution for hydrogen evolution reactions. Fullerenol was selected due to the interaction between \(\text{C}_{60}(\text{OH})_2\) and \(\text{H}^+\). Nafion was used on the electrode surface to inhibit the dissolution of...
Figure 4. The geometric parameters in Å and the interaction energy (kcal mol\(^{-1}\)) in enthalpy (the left one) and the Gibbs energy (the right one) of \(M^+ @ C_{60}\).
(Reproduced with permission from Ref. 38).

electrodeposited particles and form the Nafion/C\(_{60}(\text{OH})_8\) composite. A high electrocatalytic activity of the C\(_{60}(\text{OH})_8\) fullerol anion salt toward the hydrogen evolution reaction (HER), was observed, which may have been related to the adsorption of H\(^+\) onto C\(_{60}(\text{OH})_8\), and the fullerol anion salt deposited on the electrode showed good conductivity. An onset potential of \(-0.11\) V and an exchange current density of \(7.0 \times 10^{-7}\) A cm\(^{-2}\) at a loading of about 2\(\mu\)g cm\(^{-2}\) was observed.

Yang et al. looked at the synthesis of Pd-fullerol (Pd-F) composite nanoparticles by an electrostatic self-assembly method. The composite nanoparticles were then loaded onto carbon nanotubes (CNTs) to form an electrocatalyst for methanol oxidation in alkaline media.\(^{45}\) It was shown that the Pd-F/CNTs catalyst had a larger electrochemically active surface area and a much higher electrocatalytic activity than Pd/CNTs. The Pd-F/CNTs catalyst also had enhanced activity and stability for methanol electro-oxidation in an alkaline medium. The methanol oxidation peak current density of the Pd-F/CNTs was 32.7 mA cm\(^{-2}\), which is 1.72 times higher than that of Pd/CNTs. The discussion of the results focused on the idea that fullerol in the catalyst not only resulted in uniform and monodispersed Pd nanoparticles, but also actually cleared the intermediate species produced in the catalytic process due to the hydroxyl groups and the loss of electrons on the catalyst.

Mechanical and Electrical Tailoring

**Mechanical properties.**—A study by Saotome et al. described the mechanical properties of hydroxylated C\(_{60}\) fullerene/polycarbonate (PC) nanocomposite films.\(^{46}\) The Polyhydroxylated fullerenes, C\(_{60}(\text{OH})_{12}\) and C\(_{60}(\text{OH})_{36}\), and pristine C\(_{60}\) were investigated. The stress–strain measurements of the pristine PC film and the PC nanocomposite films were performed, and the elongation at break and yield tensile strength decreased as the hydroxylation of the fullerene proceeded. The incorporation of nanofillers would improve the mechanical properties of the composites when there is covalent bonding between nanofillers and the polymer matrix, or possibly when there is a bridging effect. The study showed that the hydroxylated fullerenes connected to the PC chains by dipole-dipole interactions did not result in a significant improvement of the mechanical properties. The glass transition temperatures for PC, PC/C\(_{60}\), PC/C\(_{60}(\text{OH})_{12}\), and PC/C\(_{60}(\text{OH})_{36}\) were 137, 135, 146, and 135°C, respectively. The decomposition temperatures measured by thermo-gravimetric analysis (TGA) were 501, 506, 522, and 480°C respectively. The result for PC/C\(_{60}(\text{OH})_{16}\) was possibly due to the larger agglomerations of hydroxylated fullerenes, and the effect of trapped water molecules that are formed at elevated temperatures. As the water is released, it would cause partial hydrolysis in the carbonate moiety of the PC polymer, which would result in the decreased thermal stability of PC. Composite materials containing nanomaterials may become brittle with increasing nanoparticle concentration. The problem can be caused by the aggregation of nanoparticles inside the polymer matrix. Increased miscibility and solubility of nanoparticles may help to reduce aggregation.

Polyurethane reinforced with fullerene C\(_{60}\) (1–10wt%) coated with the epoxy diglycidyl 1,2-cyclohexanedicarboxylate has also been investigated for mechanical properties. The films produced reported higher values of tensile strength from 86.9–90.3 MPa (a 79% increase relative to polyurethane) and a tensile modulus range of 33.3–47.6 GPa.\(^{47}\)

The mechanical properties of a polymer-fullerene derivative composite can significantly change when compared to the parent polymer. For instance, the inclusion of [6,6]-phenyl-C\(_{61}\)-butyric acid methyl ester (PCBM) to a polymer matrix improves the mechanical moduli.\(^{48–52}\) PCBM also increases the mechanical resilience of semiconducting polymers for solar cells without having an adverse effect on the photovoltaic properties.\(^{53}\) and increases interlayer adhesion in roll-to-roll flexible-inverted polymer-based solar cells.\(^{54}\) The incorporation of fullerol molecules into a polymer also dramatically increases the
Fullerenes have prevented the use of polymer-fullerene systems as semiconductors.

Electrical properties.—Fullerene derivatives, like pristine fullerenes, are semiconducting materials in which the electrons are charge carriers. These properties are due to the π-electron conjugation of the carbon cage. Usually, the electron mobility in thin films of fullerene derivatives is significantly lower than for fullerenes and varies (for the amorphous state) by about $10^{-2} - 10^{-3} \text{cm}^2\text{V}^{-1}\text{s}^{-1}$. However, in complex systems of fullerene derivative and polymers, this parameter can increase. Some pure endohedral metallofullerenes (EMFs) possess a high electron mobility, for instance, the $\text{Sc}_3\text{C}_2@\text{C}_{80}$ molecule.

A conventional bulk heterojunction (BHJ) polymer system for the donor-acceptor configuration of semiconductors can be produced with organic polymers and fullerenes. The fullerenes (or fullerene derivatives) can perform as a donor or acceptor, depending on the polymer used. Methanofullerenes like PCBM have been successfully used for this purpose. Figure 3 shows the structure of PCBM. The modification of pure fullerenes can overcome some of the limitations that have prevented the use of polymer-fullerene systems as semiconductors like materials. As stated earlier, fullerene molecules have poor miscibility and solubility causing aggregation in bulk polymers. The organic “tail” of PCBM improves solubility in many organic solvents and, consequently, extends the number of variants for possible donor-acceptor materials. The donor-acceptor pathway is used in many areas such as photovoltaics and optical limiting devices and fullerene derivatives should improve the electrical properties of these materials. For semiconductor materials, the properties are determined by the lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO) energy levels. For donor and acceptor materials, the difference between their LUMO energy levels should be greater than the exciton binding energy (0.3-0.5 eV) as well as their HOMO energy levels. Typically, the energy level differences of a polymer-methanofullerene system are sufficient for tuning donor-acceptor devices.

The LUMO energy level of PCBM for $\text{C}_{60}$ or $\text{C}_{70}$ is $-3.91 \text{ eV}$.69 The LUMO energy level is significantly increased for the Lu$_3\text{N}@\text{C}_{80}$-PCBH molecule (where the H denotes’ hexyl’). This level is higher than that of PCBM by 0.28 eV and provides an improvement over the properties of some organic photovoltaic devices.

The mechanism of the electron transfer in EMFs has been discussed with some consensus on the pathway. One suggestion is that all free electrons from metal atoms should be localized in the carbon cage, therefore a metal atom and carbon cage would form an ionic model of bonding (as a ligand). The charge of the carbon cage has been confirmed by some theoretical and experimental results. Other studies on various EMFs established that was a smaller charge on the metal atom than was expected in the anion-cation structures, and pointed toward the hypothesis of covalent bonding. Another theory suggested that some of the electrons are not completely transferred to the cage; instead, they are shared between the endohedral atoms and the carbon cage by covalent interactions. In this case, the LUMO of EMFs is localized in the metal atom.

Fullerenes (Figure 5) differ from other fullerene derivatives. These molecules behave as proton conductivity materials.61-64 At room temperature, the proton conductivity of $\text{C}_{60}(\text{OH})_{12}$ in the solid phase is $7 \times 10^{-6} \Omega^{-1}\text{cm}^{-1}$, which is much larger than the electronic conductivity ($10^{-6} \Omega^{-1}\text{cm}^{-1}$). Alternatively, highly hydroxylated molecules are associated with dielectric materials, and low hydroxylation is typically a benchmark for materials that facilitate proton conduction. The proton conductivity of fullerol is used for various applications such as fuel cells and energy conversion and storage for solar cells.105-109,119,120 Carbon nanotubes, exploiting the defects has been pivotal for cross-linking carbon nanotubes with some consensus on the pathway. One suggestion is that all free electrons from metal atoms should be localized in the carbon cage, therefore a metal atom and carbon cage would form an ionic model of bonding (as a ligand). The charge of the carbon cage has been confirmed by some theoretical and experimental results. Other studies on various EMFs established that was a smaller charge on the metal atom than was expected in the anion-cation structures, and pointed toward the hypothesis of covalent bonding. Another theory suggested that some of the electrons are not completely transferred to the cage; instead, they are shared between the endohedral atoms and the carbon cage by covalent interactions. In this case, the LUMO of EMFs is localized in the metal atom.

The Advent of Carbon Nanotubes

1995 was a turning point for carbon, but the story of carbon nanotubes is one of missed opportunities. 1991 was a pivotal year as Sumio Iijima of NEC Corporation identified multi-wall carbon nanotubes from carbon arc discharge. However, evidence of the carbon nanotubes was trace back to 1952 and a paper by Russian scientists. A fascinating editorial by Montioux et al. investigated the mystery behind who should be given credit for the discovery of carbon nanotubes. As the years progressed, new synthetic methods were established, and the price of carbon nanotubes decreased.

In comparing the separate timelines of the development of applications for carbon nanotubes and $\text{C}_60$, there have been more practical applications of carbon nanotubes possibly due to a number of factors including their high aspect ratios and high conductivity. Probably the most famous property attributed to carbon nanotubes relates to the mechanical properties where they are said to be ‘100 times stronger than steel at one-sixth the weight’. Multi-wall nanotubes are typically produced with many defects along their walls. These defects were key in introducing additional levels of functionalization. While detrimental to applications focused on the strength of the nanotubes, exploiting the defects has been pivotal for cross-linking carbon nanotubes. Unlike the related fullerene, carbon nanotubes have made more of a transition to commercial products as composite materials in bikes, headphones, antifouling paint, printed transistors and the ESD Shield on the Juno space probe. Recent commercial products have been targeted at the 3D printing market. Some examples of commercially available products containing carbon nanotubes.

As carbon nanotubes and their surface modified derivatives continue to become more affordable, they may begin to replace the use of other fillers such as carbon black in applications. One of the problems that will need to be considered is the environmental implications of these nanomaterials. If there is a significant shift toward applications with carbon nanotubes, there may need to be regulations put in place to safeguard the levels of exposure and the safe disposal of waste.

The structure of [6,6]-phenyl-$\text{C}_{61}$-butyric acid methyl ester and fullerenol is shown.
Three decades after the discovery of fullerenes, the roadmap for applications has narrowed, mostly because of a number of derivatives like PCBM that have steered research and development toward photovoltaic devices and organic field effect transistors. The future of the use of fullerenes and their derivatives may depend on ease with which they can be incorporated into composites. While hydrophilic derivatives may be preferred for use in polymer composites, hydrophobic fullerene derivatives such as metallofullerenes may also be used as sensors.

The unique capacity for radical scavenging, with the inherent electronic properties and the curved conjugated π-system, is an advantage especially with water-soluble fullerene derivatives. The solubility is essential if they are to play any role as antioxidants, pharmaceutical additives for the treatment of oxidative stress-related disease and as biocompatible actuators. Fullerene research doesn’t have to ‘change the world’, and more applications may be forthcoming once the technical procedures for making new composite materials advance. The main advantage of fullerene chemistry is the possibility of creating advanced materials that can test our understanding of the fundamental interactions between molecules, transferring as much of the nanoscale characteristics of fullerenes to macroscale composites.

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Figure 6. Products containing carbon nanotubes.


