Design, Synthesis and Functionalization Strategies of Tailored Carbon Nanodots

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CARBON-BASED DOTS

SYNTHESIS
APPLICATIONS
CDs
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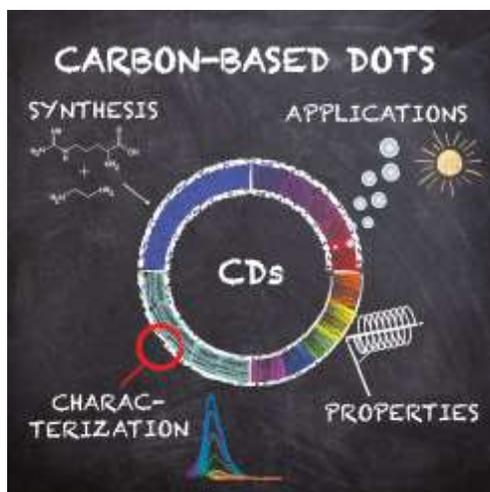
CONSPECTUS: Over the past decades, considerable effort has been devoted to synthesizing nanostructured materials with specific properties that ultimately shape their function. Especially in the carbon nanotechnology era, for nanomaterials such as fullerenes, carbon nanotubes and graphene, the main focus has been on the organic functionalization of these nanostructures, in order to tailor their processability and applicability. Carbon-based dots, quasi-spherical nanoparticles with shape under 10 nm, have popped up into this context especially due to their versatile synthesis and intriguing properties, mainly their fluorescence emission. Even though they were discovered through the top-down route of cutting large carbon nanostructures, in recent years the ease and flexibility of the bottom-up synthesis have allowed this carbon-based class of nanomaterials to advance at a striking pace. However, the fast speed of research and publication rate have caused a few issues that affect their classification, purity criteria and fluorescence mechanisms. As these are being progressively addressed, the true potential and applicability of this nanomaterials has started to unravel.

In this Account, we describe our efforts towards the synthesis, purification, characterization and applications of carbon nanodots. Special attention was dedicated to designing and customizing the optoelectronic properties of these nanomaterials, as well as their applications in hybrid and composite systems. Our approach is centered on a bottom-up, microwave-assisted hydrothermal synthesis. We have successfully exploited a multi-component synthetic approach, using arginine and ethylenediamine as starting materials. By controlling the reaction conditions, in just three minutes, blue-emitting carbon nanodots become accessible. We have improved this approach by designing and tuning the emissive, electrochemical and chiroptical properties of these nanoforms. On the other hand, we have used post-functionalization reactions as a tool for conjugation with suitable partners and for further tuning the surface chemistry. The combination of these two approaches has produced a number of carbon nanodots that can be investigated in fields ranging from biology to materials chemistry and in applications spanning from nanomedicine to energy conversion.

INTRODUCTION

The engineering of nanomaterials' properties is an essential tool en route to applications. Tuning shape, size, composition, surface chemistry, chirality along with electrochemical and photophysical properties, including ground and excited state properties, are common objectives in this research field. During our experience with carbon nanomaterials, namely fullerenes, carbon nanotubes, graphene and carbon dots (CDs), it has become clear that the modulation of the materials properties can be achieved by starting with the appropriate reagents or by post-functionalization of the as-prepared species. One simple example to illustrate this concept: CDs can be prepared very efficiently through bottom-up routes by using a plethora of starting materials and the choice of the reactants determines their properties, especially in terms of

surface coating (**Figure 1**). One very common approach involves the use of citric acid, which efficiently produces CDs characterized by the presence of a high number of carboxylic functions on their surface.[1] On the other hand, by using polyamines such as spermidine, CDs are generated that possess many amino groups.[2] This might seem an obvious reasoning, but it serves as a simple example to show that CDs can be prepared and manipulated efficiently to achieve multipurpose materials with ad hoc properties.
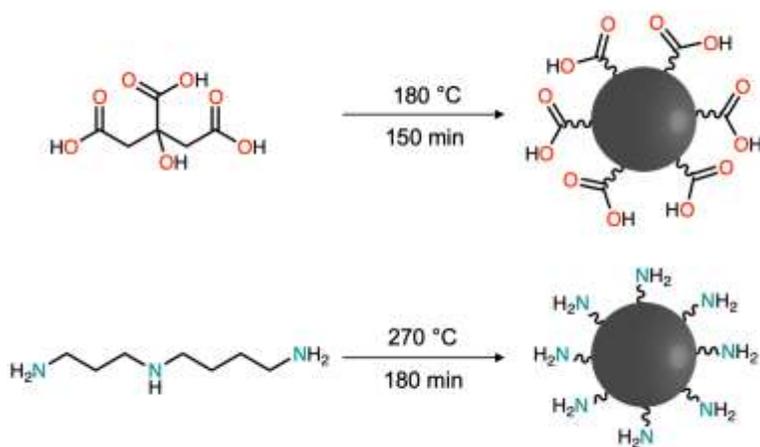
Figure 1. Carbon dots can be prepared from a multitude of starting materials, which will determine their properties. Examples of synthetic routes towards carboxylate- or amine-coated CDs.

The objective of the present Account is to describe our approach towards the synthesis and property modulation of CDs, small (<10 nm), quasi-spherical, nanoparticles composed of carbon, hydrogen and oxygen atoms. These nanoparticles consist of a carbon core surrounded by surface groups such as carboxylic acids, alcohols and amine functionalities, which are responsible for making CDs compatible with aqueous media, environmentally benign, with very low toxicity levels. What characterizes CDs most lies in their photophysical properties, especially

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fluorescence.[3,4] The photophysical properties, along with their structure and composition, can vary broadly depending on the choice of starting materials and preparation procedure.

Since CDs are not the only carbon nanoparticles, to put them in context it is important to recall the classification of carbon-based nanoparticles: Carbon NanoDots (CNDs), Carbon Quantum Dots (CQDs) and Graphene Quantum Dots (GQDs).[5] GQDs are disc-shaped two-dimensional nanoparticles or fragments of one (or few-layer) graphene sheets formed during the exfoliation of graphitic materials. Multi-layer, quasi-spherical nanoparticles with crystalline graphitic core are called CQDs, with the term 'quantum' referring to nanoparticles possessing delocalized band structures, possibly with some contribution from molecular-like and surface states. On the other hand, amorphous quasi-spherical nanoparticles that do not show quantum confinement effect, but possess excited states arising entirely from molecular-like species are called CNDs. However, discriminating between CQDs and CNDs often remains a challenge, since the relative contributions from the structure and the excitation states can be difficult to resolve. To this end, it has been suggested to use the term carbon dots (CDs) to describe all quasi-spherical carbon nanoparticles, which include those with molecular-like behavior, delocalized electronic structure and all the carbon nanoparticles that range between CNDs and CQDs.[6,7] CDs are then classified based on the characteristic structural elements, rather than on the 'quantum effects', *i.e.,* graphitic (*g*-CDs) or amorphous (*a*-CDs). Finally, heteroatom doping information should also be included when denoting to CDs by an addition prefix, *e.g.*, nitrogen doped amorphous carbon dots are denoted as *a*-N-CDs.

SYNTHESIS, PURIFICATION AND CHARACTERIZATION

Relatively small (<10 nm) CDs can be typically produced by hydrothermal treatment or pyrolysis of organic precursors, be it molecules or polymers. It has been reported that different types of CDs can be produced by controlling the temperature of the reaction, as T <300 °C usually leads to amorphous nanoparticles (*a*-CDs), while higher temperatures are responsible for graphitized structures (*g*-CDs). The choice of the precursors has a strong influence on the surface functional groups of the resulting nanoparticles. Amines and carboxylate groups are the most common surface coatings that can be obtained using precursors such as polyamines or citric acid and may allow post-synthetic functionalization reactions. Furthermore, bottom-up methods allow using not only one compound as a source in the synthesis, but also multiple precursors, in order to obtain CDs with different structures and properties.

In the early stages of our involvement in this research, we identified amino acids as an appropriate source for the synthesis of CDs, being abundant and inexpensive precursors, able to undergo dehydration and decarboxylation reactions, as well as capable of producing heteroatom-doped CDs.[8,9] Indeed, it was well-established that, for example, nitrogen-doping is responsible of more favorable optoelectronic properties, usually resulting in red-shifted absorption and improved photoluminescence quantum yields. Additionally to using amino acids (arginine, Arg), we decided to employ a second precursor in the mixture, in order to take advantage of its different reactivity and to act as 'passivating agent' or 'capping agent' for the surface of the dots.[10,11] We identified this additional species with ethylenediamine (EDA), as we reasoned it would be responsible for incorporating nitrogen atoms and for improving the solubility of the final nanoparticles in water.

Among the many possible synthetic procedures, we exploited the hydrothermal method, assisted by microwave heating. The hydrothermal synthesis provides low toxicological impact of

materials and processes and has been widely used for the preparation of various carbon materials.[12] The use of hydrothermal conditions results in increased or altered solubility of the reagents, improves their physical and chemical interactions and facilitates the final formation of the carbonaceous structures. The hydrothermal process at high temperatures (between 300 and 800 °C) is a well-established production method for materials with high carbon content such as carbon nanotubes or graphitic carbon materials. Instead, when the carbonization is performed at lower temperatures (below 300 °C) the materials result from dehydration and polymerization processes and present typically various surface functional groups.[12] This latter process has been recently widely explored for CD synthesis and usually accomplishes the formation of CDs soluble in aqueous media. On the other hand, the microwave (MW) technique has become an increasingly popular method for nanomaterial synthesis, because it addresses problems encountered in the preparation of nanomaterials by conventional heating process: For instance, poorly soluble materials usually lead to inhomogeneous heating, which then results in broad size distributions of the nanoparticles, especially in large-scale reactions.[13,14] Because of its high efficiency in energy utilization, MW irradiation offers a clean, cheap, and convenient method of heating, which often results in higher yields and especially shorter reaction times.[15] As a result, the MW-assisted hydrothermal method has become a very important production process for CDs, since it combines both the advantages of hydrothermal and MW techniques.

In our experiments, the successful formation of CDs can be observed by the formation of a brown solution, in daylight, that produces a bright blue emission, under UV illumination (**Figure 2b**, inset).[16] The easy, scalable and reproducible synthesis is combined with straightforward purification steps, consisting of filtration and dialysis. Filtration over a membrane is necessary to remove a small portion (<1% wt) of an insoluble material formed during the reaction, while

dialysis is necessary to remove small molecule impurities. Finally, the dialyzed solution of CDs is lyophilized, and a yellow solid is obtained. The *a*-N-CDs show an absorption band at 286 nm that can be ascribed to π-π transition of C=C units from the carbon core, while their blue fluorescence (FL) shows the commonly observed excitation wavelength dependence with a FLQY of 17% (**Figure 2c**). Structural investigations (XPS and FT-IR spectroscopies) reveal multiple oxygen and nitrogen functional groups on the particle surface. Their quasi-spherical shape, their small size and narrow size distribution (2.47 ± 0.84 nm) was confirmed by atomic force microscopy (AFM). TEM was not appropriate in this case because of the low contrast and the tendency of the CDs to aggregate on the grid. In order to get insight in the structure of our *a*-N-CDs, we used ^{13}C-enriched starting materials.[16] Through a detailed mono- and bi-dimensional ^{13}C-NMR analysis of our *a*-N-CDs, we observed a core/shell type of structure (**Figure 2a**). We evaluated the contribution of each precursor by using separated and combined ^{13}C-Arg and ^{13}C-EDA. Our ^{13}C-NMR studies show that, while the aromatic core mainly originates from Arg, EDA mostly contributes to the formation of the shell, confirming its surface doping and passivation role in the synthesis. Additionally, bidimensional experiments (^{1}H-^{13}C and ^{13}C-^{13}C) showed that protons observed in the aliphatic region, and close to heteroatoms, correlate through multiple bonds with the aromatic sp^2-carbon core. Diffusion-ordered spectroscopy through ^{1}H-^{13}C multiple-bond correlation allowed us to assign the signals to macromolecular species, confirming the successful purification from small molecular weight byproducts and unreacted species. It is therefore possible to confirm the presence of various functional groups, consistent with aza-aromatic rings (mainly coming from Arg) and aliphatic primary amines. The amino-rich surface of the CDs was also confirmed by chemical reactivity experiments: using the ninhydrin-based Kaiser test, we estimated the presence of 1350 µmol g^{-1}.
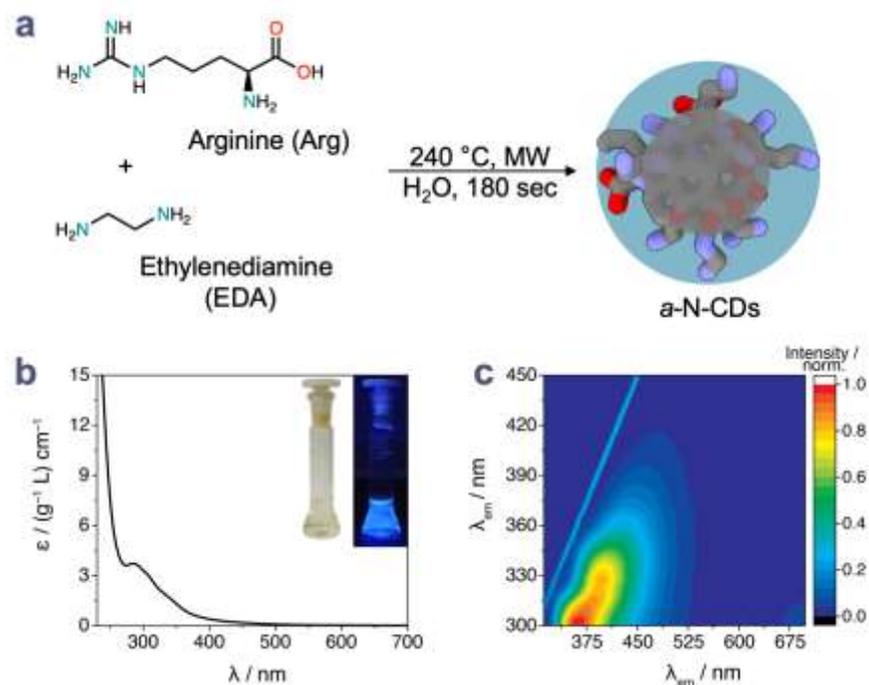
Figure 2. (a) Our original synthetic protocol consisting of microwave-assisted multi-component hydrothermal synthesis of amorphous nitrogen-doped CDs (*a*-N-CDs); (b) UV-Vis spectra of *a*-N-CDs (inset shows photographs of 1.0 mg mL^{-1} aqueous solution under daylight and upon irradiation with a UV lamp λ_{ex} = 365 nm); (c) fluorescence matrix scan of *a*-N-CDs.

In our original work we also showed that the *a*-N-CDs could be further separated by means of low-pressure gel filtration chromatography, resulting in three fractions of CDs, with narrower range of sizes. We also found that the fluorescence properties are dependent on the size (distribution) and the surface functional groups: the smaller CDs exhibit the higher FLQY (46%). In the course of our research, we settled on our original synthetic protocol and in the following sections we demonstrate the power of tuning the properties and the functions of CDs through the choice of the molecular precursors and/or by surface functionalization (**Figure 3**). Experimental

details of the preparation, purification and characterization procedures, which were employed during the course of our research, have been reported in a recently published protocol.[17]
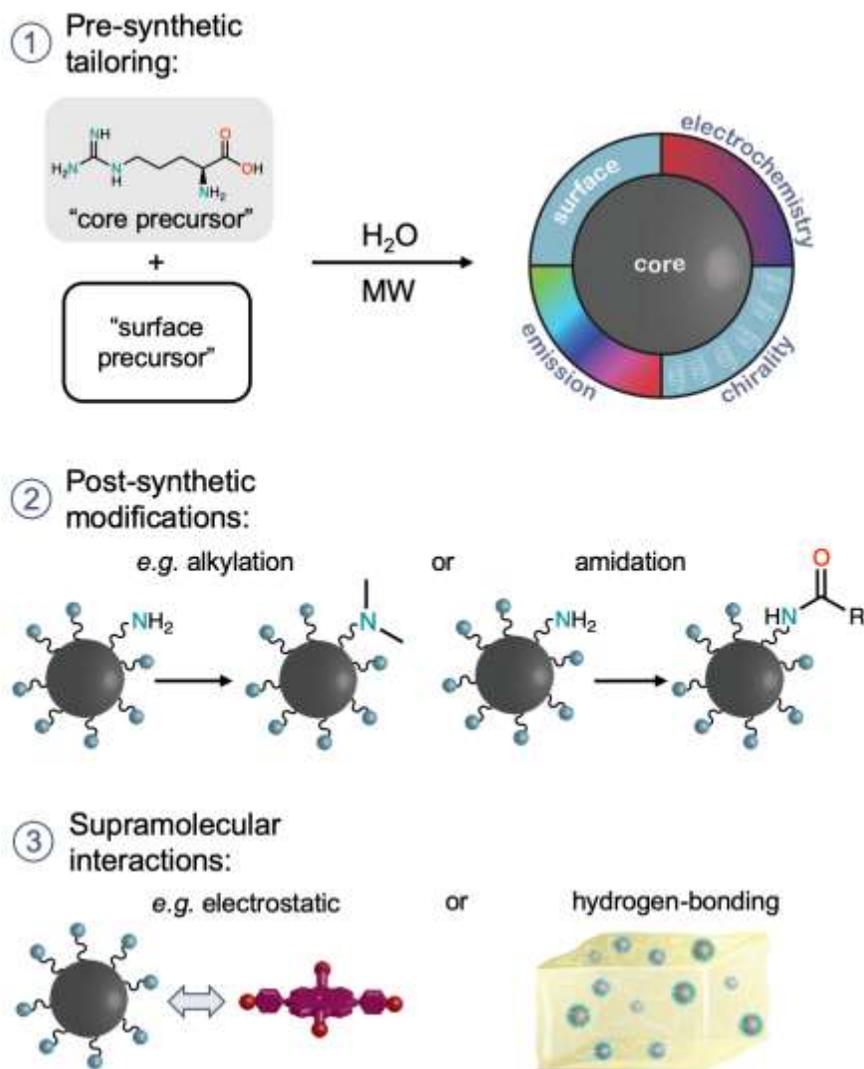
Figure 3. Overview of pre- and post-synthetic approaches to tune the properties of *a*-N-CDs.

PRE-SYNTHETIC DESIGNER CONTROL OF THE PROPERTIES

A big advantage of the bottom-up approach to CDs is the possibility to produce nanoparticles possessing specific properties, through the correct selection among a multitude of starting materials. The choice of the correct, simple molecular precursors will dictate the photophysical and electrochemical properties of the resulting nanoparticles.

One relevant property to tailor would be the emission of CDs. CDs are attractive light-emitting materials for a variety of applications, where the modulation of their emissive properties would therefore be a winning strategy. To this aim, a multitude of starting materials, procedures and conditions could serve the scope. For example, for *g*-CDs, it is possible to obtain red-shifted absorption through different approaches: (*i*) increasing the oxidation state of the surface;[18] (*ii*) nitrogen-doping in the graphitized core;[19] (*iii*) solvatochromism,[20] (*iv*) employing phenylenediamines, naphthalenediamines, or trihydroxybenzene, among other precursors, under harsh conditions.[21–24] We decided to use our multi-component approach, using EDA and Arg, by adding chromophores that would be incorporated in the CD structure and modulate the emission. Our investigations started with chromophores possessing a well-known chemistry and spectroscopy in order to have some predictability. Our preliminary attempts with substituted porphyrins or perylene bisimides under hydrothermal conditions were not successful, probably owing to the insolubility and/or aggregation of these species in water. We reasoned that only smaller π-conjugated cores would be able to react, so that we focused on naphthalene diimides (NDIs) mainly because *(i)* we anticipated that, in our hydrothermal conditions, the naphthalene dianhydride (NDA) would react with amines forming naphthalene diimides (NDIs) and *(ii)* core-substituted NDIs could lead to emission in the red region.[25] Therefore, by adding the suitable NDA precursors to the Arg + EDA mixture, we obtained blue- or orange-emitting *a*-N-CDs, respectively (**Figure 4**). Eventually, by carefully adjusting the reaction conditions, especially by

controlling the molar ratios of the precursors, we were able to prepare *a*-N-CDs with white light emission (WCDs, **Figure 4b,c**). While our white- and orange-emitting *a*-N-CDs are highly photostable (at least after 5 hours of continuous UV irradiation), their QYs (8% for white-emitting *a*-N-CDs and 12% for orange-emitting *a*-N-CDs) are relatively low. Also, the entire visible spectrum could not be covered by using this route, *e.g.*, emission in the green region of the spectrum was not accessible. We expect, however, that our rational approach will lead to the synthesis of CDs with versatile photoluminescence in a controlled manner. Other recent examples, including a recent photo-switched multicolor luminescent supramolecular assembly,[26] are expected to contribute to the development of synthetic procedures for easily tunable photoluminescent CDs.[27]
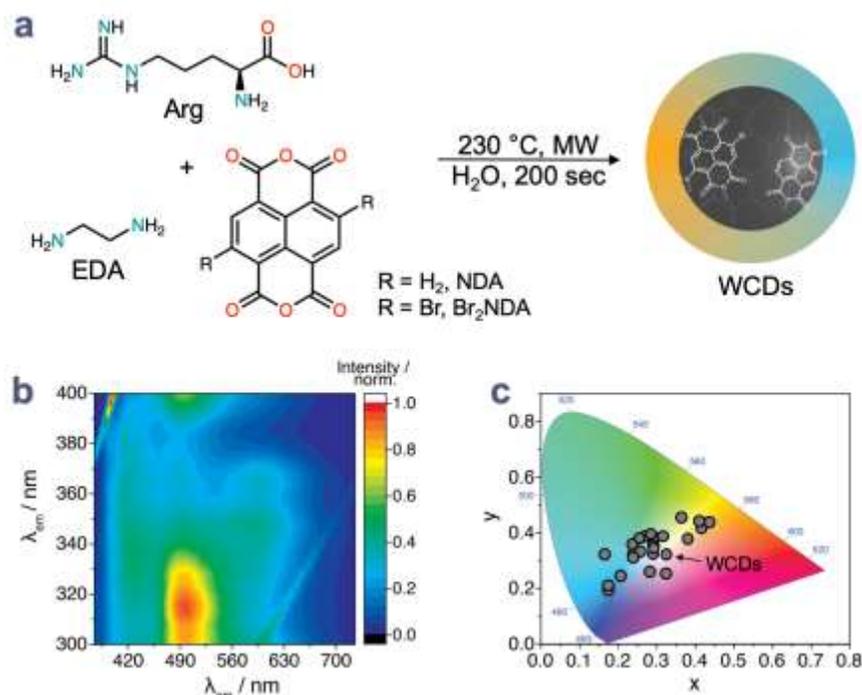
Figure 4. Preparation of white-light emitting *a*-N-CDs (WCDs). (a) Synthetic scheme for the preparation of WCDs; (b) fluorescence matrix scan of WCDs; (c) 1931 CIE chromaticity diagram showing color emission obtained by

tuning the starting materials molar ratio, molarity and temperature of the microwave-assisted hydrothermal reaction (WCDs, $x = 0.33$, $y = 0.33$).

CDs have been shown to play an important role in energy conversion and photocatalysis, where graphitization has been proposed to improve their redox properties.[7,28] On the other hand, we reasoned that the electrochemical properties of the CDs could be modified and customized by incorporation of known redox active molecules, such as quinones. In addition, a great variety of commercially available quinones would allow the preparation of a library of nanoparticles and validate our approach. The introduction of quinones in our reaction mixture of Arg and EDA has actually resulted in a powerful strategy for preparing CDs with tunable electrochemical properties (quinone carbon dots, QCDs, **Figure 5a,b**).[29] The use of the quinones results, as expected, in less negative reduction potentials for all the QCDs (ranging from -1.52 to -2.04 V vs. SCE) than a-N-CDs (-2.52 V vs. SCE). On the other hand, some QCDs showed higher oxidation potentials (ranging from $+1.31$ to $+1.48$ V vs. SCE) as compared to a-N-CDs ($+1.18$ V vs. SCE). The observed values and tunability may lead to new opportunities, for instance, for water oxidation reaction or proton reduction. While these quinone-containing CDs are per se valuable materials for photocatalysis, our methodology demonstrates that the *in situ* tuning of the electrochemical properties is a feasible avenue to produce materials with desired energy levels for targeted applications. For example, we investigated if QCDs could be suitable photosensitizers in solar-driven catalysis (**Figure 5c**). We examined the QCD reducing power by studying the photoreduction of methyl viologen (MV^{2+}) ($E^{0'} = -0.69$ V vs. SCE), which proceeds through a reductive quenching mechanism (photoexcitation of QCD is followed by electron donor hole scavenging and finally an electron transfer from QCD^{-} to MV^{2+}). They were found

considerably more efficient (*i.e.* with faster kinetics and higher conversion) than *a*-N-CDs as well as previously reported graphitized dots,[30] thus demonstrating their promising electron transfer properties for proton reduction and photocatalysis in general.
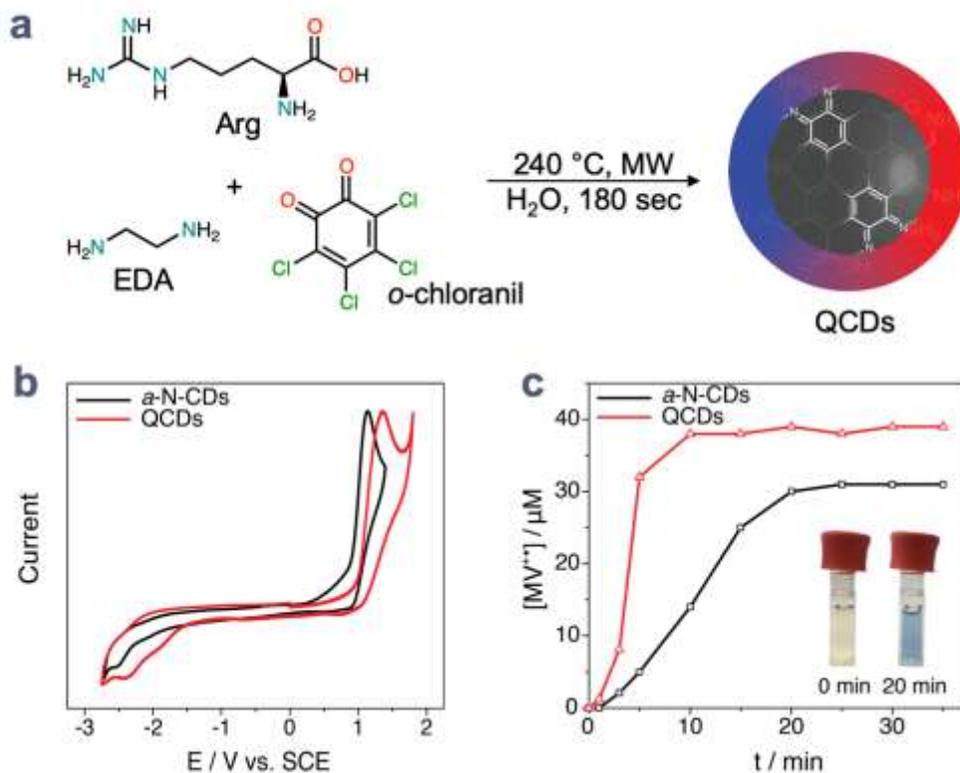
Figure 5. Preparation of quinone-based *a*-N-CDs (QCDs). (a) Synthetic scheme for the preparation of QCDs; (b) Cyclic voltammetry scans of *a*-N-CDs (black) and QCDs (red); (c) Plots of methyl viologen (40 μM) radical cation formation, in aqueous EDTA (0.1 M, pH = 6), for *a*-N-CDs (black, 0.50 mg mL^{-1}) and QCDs (red, 0.17 mg mL^{-1}) under irradiation AM1.5G (inset shows cuvette before and after irradiation).

The synthesis of chiral nanoparticles is a matter of intense interest, given the potential applications that chiral (nano)structures can play in (bio)sensing and chiral photo- and organo-catalysis.[31] For example, inorganic quantum dots with the same composition and size, but

different surface chirality (L- or D-glutathione as stabilizers), were shown to possess different cytotoxicity.[32] Also, chiral GQDs were prepared by covalently attaching L- or D -cysteine to the carboxy-rich edges of GQDs, showing, again, difference in cytotoxicity.[33] However, a one-step synthetic procedure affording chiral CDs, with all the tunability and versatility of our approach became an interesting objective. Since we use L-(+)-Arginine as a precursor in the preparation of CDs, we expected that the chirality of the amino acid would be lost during the harsh reaction conditions. As a matter of fact, this is what we found out during the hydrothermal microwave-assisted heating, giving dots with a flat circular dichroism spectrum. The relatively high temperature and pressure led to a complete loss of the chiral information of the starting material. Consequently, we focused on configurationally more stable starting materials such as (*R,R*)- and (*S,S*)-1,2-cyclohexanediamine (CHDA), which would allow us to obtain chiral carbon nanoparticles with opposite surface chirality (**Figure 6**).[34] The CDs prepared using Arg and (*R,R*)- or (*S,S*)-CHDA display mirror-image profiles both in the UV-Vis and in the infrared regions, as detected by electronic and vibrational circular dichroism, respectively (**Figure 6b**).[34] We also used the chiral CDs as templates for the formation of chiral chromophoric (porphyrin) assemblies in water. Electrostatic interactions between the positively charged CDs and the negatively charged *meso*-tetrakis(4-sulfonatophenyl)porphyrin (H_2TSPP^{4-}) were first established. Then the pH was decreased, in order to obtain the zwitterionic porphyrins (H_4TSPP^{2-}), which undergo aggregation. Depending on the CDs used as template, the chirality of the porphyrin assemblies could be affected, observing mirror image spectra in the porphyrin aggregates absorption region with bands centered at 420 and 490 nm (**Figure 6c**). Besides investigating whether the chiral information could be transferred, another interesting question was if other core precursors could be used to obtain CDs with different structure and photophysical properties. For

example, using citric acid instead of Arg led to chiral CDs, in which the lowest-energy chiroptical peak is red-shifted (from 320 to 340 nm). Therefore, different starting materials and synthetic methods hold great potential in preparing CDs that possess circularly polarized luminescence or for preparing chiral assemblies. Current studies are directed towards the effects that the chiral surface of CDs has on proteins and cells.
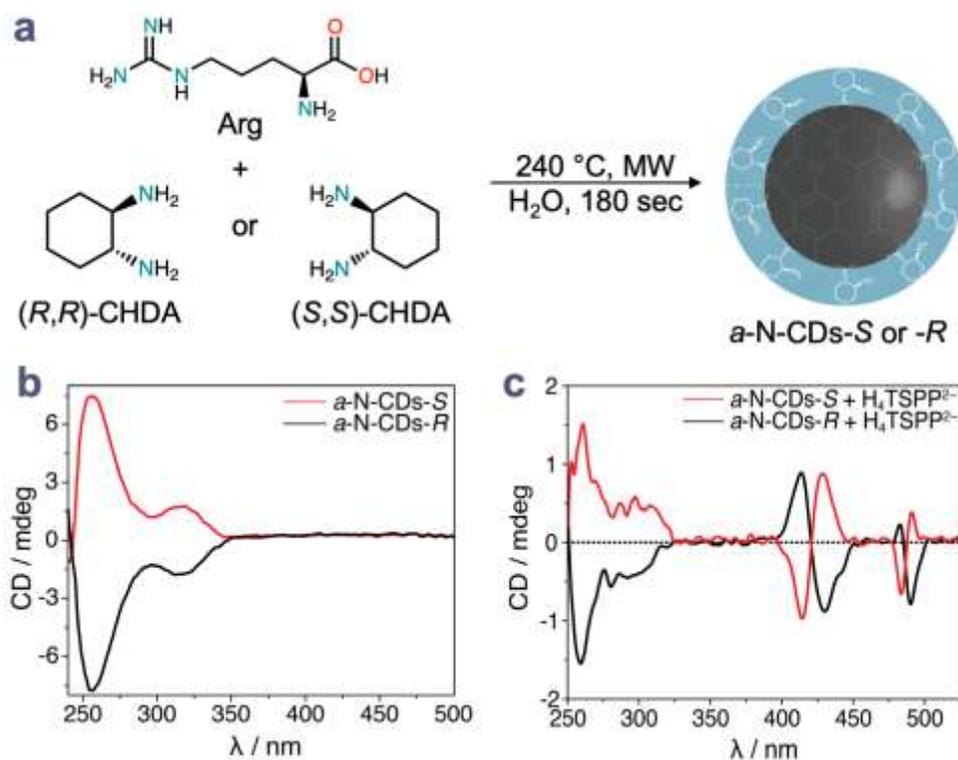
Figure 6. Preparation of chiral *a*-N-CDs. (a) Synthetic scheme for the preparation of chiral *a*-N-CDs; (b) Electronic Circular Dichroism of *a*-N-CDs-*R* (black) and *a*-N-CDs-*S* (red); (c) Electronic Circular Dichroism of *a*-N-CDs-*R* (black) and *a*-N-CDs-*S* (red), both in the presence of H$_4$TSPP^{2-}.

POST-SYNTHETIC SCHEMES ALLOW TUNING OF PROPERTIES

A key to access advanced CD materials able to meet precise requirements and to fulfill specific functions is to further engineer the surface of customized CDs through ad hoc designed post-synthetic strategies either by modifying the surface coating or by integrating diverse functionalities into a single material. The careful integration of pre- and post-synthetic schemes is a powerful strategy to enhance the functionality of nanomaterials in light of perspective applications. The main advantage of CDs over other carbon nanostructures is a rich surface chemistry that can fulfill particular functions but that can also be exploited for further modifications to tune/add features. For example, surface functional groups such as amines and carboxylates can be easily used for covalent functionalization in well-established reactions and have, therefore, inspired the preparation of covalent hybrids for various applications.[35] Because of their luminescence, their high solubility in water and low toxicity, CDs were especially investigated for biological purposes, such as hydrophobic drug-carriers, with many efforts, including ours, in preparing covalent hybrid materials.[36,37] In our case, we showed that the rich functional group surface on a-N-CDs supplies a high intrinsic solubility while providing reactive sites for further functionalization.

During the development of CDs for practical applications, both the implementation of CDs in electrochemiluminescence (ECL)-based technologies and the charge-transfer properties of CDs have attracted a lot of attention, given the general relevance of carbon nanomaterials in these fields.[38,39] In both cases the presence of amino groups on the surface of our a-N-CDs is pivotal for the formation of hybrid materials as well as for the incorporation of CDs into materials.

In a standard ECL scheme, amines are used as co-reactants, namely species that, upon oxidation or reduction, produce an intermediate that can generate the excited state of a luminophore.[40] We investigated therefore our a-N-CDs as a non-toxic co-reactant for ECL-based

analytical applications (**Figure 7**) since the high current and steep slope of the oxidation peak (+1.14 V vs. SCE) in their cyclic voltammogram reveals that a high number of amines can be easily oxidized (**Figure 5b**).[41] Tripropylamine (TPrA) is the most widely used ECL co-reactant, and the $Ru(bpy)_3^{2+}$/TPrA system is currently the basis of various analytical applications and commercial ECL immunoassays.[42] TPrA, however, is toxic, corrosive, volatile, and not readily soluble in water. In addition, TPrA is used in very high concentrations (usually up to 100 mM) to obtain a reasonable sensitivity.[43] Therefore, there is a considerable interest in the development of alternative co-reactants, but to date, TPrA provides the best ECL results in combination with $Ru(bpy)_3^{2+}$. Our *a*-N-CDs *(i)* match the redox potentials and *(ii)* possess water solubility, characteristics that promote our *a*-N-CDs as effective co-reactant for $Ru(bpy)_3^{2+}$ ECL generation, because they enable *(i)* fast charge transfer kinetics and *(ii)* rapid degradation routes to produce high energy radicals capable of initiating the ECL process. Upon oxidation, the amino groups become unstable reductive intermediates, able to give rise to the $Ru(bpy)_3^{2+}$ emissive excited state through a highly energetic electron transfer (**Figure 7b**). Having shown that these amines can act as efficient co-reactants in the classic form of ECL involving electron transfer between electrochemically generated radical ions in solution, we examined if the ECL performance can be enhanced by tuning the surface functionalities. We explored two strategies: (*i*) modifying the primary amines in methylated amines on the *a*-N-CD surface, since generally the ECL intensity increases using amines as co-reactant in the order primary < secondary < tertiary and (*ii*) design a single system that incorporates both the luminophore and the co-reactant, possibly resulting in ECL auto-enhancement.[44] In the first case, the methylated *a*-N-CDs (*a*-mN-CDs) provided in fact an enhanced ECL emission as compared to the *a*-N-CDs bearing primary amines. We also observed that the modified dots are a promising alternative to TPrA since (*i*) the same ECL

intensity is recorded with a concentration *ca.* 150 times higher of TPrA (**Figure 7c**) and (*ii*) *a*-N-CDs show a higher electrochemical stability than TPrA. In the second approach, we exploited the surface reactivity of the *a*-N-CDs amines in preparing a covalent hybrid, using an NHS-ester activated Ru(bpy)$_3^{2+}$ derivative. The resulting hybrid acts as ECL self-enhanced system with an emission intensity two times higher when compared to the uncoupled components, which we attribute to a more efficient electron transfer in the intramolecular system (**Figure 7d**).
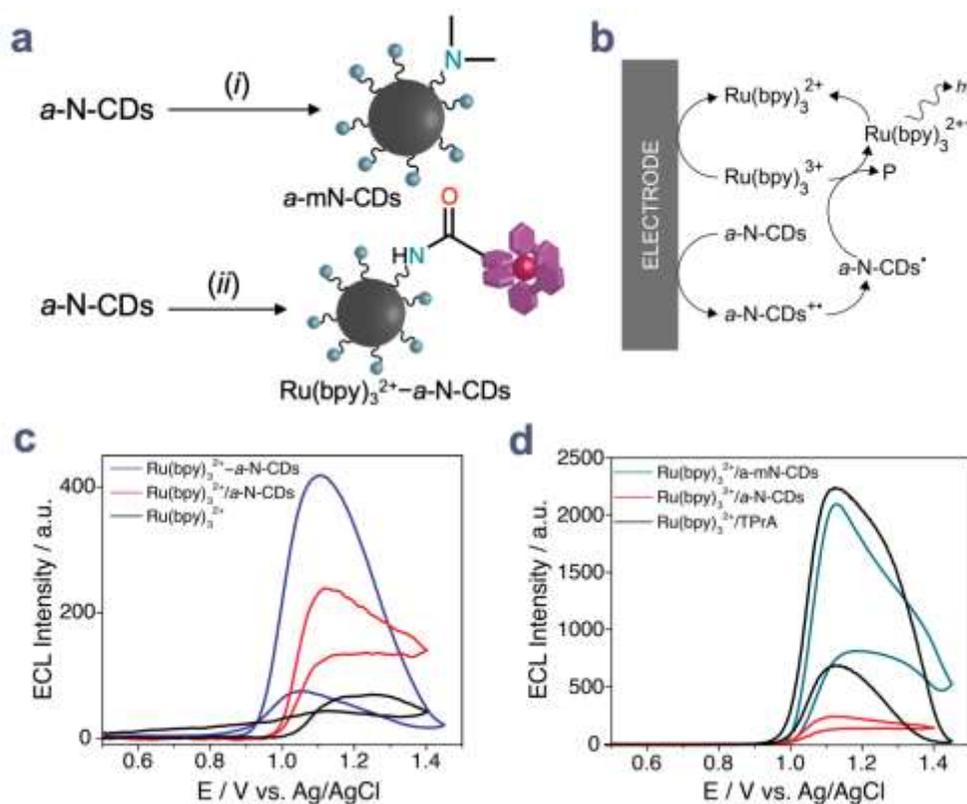
Figure 7. Preparation of *a*-N-CDs for electrochemiluminescence. (a) Preparation of *a*-mN-CDs and Ru(bpy)$_3^{2+}$−*a*-N-CDs hybrid: *(i)* HCHO, KOH, HCOOH, reflux, 48h; *(ii)* Ru-COOSu, PBS, r.t., 16h; (b) ECL proposed mechanism for Ru(bpy)$_3^{2+}$/*a*-N-CDs system; (c) ECL emission of Ru(bpy)$_3^{2+}$ enhanced by *a*-N-CDs and *a*-mN-CDs (red and green, respectively) and TPrA (black); (d) ECL emission of Ru(bpy)$_3^{2+}$ (black) upon addition of 0.1 mg mL^{-1} of NCNDs (red) and of Ru(bpy)$_3^{2+}$−*a*-N-CDs hybrid (blue).

We studied similar covalent post-functionalization schemes, as well as supramolecular donor-acceptor ensembles (**Figure 8**), for the design of charge-transfer systems. Among various potential partners, porphyrins are known for their extraordinary donor-acceptor partnership with carbon nanomaterials, due to favorable light-induced charge separation events.[45] We prepared a hybrid material through an amidation (carbodiimide condensation) reaction of the amino surface groups of *a*-N-CDs with a carboxyphenyl peripheral moiety of a porphyrin (**Figure 8a,b**).[46] In addition, we looked at supramolecular donor-acceptor architectures.[47,48] A library of positively charged porphyrins and carboxylic acid-coated (negatively charged) *g*-N-CDs was studied to assess the electrostatic interactions in guiding the formation of supramolecular assemblies and charge separation (**Figure 8c,d**).[49] Detailed photophysical characterization of the covalent and supramolecular hybrids showed markedly different behavior. Visible light excitation of the covalent hybrid yields a porphyrin singlet excited state that, in an ultrafast process, forms a short-lived charge-separated (CS) state (**Figure 8b**). The supramolecular hybrids of *g*-N-CDs (derived from citric acid and urea) and positively charged porphyrins, once excited by visible light, result in the population of the charge-transfer (CT) state, which decays into a CS-state and a *g*-N-CDs state (**Figure 8d).**
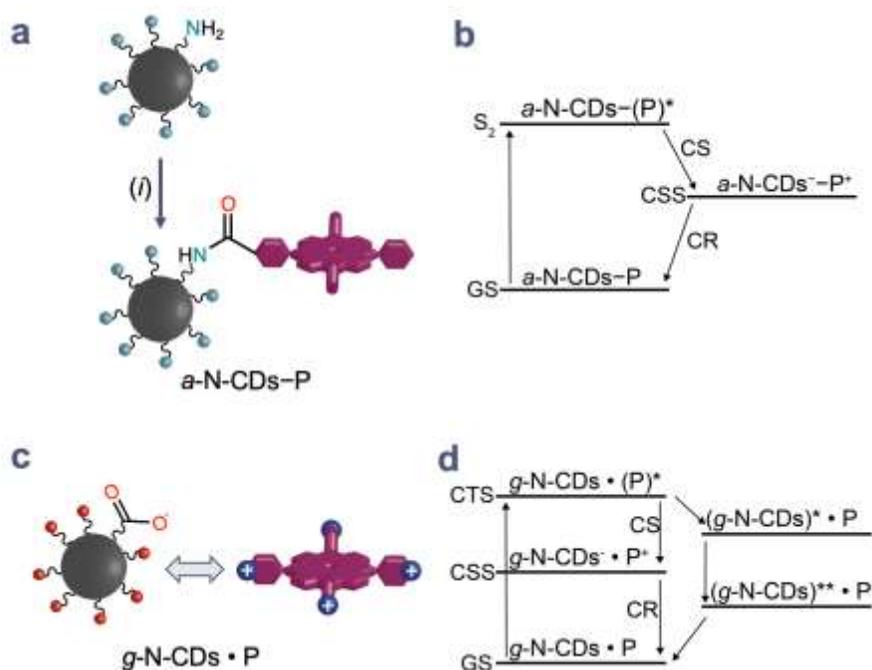
Figure 8. Carbon dots and porphyrin electron acceptor-donor covalent and supramolecular systems. (a) Preparation of covalent *a*-N-CD−porphyrin hybrid: (*i*) 5,10,15-tri(4-*tert*-butylphenyl)-20-(4-carboxyphenyl)porphyrin, EDC·HCl, 4-dimethylaminopyridine, DMF, Ar, r.t., 16 h. (b) Energy diagram illustrating the excited-state deactivation for the covalent system. (c) Representation of electrostatic interaction between CDs and 5,10,15,20-tetrakis(*N*-methyl-4-pyridinio)porphyrin (H_2P^{4+}) and (d) energy diagram illustrating the excited-state deactivation.

Our studies highlight the potential of the CD tunable surface functionalities but, more importantly, such surface modification strategies, together with pre-synthetic schemes targeting modulation of the CD properties, could give a great contribution in extending the applicability of the CDs in various fields.

The tunable nature of the functional groups on the CD surface may be also a powerful tool for the preparation of composite materials in which the nanoparticles can be embedded or immobilized in host matrices. These latter have the advantage of expanding on various technologies that cannot operate in solution, such as LEDs or photovoltaic devices.[50,51] Several

groups, including ours, have used the CD luminescent properties for the preparation of organic-hybrid gel glasses or thin films as optical materials or sensors.[52,53] Other examples demonstrate the power of manipulating the interactions between nanoparticles for, as example, the self-healing properties in polymer composites,[54,55] hydrogel sensors for heavy metal ions[56] or performing photochemical reactions.[52] We explored the effect that CDs have in the preparation of gel matrices, consisting of ionic liquids and dicationic organic salt gelators.[57] We investigated the influence of surface functional groups on the CDs on the formation of gel phases, discovering that a high amount of surface amino groups are critical for favoring gel formation, due to the presence of hydrogen bonds among the three components. The hydrogen bond donating ability of the amino groups was essential to stabilize the free radicals, thus making the hybrid ionogels efficient radical scavengers.

The examples reported above show that the surface functionalization of the CDs may open interesting avenues for (*i*) simplifying analytical procedures and enhancing detection sensitivity and (*ii*) designing novel donor-acceptor arrays or composite functional materials that display improved performances. With the growing number of studies in the carbon nanoparticle field, the possibility to easily tune the surface chemistry of this nanomaterial represents a unique opportunity towards design and preparation of complex materials, which will be critical for their implementation in a wide range of biomedical or energy applications.

OUTLOOK

Carbon-based dots have proven to be an interesting class of nanomaterials with great potential in many applications. Most notably, their structural and PL properties have been employed from

imaging and sensing to photocatalysis and photovoltaic devices. Their low-cost, low-toxicity, good solubility and high photo-stability are appealing properties for their utilization.

In the biomedical field, the multitude of synthetic methods and starting materials have allowed the preparation of carbon dots for advancing photothermal therapy,[58,59] singlet oxygen generation for photodynamic therapy,[60,61] cancer targeting and drug delivery,[36] electrochemical imaging[62] and interaction with α-synuclein fibrils.[63]

Control over the surface chemistry and core graphitization of carbon dots was shown to be very important also for photocatalysis and energy conversion applications[64,65] and for incorporation of CDs into optoelectronic devices.[50,66–68] For example, using multi-component synthesis it was possible to investigate the importance of nitrogen incorporation in the CD structure.[69] Specifically, the presence of nitrogen atoms in CDs was critical for the photocatalytic hydrogen evolution from water, as a synergistic action from pyrrolic nitrogen edges as electron transfer mediator, graphitic nitrogen as catalytic site and surface amines as hole traps. Similarly, control over the surface and internal structure is important also in the cases when CDs are used as light harvesters, together with co-catalysts and enzymes.[70,71] Tuning the charge on the CDs surface plays an important role in the electrostatic interactions with negatively charged enzymes,[72] where ammonium-terminated CDs are capable of harvesting light and of transferring electrons for hydrogenation reactions and reductions of protons to hydrogen, while carboxylate-coated CDs show no or little activity. Further studies on graphitized CDs have shown that introduction of nitrogen-atoms in the core is important for higher photocatalytic performance, through higher extraction of photogenerated charges.[30] The photoreduction potential of CDs was also investigated by preparing four different types of CDs (graphitic or not, nitrogen-doped or not) via different methods (hydrothermal and pyrolytic).[73] The photocatalytic activities (in terms

of methyl viologen photoreduction) were shown to be the greatest for amorphous N-doped CDs, where molecular fluorophores are responsible for light absorption and generation of photoexcited states. Heteroatom-doped CDs are starting to be employed as photocatalysts also for polymerization reactions, such as the reversible addition–fragmentation chain-transfer.[74] Furthermore, CDs can be employed not only for the photocatalytic-related properties. The amine-rich surface is able to undergo reversible acid-base reactions with CO_2, with formation of hydrophilic ammonium salts able to drive phase transfers between organic solvents and water.[75] Applications in electrocatalysis are also being explored, as the surface of CDs provides sites for binding ruthenium, resulting in stable and very active hydrogen evolution reaction electrocatalysts.[76]

In this Account, we described our efforts towards the synthesis and post-functionalization of amorphous nitrogen-doped CDs. In our research, we focused on the design and customization of the optoelectronic properties of this nanomaterial, as well as on their applications in hybrid and composite systems. As CDs are becoming a broad class of fully-fledged nanomaterials, it is fascinating to observe the fast progress in this area of nanocarbons.

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Biographies

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Luka Đorđević obtained his Ph.D. in Chemistry from the University of Trieste, working with Prof. Maurizio Prato and Prof. Davide Bonifazi. During his Ph.D. he was a visiting scholar at the Broad Institute of MIT and Harvard University. After graduating, he performed postdoctoral research with Prof. Bonifazi (at Cardiff University) and Prof. Prato (at University of Trieste). He is currently a post-doctoral fellow with Prof. Samuel I. Stupp at the Simpson Querrey Institute of Northwestern University. His current research focuses on supramolecular organic materials for energy conversion.

Maurizio Prato is Professor of Organic Chemistry at the University of Trieste and Ikerbasque Research Professor at CIC biomaGUNE, Spain. He was the recipient of an ERC Advanced Research Grant, European Research Council, in 2008 and became a Member of the National Academy of Sciences (Accademia Nazionale dei Lincei) in 2010. His research focuses on the synthesis of novel functional materials, for applications in materials science and nanomedicine. Currently, he attempts to transfer the properties of these new materials into applications, which include spinal cord repair, splitting of water, and reduction of carbon dioxide into useful chemicals.

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