Click Metallodendrimers and Their Functions

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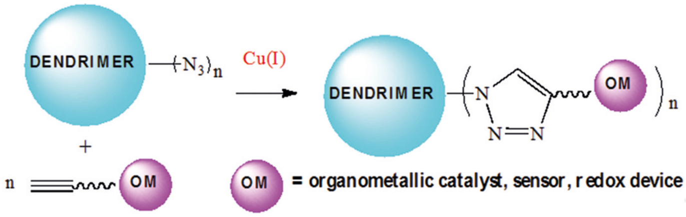

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This article is dedicated to our distinguished friend and colleague Professor K. Peter C. Vollhardt.

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Abstract Click chemistry involving copper-catalyzed azide–alkyne cycloaddition (CuAAC) is one of the most useful and powerful methods to construct metallodendrimers. The design of such strategies includes the choice of the copper(I) catalyst source which is critical in the case of the click synthesis of dendrimers. The 1,2,3-triazolyl-containing dendrimers that are produced provide useful intradendritic ligands that are active in supramolecular recognition and catalysis. This account dedicated to K. Peter C. Vollhardt summarizes work conducted mainly in the authors' Bordeaux laboratory.

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Key words click chemistry, dendrimers, triazoles, metallocenes, catalysis, sensing

1 Introduction

The star chemist and lecturer, Peter Vollhardt, among his spectacular synthetic achievements, is the father of star-shaped molecules such as hexaethynylbenzene,[1] hexabutadiynylbenzenes,[2] and even the so-called 'impossible molecule' hexaferrocenylbenzene.[3] His reports have inspired the organic and organometallic communities,[4] including ourselves, towards the synthesis of star-shaped organometallics such as hexa(ferrocenylethynyl)benzenes[5,6] and many ferrocene-containing star-shape[6] and dendritic molecules.[7]

The concept of click chemistry[8–12] has introduced major facile methods in synthetic chemistry, in particular copper(I)-catalyzed azide–alkyne cycloaddition (CuAAC) using terminal alkynes such as Vollhardt's alkynyl-containing molecules.[2–5] This reaction has been applied to an enormous range of compounds from organic derivatives of biomedical interest to macromolecules and nanomaterials.[13–33] The first exploration of a convergent dendrimer synthesis and its extension to the syntheses of higher-generation dendrimers was reported by the Sharpless and Fréchet groups in 2004,[34] and the field of click dendrimer synthesis has been reviewed by Franc and Kakkar.[35,36] Dendrimer synthesis using the CuAAC reaction is especially appropriate because this reaction involves mild conditions for completion, and the copper(I)-catalyzed cycloaddition allows perfect 1,4-regioselectivity for 1,2,3-triazole (trz) formation. These conditions are essential for the clean construction of dendrimers.

In 2007, our group reported the first click synthesis of metallodendrimers (Scheme 1).[37] Iterative click construction of several generations was achieved, and the use of these trz-metallodendrimers in redox sensing[37] and catalysis[38] was reported. Indeed, we believed that the CuAAC click reaction was not only an appropriate tool for the synthesis of metal-containing dendrimers, but also a practical method to introduce useful trz ligands for the above functions. In

Biographical Sketches

Didier Astruc studied in Rennes, completing two theses working with R. Dabard before doing postdoctoral studies at the Massachusetts Institute of Technology (MIT) with R. R. Schrock. He became Professor of Chemistry in Bordeaux in 1983 and did a sabbatical at the University of California (UC), Berkeley, with Peter Vollhardt in 1990–1991. He is a member of the Institut Universitaire de France and of several academies.

Roberto Ciganda completed his Ph.D. with M. A. Garralda Hualde in 2013 at the University of San Sebastian before working there with R. Hernandez. He is now doing postdoctoral studies with Didier Astruc on catalysis with metallodendrimers and nanoparticles.

Christophe Deraedt completed his Ph.D. with Didier Astruc on catalysis in dendritic nanoreactors in 2014 and is now doing postdoctoral studies in Tokyo with M. Fujita on nanoreceptors.

Sylvain Gatard obtained his Ph.D. in 2002 with Didier Astruc and did postdoctoral studies with R. Neumann at the Weizmann Institute and then O. V. Ozerov at Brandeis University. He is now Assistant Professor at the University of Reims Champagne-Ardenne, and his research interests are in organometallic and carbohydrate chemistry.

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Na Li studied with S. Yan in Lanzhou and then joined Didier Astruc's group, where she completed her Ph.D. in 2014 on gold nanoparticle sensors. She is now doing postdoctoral studies on dendrimers with A. Kakkar at McGill University, Montreal.

Catia Ornelas studied in Madeira with J. Rodrigues, completed her Ph.D. with Didier Astruc on nanochemistry in 2007, and did successive postdoctoral studies with M. Weck at New York University, J. M. J. Fréchet at UC Berkeley, and A. Moore at Arizona State University. She is Assistant Professor at UNICAMP, Sao Paulo, working on nanomaterials in biomedicine.

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Jaime Ruiz studied with E. Roman in Santiago de Chile, completed his Ph.D. in organometallic chemistry with Didier Astruc in 1989, and did postdoctoral studies with A. H. Cowley at the University of Texas at Austin. After his habilitation, he became an engineer. His interests are in inorganic electrochemistry, nanoparticles, and metallodendrimers.

Dong Wang studied organic chemistry with B. Chen in Lanzhou where he received a doctoral degree. He completed a second Ph.D. with Professor Didier Astruc in 2014 on magnetic and dendritic nanocatalysis and is presently working as a postdoctoral researcher with D. Song in Toronto.

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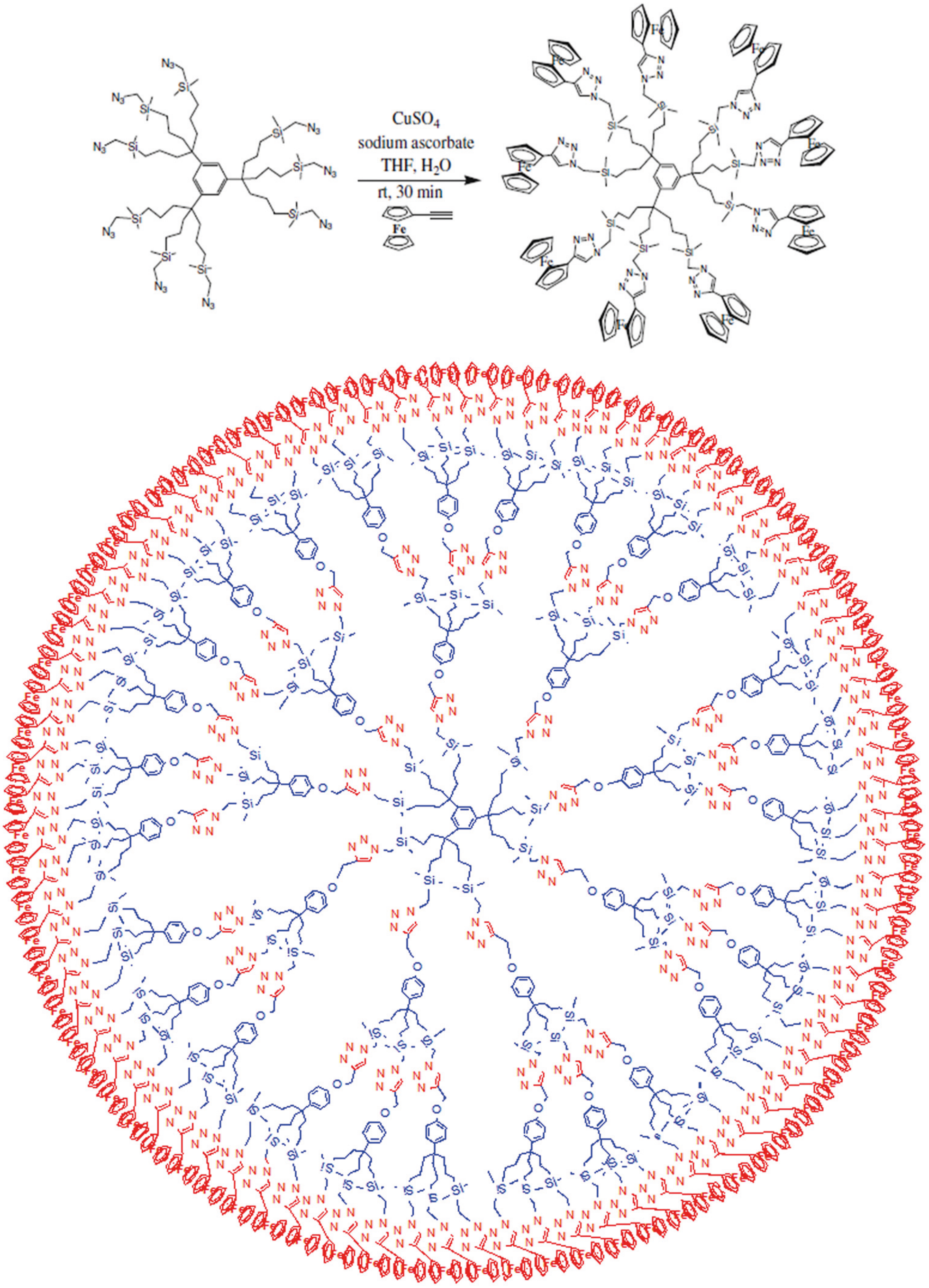
Pengxiang Zhao studied in Chengdu with W. Chen and completed his Ph.D. with Didier Astruc in 2012 on functional gold nanoparticle vectors for docetaxel delivery. He is an independent researcher in Mianyang and his is interests are in gold nanoparticle vectors, sensors, and catalysts.

the present account, we summarize our work and results on the click syntheses of metallodendrimers, the products' resulting supramolecular properties, and the functions and applications of the trz groups in click metallodendrimers.

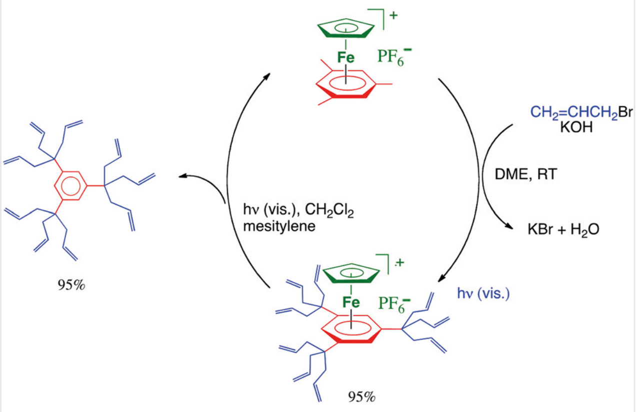
2 Click Copper Catalyzed Azide–Alkyne Cycloaddition Metallodendrimer Constructions

The CpFe$^+$-induced [CpFe$^+$ = η^5-cyclopentadienyl-iron(1+)] nona-allylation of mesitylene using allyl bromide and potassium hydroxide in tetrahydrofuran or 1,2-dime-



Scheme 1 Click (CuAAC) synthesis of a zeroth-generation (G$_0$) ferrocenyl-terminated dendrimer (top); the dendritic construction of the larger dendrimers (G$_1$–G$_4$) then proceeds according to 1 → 3 connectivity (*vide infra*, Scheme 2) and the 81-ferrocenyl dendrimer (G$_2$) is represented (bottom)

thoxyethane under ambient conditions[39,40] followed by visible-light photodecomplexation[41] in the presence of mesitylene provides a remarkable access to useful nona-allyl arene-centered dendritic core **1**.[39,40] This reaction involving dendrimer construction according to 1 → 3 connectivity[42,43] is not catalytic, but at least results in the recovery of the starting complex [CpFe(η^6-mesitylene)][PF_6][44] and in this sense is relevant to 'green chemistry' (Scheme 2).

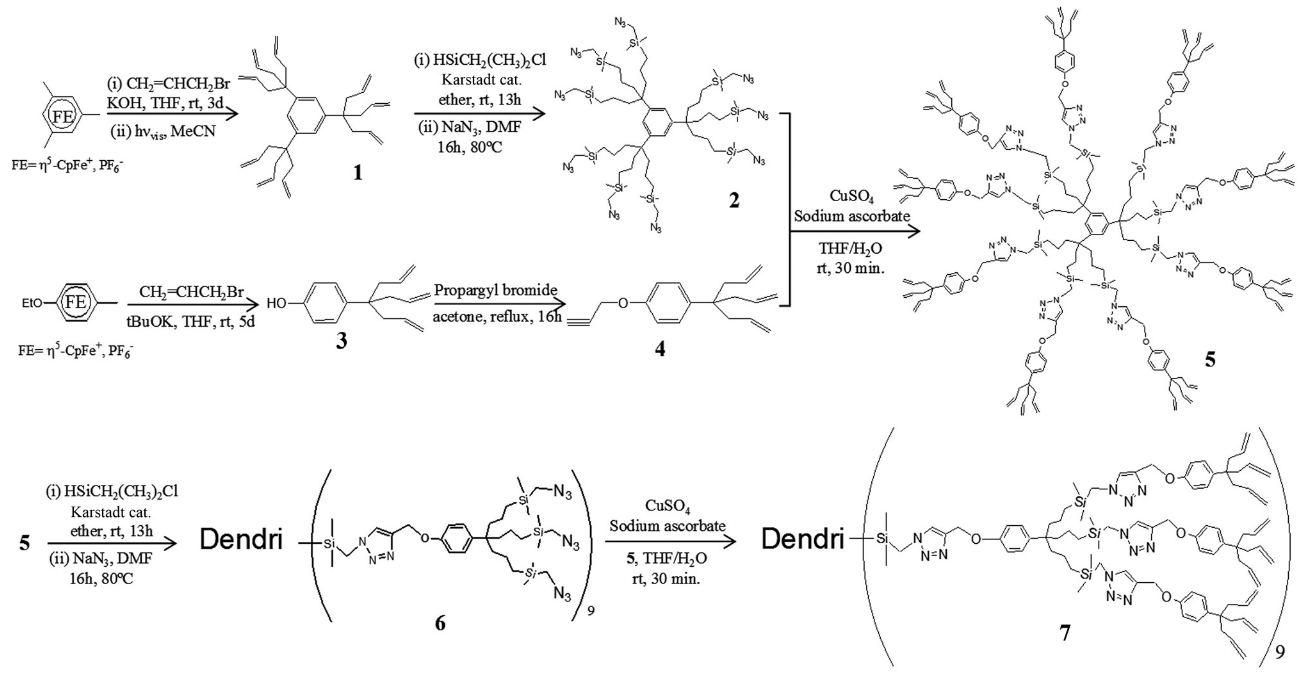


Scheme 2 η^5-Cyclopentadienyliron(1+)-induced nona-allylation of mesitylene: a 'green chemistry' concept involving the efficient recovery and reuse of the activating 12-electron η^5-cyclopentadienyliron(1+) fragment

Further hydrosilylation of **1** with (chloromethyl)dimethylsilane using the Karstedt catalyst[45] followed by azidation with sodium azide provides clickable dendritic nona-azido precursor **2** (Scheme 3).[37] Dendron **3**, synthesized by CpFe$^+$-induced triallylation of 4-ethoxytoluene,[17,18] can be propargylated at the phenol focal point to provide clickable dendron **4** that also possesses 1 → 3 connectivity. The click reaction between **2** and **4** provides the first-generation polyallyl dendrimer **5** that contains 27 allyl groups, and the second-generation dendrimer **7** that contains 81 allyl groups is obtained using the same reaction sequence.

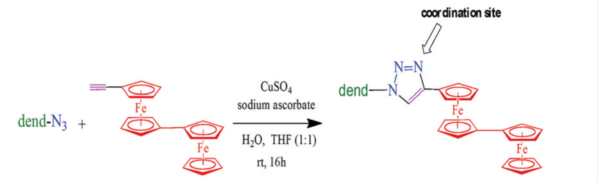
At each of the three generations (G_0, G_1, G_2) of the azido-terminated dendrimer, the click reaction with ethynylferrocene provides a trz-ferrocenyl-terminated dendrimer.[37] Alternatively, Williamson reactions between chloromethylsilyl-terminated dendrimers and **3** provides dendrimer growth by 1 → 3 connectivity,[46] and the dendrimer surface coverage with organometallic groups is conducted by click reactions with ethynylferrocene,[37,38] ethynylcobaltocenium hexafluorophosphate[47] or other ethynyl-containing organometallic groups.[48–50] 'Inverse' click chemistry can also be conducted by introducing propargyl groups on the dendrimer before a CuAAC reaction with azidomethylferrocene.[51]

Indeed, late transition metal sandwich complexes withstand two or several stable oxidation states that are useful in terms of redox applications.[52,53] As another example, click triazolylbiferrocenyl (trz-biFc) dendrimers were synthesized by reactions of dendrimers containing 9 (G_0), 27



Scheme 3 Synthetic strategy for the construction of polyallyl dendritic precursors of click metallocenyl- and other organometallic-terminated dendrimers

(G_1), 81 (G_2), 243 (G_3), and 729 (G_4) terminal azidomethyl groups with ethynylbiferrocene yielding the five generations of trz-biFc dendrimers up to the theoretical number of 729 biferrocenyl termini (Scheme 4). The G_4 dendrimer has a hydrodynamic diameter of 27 nanometers, as determined by dynamic light scattering.



Scheme 4 Click synthesis of triazolylbiferrocenyl dendrimers (G_0–G_4)

The neutral G_1 dendrimer was oxidized with ferrocenium tetrafluoroborate, yielding a dendrimer with mixed-valence cations (27 positive charges) (Figure 1). The Mössbauer spectrum of the oxidized dendrimer showed a localized mixed-valence structure with the terminal (outer) ferrocenyl groups oxidized and the inner ferrocenyl groups, directly bound to the electron-withdrawing trz rings, remaining in the iron(II) oxidation state.[54]

In biferrocene compounds, three oxidation states (neutral, monocationic, and dicationic) are accessible by cyclic voltammetry (CV), but only two of them, the neutral and class-II mixed-valence monocationic forms, are easily isolable. For dendrimers bearing the fragment 1,3-[ethynylFeCp*(dppe)]$_2C_6H_4$ [Cp* = η^5-pentamethylcyclopentadienyl, dppe = 1,2-bis(diphenylphosphino)ethane], however, derivatives of the three oxidation states are now easily isolable, including the class-II mixed-valence monocationic derivative in which the two iron groups interact electronically.[55,56] The bimetallic dendron bearing an ethynyl group at the focal point (group in the *meta*-position) was either clicked with azidomethyl-terminated dendrimers (Scheme 5) or linked by Sonogashira coupling to iodoaryl-terminated dendrimers. In the first case, the dendrimers possess intradendritic trz groups, but not in the second one (Figure 2).[49]

The neutral dendrimers represented in Figure 2 reduce gold(III) to gold nanoparticles (AuNPs) stabilized by the mixed-valence dendrimers. In trz-containing dendrimers, the Au(III) cations precoordinated to trz are reduced inside the structure to give small dendrimer-encapsulated AuNPs (1.4 nm), whereas the dendrimers that do not contain these

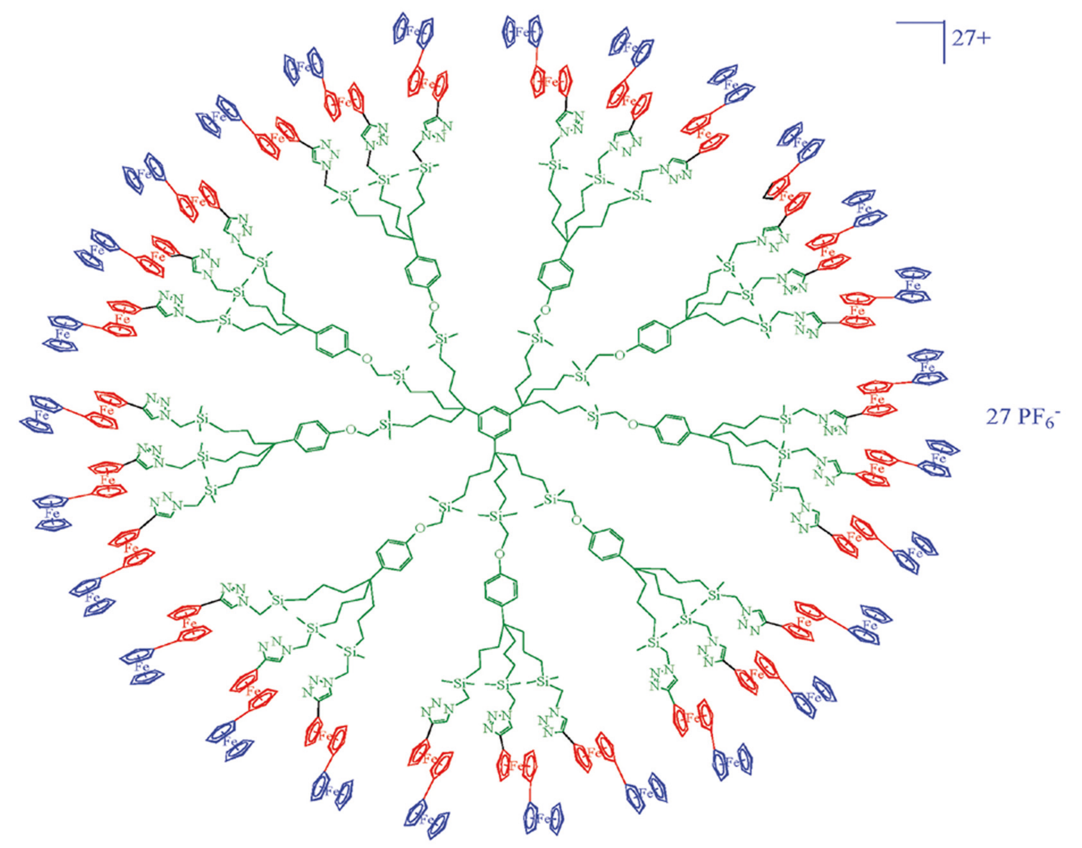
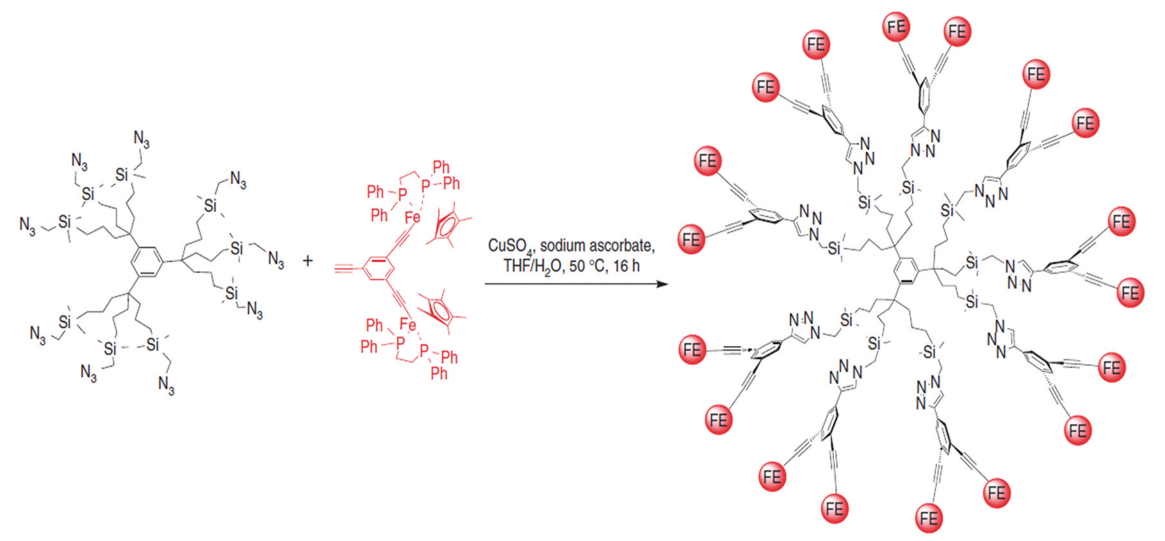


Figure 1 Class-II mixed-valence G_1 triazolylbiferrocenium dendrimer synthesized by oxidation of the G_1 triazolylbiferrocenyl dendrimer with 27 equivalents of ferrocenium hexafluorophosphate

trz ligands can only reduce gold(III) cations outside the dendrimers to give large interdendritically stabilized AuNPs (20 nm).[49,56]

3 The Copper-Catalyzed Azide–Alkyne Cycloaddition Reactions in Dendrimers: Mind the Copper(I) Catalyst

The initially used Sharpless–Fokin catalyst ($CuSO_4·5H_2O$ with sodium ascorbate) is very cheap and easy to use.[9] Indeed, it is still used in most reported CuAAC reactions for



Scheme 5 Click dendrimer decoration with dendrons containing electronically connected iron centers [FE = FeCp*(dppe)]

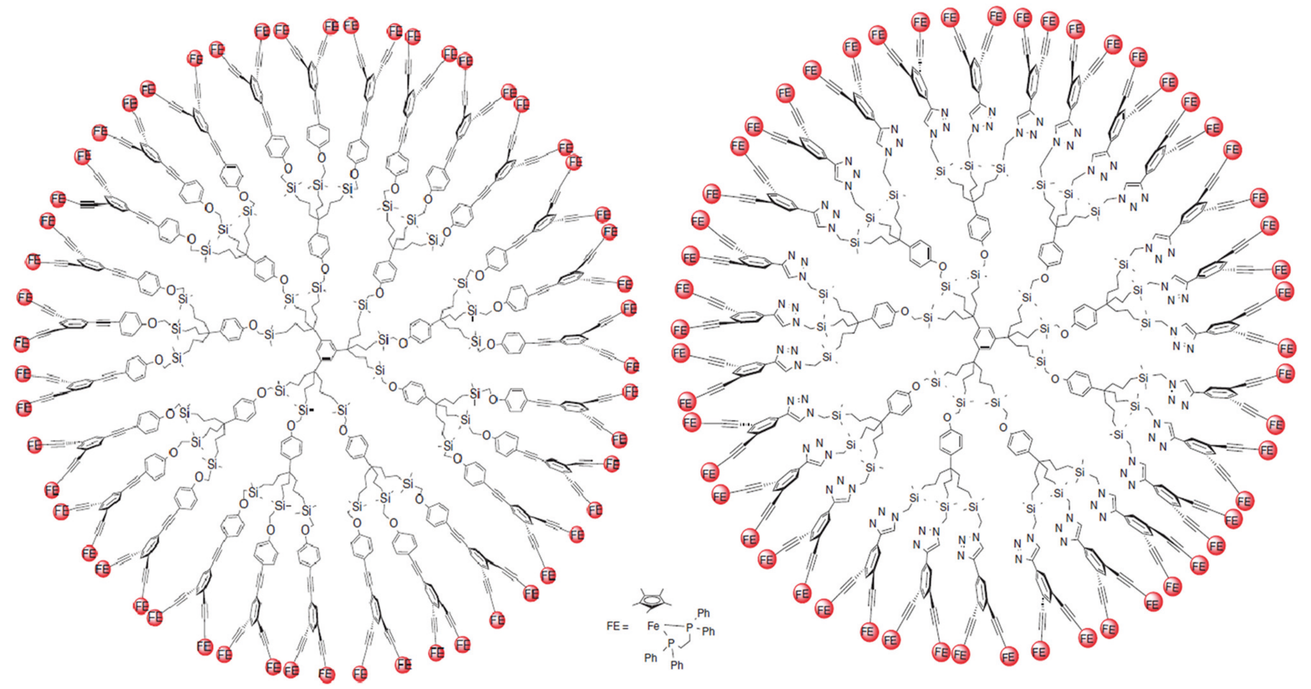


Figure 2 Dendrimer assembled using Sonogashira coupling (left), thus not containing intradendritic triazoles, and a dendrimer assembled using the ‘click’ copper-catalyzed azide–alkyne cycloaddition forming 27 intradendritic triazoles (right)

these reasons. In some cases, mild heating (40 °C) is necessary, but excessive heating must be avoided because at temperatures of 60–80 °C, the uncatalyzed Huisgen cycloaddition occurs, providing a mixture of 1,4- and 1,5-regioisomers.[57] For substrates with electron-withdrawing substituents, it was shown that at 60 °C and low catalyst concentrations, the reaction followed a mixture of catalyzed and uncatalyzed processes.[58] Indeed, for electron-deficient alkynes such as ethoxycarbonylacetylene, the noncatalyzed Huisgen reaction between azides and alkynes proceeded ‘on’ water even at room temperature.[58] Therefore, it is probable that in many cases, the Sharpless–Fokin catalyst is used in relatively large quantities to avoid the formation of the 1,5-isomer, or if not, that some amounts of this minor isomer is formed.[59]

In our initial report, the Sharpless–Fokin catalyst was used; however, we reported that copper(I) quantities lower than stoichiometric ones could not lead to the completion of the click dendrimer synthesis and that this catalyst was in fact required in stoichiometric amounts. The copper salts were then removed after the reaction by washing several times with an ammonia solution until the solution was no longer blue, the color of $[Cu(NH_3)_6]^{2+}$ salts.[37] Thus, our work suggested that the copper ions were stoichiometrically trapped inside the dendrimers through interaction with the trz ligands that were formed in the dendrimer construction and this was further confirmed by CV.[37]

Matyjaszewski’s group has shown that nitrogen ligands such as the tris(2-aminoethyl)amine (so-called tren) ligands considerably accelerate the CuAAC reaction.[60] Indeed later, the first-generation dendrimer **5** (see Scheme 3) could be formed using catalytic amounts of $[Cu(C_{18}H_{37})_6tren]Br$,[56] although this catalyst could not complete the formation of the second-generation dendrimer with 81 trz-ferrocenyl termini.[61] The synthesis of this latter dendrimer could be completed, however, using the less bulky catalyst [Cu(hexabenzyltren)]Br.[59] This catalyst was also found to considerably facilitate CuAAC reactions at the surface of AuNPs which cannot be conducted without AuNP aggregation using the simple Sharpless–Fokin catalyst.[62,63]

Altogether, there have been many reports on the catalysis of the CuAAC reactions using very efficient presynthesized copper(I) catalysts with amine, phosphine, or *N*-heterocyclic carbene ligands which can be applied to dendrimer synthesis.[64] Although the divergent dendrimer construction has the reputation to yield dendrimers that are not as pure are those obtained by convergent methods, the CuAAC reaction efficiently gives the pure 1,4-regioisomer under ambient conditions if the copper(I) catalyst is well designed. Completion of reactions is ascertained by the absence of bands from alkyne and azide functionalities in the infrared spectra and by MALDI TOF (matrix-assisted laser desorption ionization time-of-flight) mass spectrometry. However, click dendrimers tend to trap solvent and other impurities that are more or less difficult to remove.

4 Redox Recognition with Triazolylferrocenyl- and Triazolylbiferrocenyl-Terminated Dendrimers

Redox recognition of oxoanions by dendrimers has been extensively investigated and demonstrated with amidoferrocenyl dendrimers.[65] When investigating the molecular recognition applicability of the trz-ferrocenyl dendrimers, the key functionality interacting with the substrates is the electron-withdrawing trz potential ligand located near the ferrocenyl groups at the dendrimer termini.

With the trz-ferrocenyl dendrimers of zeroth (G_0), first (G_1), and second (G_2) generations, the titration of palladium(II), platinum(II), copper(I), and copper(II) was conducted by adding a dichloromethane (CH_2Cl_2) solution of acetonitrile complexes of these salts to a CH_2Cl_2 solution of the dendrimer.[37,66] The separation between the initial and new CV waves increased together with the dendrimer generation type, whereas the simple, nondendritic trz-ferrocenyl (linear-shaped) derivatives did not provide any CV wave separation (Figure 3).

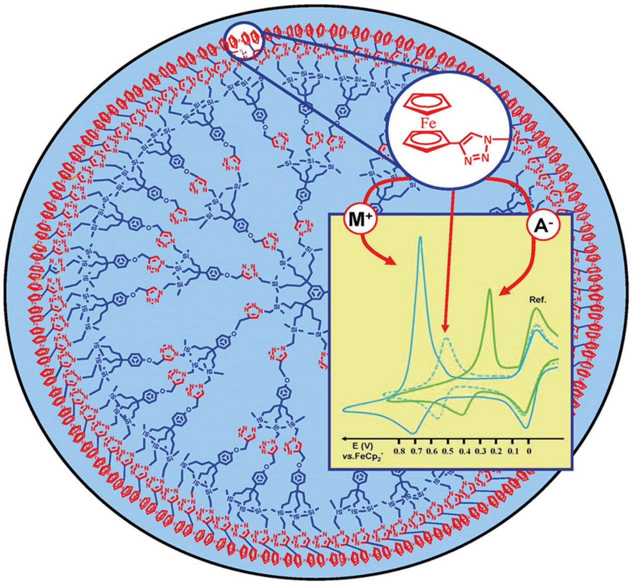


Figure 3 Redox recognition by cyclic voltammetry of a 81-trz-ferrocenyl dendrimer (a new wave appears at a more anodic potential upon the addition of a transition-metal cation, such as palladium(II), and at a more cathodic potential upon the addition of an oxoanion, such as ATP^{2-})

This positive dendritic effect reflects the synergy between the electrostatic factor, the interaction factor (in this case coordination), and the topology factor[1,2] (narrow channels between the dendritic tethers of the exoreceptor) which had already been noted with the amidoferrocenyl dendrimers.[14] The trz-ferrocenyl dendrimers recognize not only late transition metal cations, but also oxoanions such as $H_2PO_4^-$ and ATP^{2-} as their tetra-*n*-butylammonium salts in CH_2Cl_2. Addition of these salts to the solutions of the trz-ferrocenyl dendrimers provokes the rise of a new wave at less positive potentials (opposite effect compared with that of the cations) owing to the electron-releasing character of these oxoanions when they interact with the ferrocenyl and ferrocenium groups (Figure 3).[37,66]

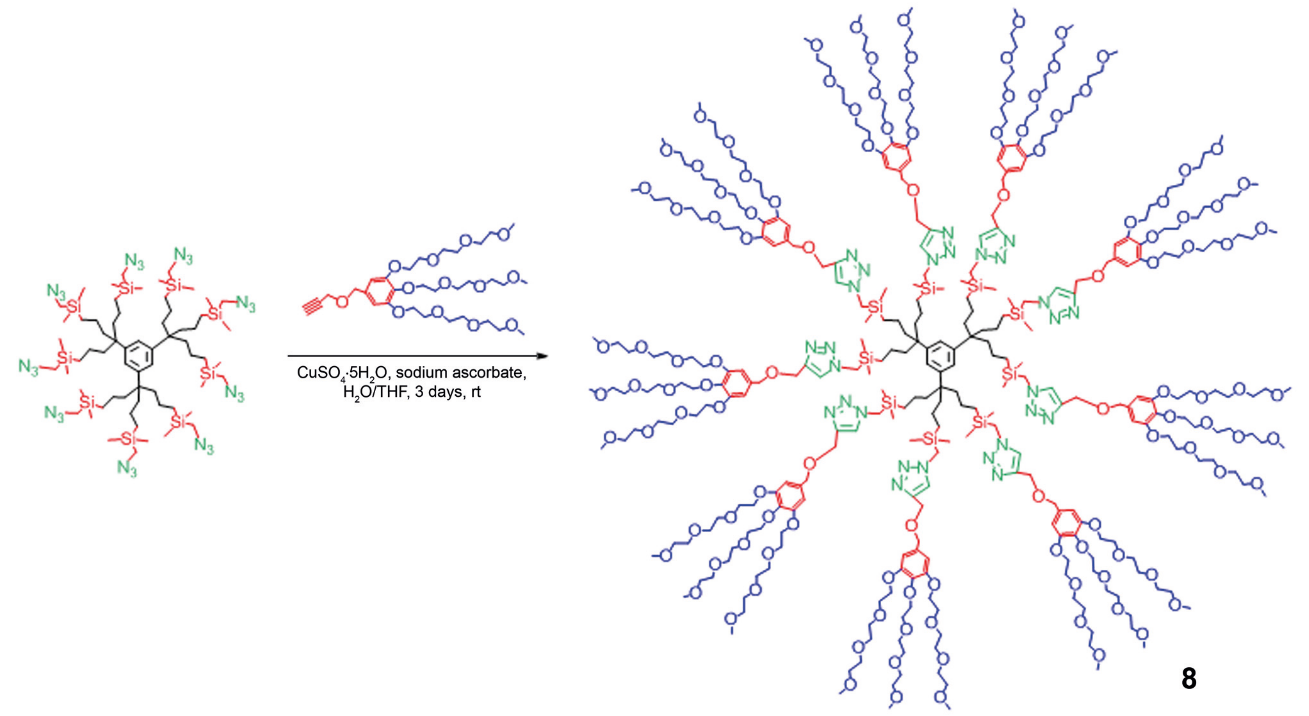
Cyclic voltammetry of the trz-biFc dendrimers in CH_2Cl_2 showed two waves at 0.43 and 0.75 volts versus $Cp_2Fe^{+/0}$.[54,67] Adsorption of the dendrimers onto the platinum electrode dramatically increased with an increase in the dendrimer generation type which was an advantage for the fabrication of modified electrodes. The modified electrodes were tested for molecular recognition by the addition of ATP^{2-} as its tetra-*n*-butylammonium salt which provoked the splitting of the outer ferrocenyl wave, whereas addition of palladium(II) acetate provoked the splitting of the inner ferrocenyl wave. Thus each CV wave allowed the selective recognition of either late transition metal cations or oxoanions which confirmed the above CV wave assignments.[54,67]

5 Click Catalysis with Extremely Efficient Intradendritic Triazolyl–Copper(I) Complexes

As indicated by Newkome in his seminal article in 1985,[42] dendrimers with a hydrophilic periphery and hydrophobic interior serve as unimolecular micelles. Thus we have used this property for catalytic applications. Dendrimer **8**, built through click chemistry (Scheme 6) and having a hydrophilic periphery owing to its ethylene glycol moieties, hosts and facilitates catalytic reactions of hydrophobic substrates and catalysts in water. We reported significant examples of catalysis in water using this dendrimer as a nanoreactor which include olefin metathesis using the second-generation Grubbs catalyst[68] and the CuAAC reaction catalyzed by presynthesized copper(I) complexes.[69]

As indicated in Section 3, trz-containing dendrimers trap copper(I) species generated upon addition of ascorbate to copper(II) sulfate, but the catalyst [Cu(hexabenzyltren)]Br is efficient in click dendrimer synthesis. Dendrimer **8** was shown to considerably enhance the catalytic activity of this catalyst for CuAAC reactions of hydrophobic organic substrates in water. Moreover, 600 MHz ^1H NMR spectroscopy showed that the [Cu(hexabenzyltren)]Br catalyst interacts with the intradendritic trz ligands, and its formation is even autocatalyzed in the presence of [Cu(hexabenzyltren)]Br.[69]

Further research using dendrimer **8** involved attempts to use the stoichiometric complexation of copper ions by intradendritic trz ligands to catalyze click reactions, taking advantage of both the micellar effect and the intradendritic trz ligand acceleration of copper(I) catalysis. It was found that using the Sharpless–Fokin catalyst for the CuAAC reaction between phenylacetylene and benzyl azide in the presence of dendrimer **8** at 30 °C in water allowed the use of a parts per million (ppm) amount of copper and the den-



Scheme 6 Click synthesis of a water-soluble dendrimer that serves as a nanoreactor

drimer, instead of large quantities in the absence of the dendrimer. This very efficient system was also applied to the CuAAC synthesis of compounds of biomedical interest.[69]

6 Click Dendrimers as Stabilizers for Very Efficient Nanoparticle Catalysis of Cross-Coupling Carbon–Carbon Bond Formation and Redox Reactions

Seminal work by the Crooks group demonstrated the encapsulation of palladium nanoparticles (PdNPs) using poly(amidoamine) dendrimers (PAMAM) together with their activity in hydrogenation and Suzuki coupling reactions.[70–72] Reduction of palladium(II) ions bound to intradendritic trz ligands of trz-ferrocenyl-terminated click dendrimers also produced dendrimer-encapsulated PdNPs in first- and second-generation dendrimers. Respectively, these dendrimers contain in principle 36 (9 + 27) and 117 (9 + 27 + 81) trz groups and palladium atoms which was verified by comparing the theoretical sizes of PdNPs containing such numbers of atoms (1.0 and 1.6 nm, respectively) and the experimental sizes determined by transmission electron microscopy (TEM, 1.1 ± 0.2 and 1.6 ± 0.3 nm, respectively). For dendrimer G_0, the PdNPs obtained were larger (2.5 ± 0.3 nm) because the nonabranched dendrimer

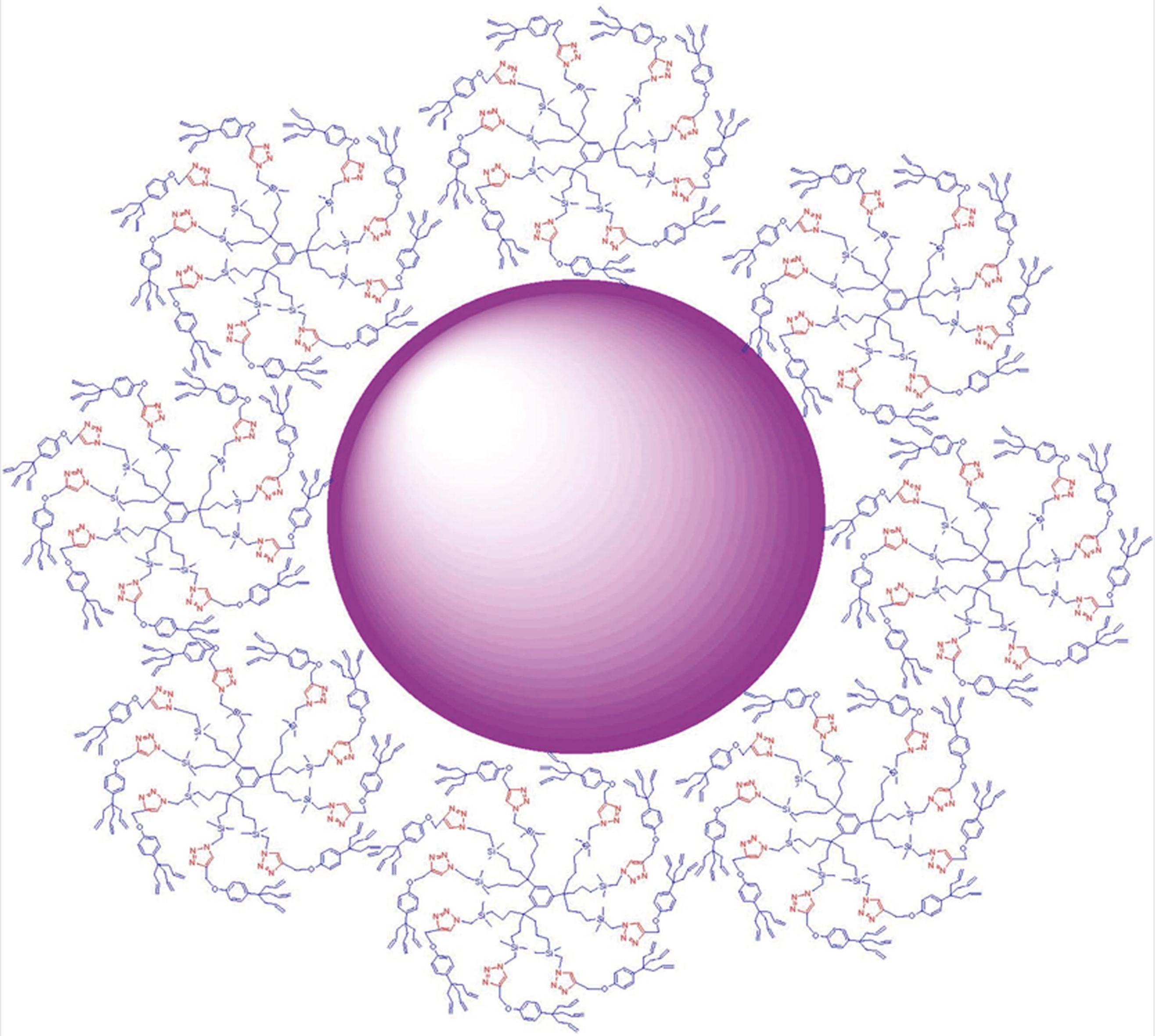


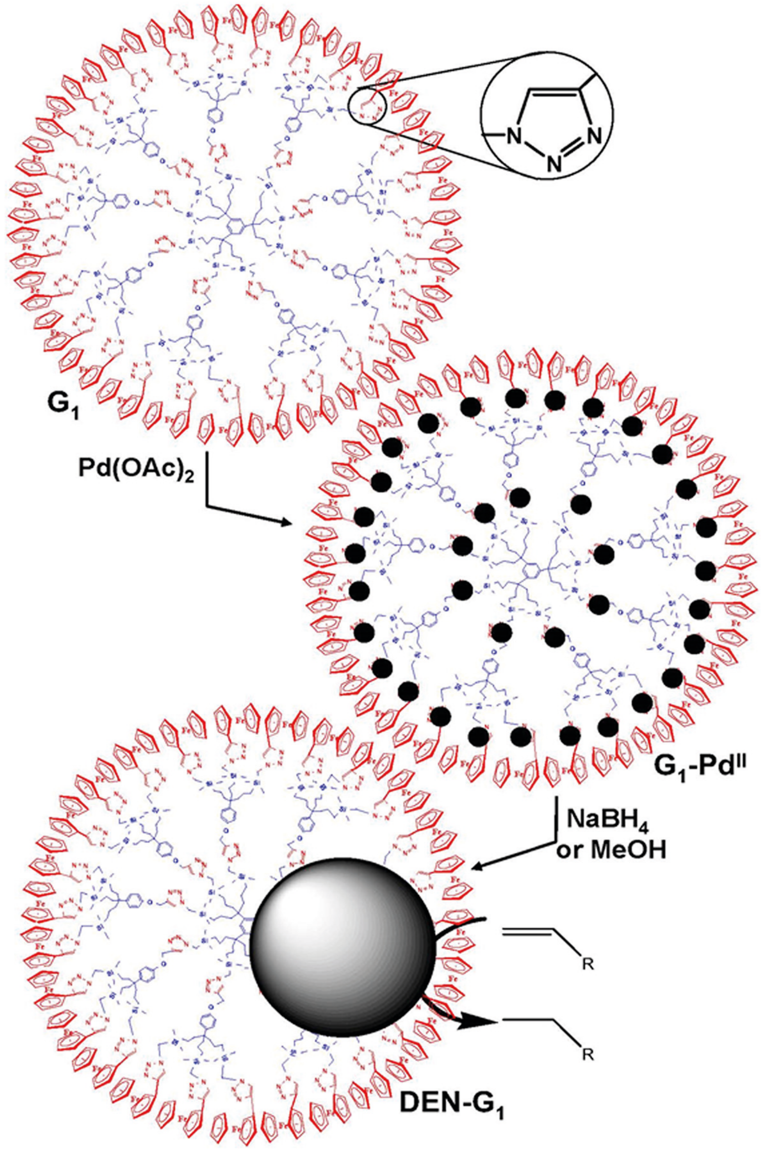
Figure 4 Palladium nanoparticle stabilized by several zero-generation allyl-terminated dendrimers

is small and it stabilizes the PdNP by surrounding it whatever the terminal groups (ferrocenyl or allyl) (Figure 4).[40]

All PdNPs stabilized by the trz-containing dendrimers were found to be extremely active catalysts. For styrene hydrogenation, the most active PdNP catalysts were the smallest ones and, as with polymer-stabilized PdNPs,[73] the smaller the PdNP size the higher the activity (Scheme 7).[40] For the Suzuki coupling reaction between iodobenzene and phenylboronic acid, however, coupling proceeded under ambient conditions at about the same rate whatever the dendrimer generation, and the catalytic turnover number and turnover frequency values were higher at high dilution. These PdNPs were found to be active down to 1 ppm of palladium versus substrate.[40,74] It is likely that, as for Heck reactions at high temperatures (130 °C),[75] palladium atoms are leaching into the solutions where they show high activity, but are caught by the PdNPs all the more efficiently as the PdNP concentration is higher.[40]

Such very efficient catalytic reactions could also be extended to aqueous media upon replacing the terminal ferrocenyl groups with sulfonate groups through 'click' reactions between the azido-terminated dendrimers and propargyl sulfonate.[76] More recently, in the same way, sub-ppm amounts of PdNPs were sufficient to catalyze the Suzuki–Miyaura reaction of bromoarenes with phenylboronic acid at 80 °C using dendrimer **8**.[77–79]

Gold nanoparticles were also synthesized within dendrimers upon coordination of the intradendritic trz ligands



Scheme 7 Formation of a first-generation triazolylferrocenyl dendrimer encapsulated palladium nanoparticle and its catalysis of hydrogenation reactions

to gold(III) followed by reduction to gold(0), and these dendrimer-encapsulated AuNPs were shown to be active catalysts for 4-nitrophenol reduction by sodium borohydride to give 4-aminophenol.[80–82] Comparison between various stabilizing frameworks based on the trz coordination to the AuNPs shows that trz is a mild ligand that is ideal for both stabilization and catalysis and that steric bulk slows down the reaction.[80] Trends relating to the latter confirm the Langmuir–Hinshelwood mechanistic model proposed by Ballauff's group involving the adsorption of both reactants on the surface of the catalyst for AuNPs.[82–84]

7 Click Dendrons and Dendrimers for Efficient Catalysis Using Magnetically Recoverable Catalysts

Alper's group pioneered magnetically recoverable dendritic catalysts for hydroformylation reactions.[85] Bronstein's group recently reported magnetically recoverable PdNP catalysts that were stabilized by rigid polyphenylenepyridyl dendrons of second- and third-generation molecules with dodecyl peripheries located on the surface of iron oxide magnetic nanoparticles.[86,87] We have exploited the trz coor-

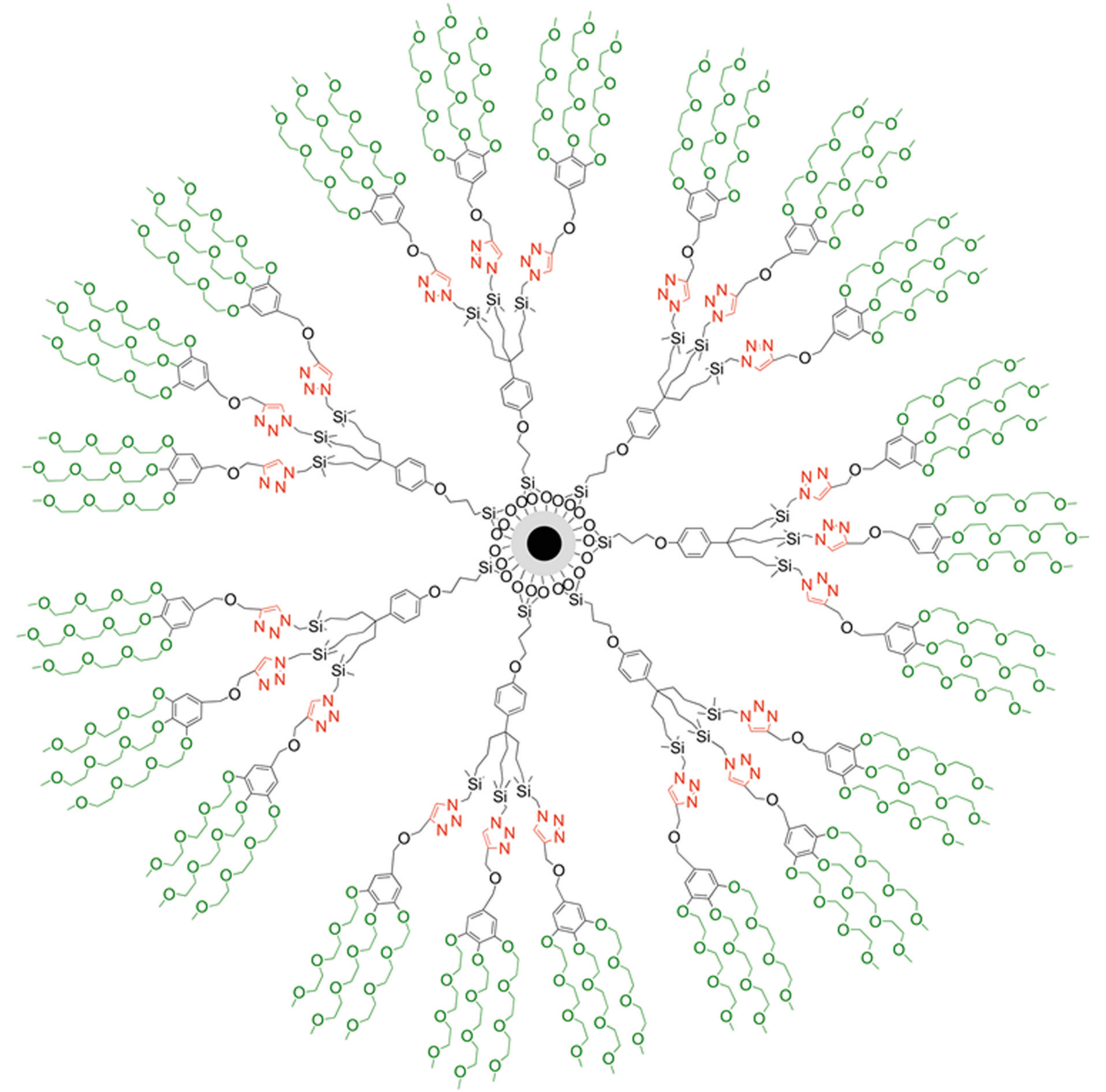


Figure 5 A γ-Fe_2O_3@SiO_2 nanoparticle core terminated by triethylene glycol groups containing intradendritic trz ligands

dination in click dendrimers to design magnetically recoverable catalysts. The catalyst with a γ-Fe_2O_3@SiO_2 nanoparticle core, terminated by triethylene glycol groups containing intradendritic trz ligands (Figure 5), and incorporating PdNPs was highly active, dispersible, and magnetically recoverable many times in Suzuki, Sonogashira, and Heck reactions. A series of pharmacologically relevant or natural products were successfully synthesized using this catalyst. Strong positive dendritic effects concerning ligand loading, catalyst loading, catalytic activity, and recyclability were observed, i.e. the dendritic catalysts were much more efficient than the nondendritic analogues.[88]

Simple impregnation of maghemite γ-Fe_2O_3@SiO_2 (10 nm) with an aqueous solution of a dendrimer containing stabilized PdNPs is another method of producing highly efficient heterogeneous catalysts for carbon–carbon cross-coupling reactions and the selective oxidation in water of benzyl alcohol to benzaldehyde.[89] The latter reaction was also conducted in air under ambient conditions using a magnetically recoverable γ-Fe_2O_3@SiO_2-immobilized PdNP catalyst functionalized with a tris(triazolate) dendronic ligand.[90]

8 Conclusion and Prospects

The most common click reaction, CuAAC, is a facile method for dendrimer and metallodendrimer construction when appropriate care is exercised concerning the copper(I) catalyst. The resulting trz-containing dendrimers possess rich properties resulting from the potential coordination and supramolecular chemistry of the trz ligands and micellar effects of the dendrimers. The intradendritic trz ligands stoichiometrically bind transition-metal cations, sometimes considerably enhancing their catalytic function. This coordination also allows their redox recognition with trz-ferrocenyl or trz-biFc dendrimers and the formation of small size-controlled metal nanoparticles that are useful for intradendritic catalysis. Sophistication of the design of catalytically active dendrimer-encapsulated nanoparticles by covalent or supramolecular attachment to superparamagnetic iron oxide nanoparticles leads to the formation of robust recyclable catalysts that are active for a number of reactions involving carbon–carbon bond formation or aerobic alcohol oxidation.

These principles involving coordination,[91] micellar effects,[68,69] and supramolecular chemistry[69] can be exploited for sensing,[37] catalysis,[40,68,78,80] and nanomedicine,[92,93] and potentially can be extended to other metals, substrates, and reactions including applications relevant to biocompatible and sustainable processes.

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