Letter

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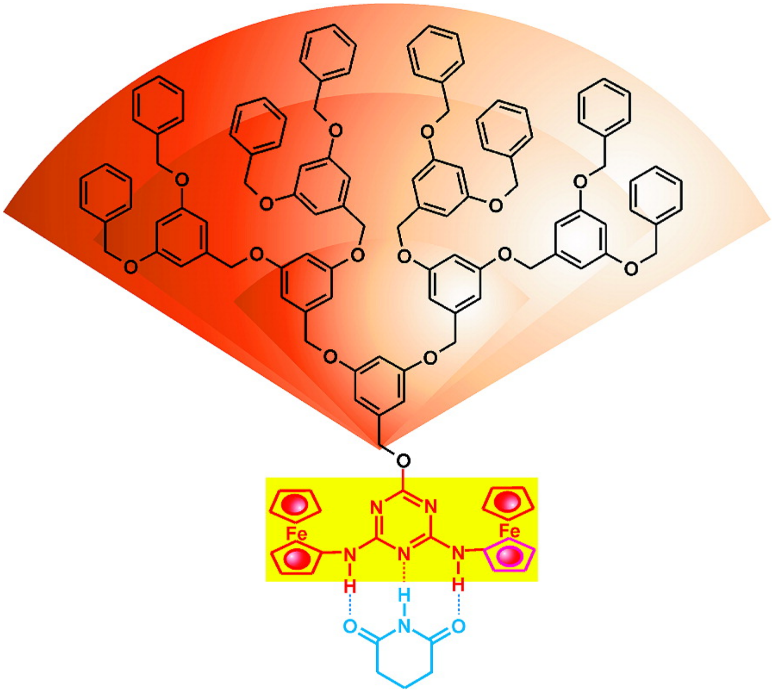

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A New Series of Dendrimers Containing Two Ferrocenyl Units and a Fréchet Dendron around a Triazine Nucleus

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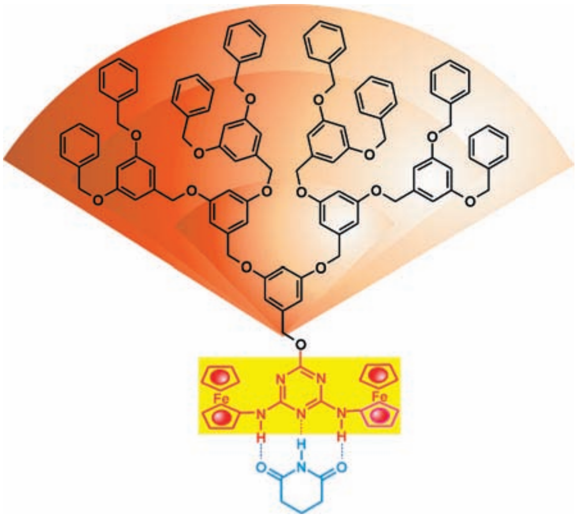
ABSTRACT



The preparation and characterization of a new series of dendrimers containing two identical aminoferrocenyl units and a Fréchet dendron around a triazine nucleus is described. A sizable degree of electronic communication between the two redox active ferrocenyl residues was detected in dichloromethane solution containing tetrabutylammonium tetra(pentafluorophenyl)borate as the supporting electrolyte. Binding of glutarimide via hydrogen bonding interactions to all the dendrimers was easily detected by using ^{1}H NMR spectroscopic and voltammetric techniques.

The reactivity of the trichlorotriazine nucleus offers interesting possibilities for derivatization in successive nucleophilic substitution steps. The groups of Simanek and Wang have reported nice examples of this stepwise chemistry and prepared novel dendrimers[1] and calixarene[2] derivatives, respectively. We have recently used the triazine nucleus as the backbone for the preparation of redox active, hybrid dendrimers[3] containing three different peripheral residues: (1) a ferrocenyl amine, (2) a Fréchet dendron,[4] and (3) a Newkome dendron.[5] This molecular design allowed us to investigate the relative effects of both types of popular

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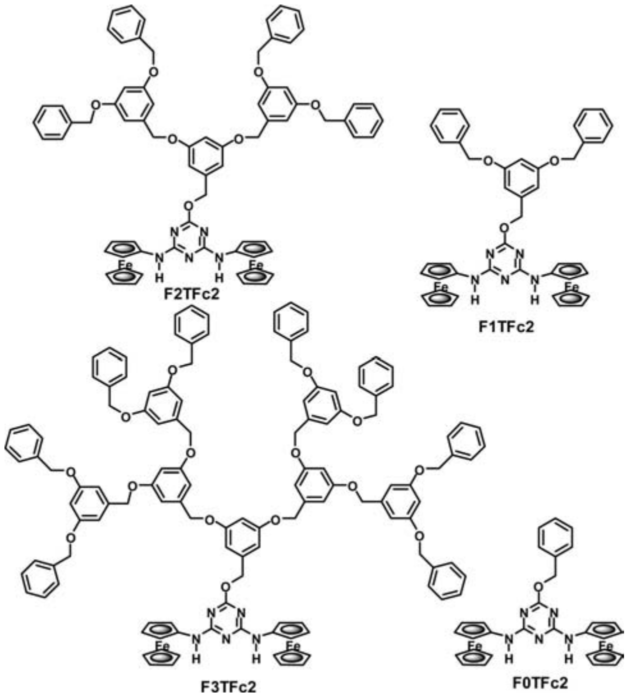
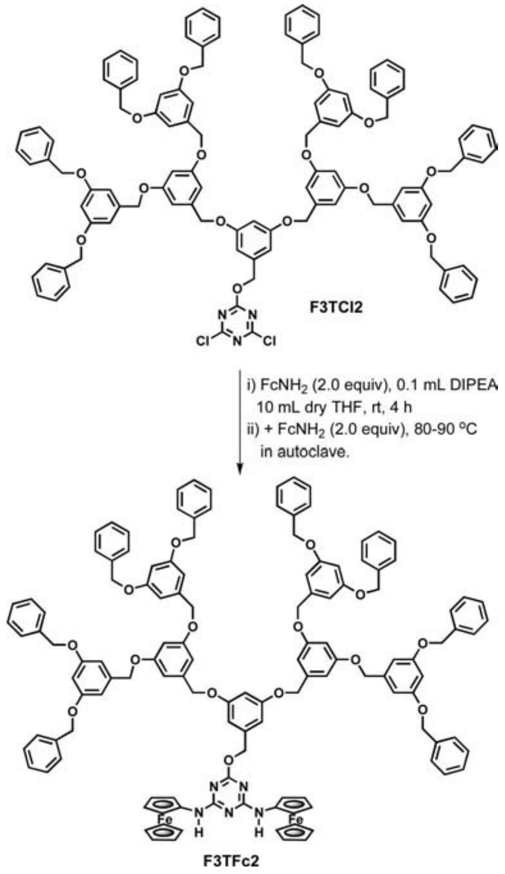


Figure 1. Structures of the dendrimers used in this work. The naming system describes the building blocks present in each compound around the triazine nucleus (**T**): **Fc**, ferrocenyl, and **F*n***, *n*th generation Fréchet dendron (*n* = 0−3).

Scheme 1. Synthetic Steps for the Preparation of Dendrimer **F3TFc2**



dendrons on the electrochemical parameters for the oxidation of the ferrocene center and the diffusional properties of these macromolecules. Here we report a new series of dendrimers containing a triazine core and three pendant residues, that is, two identical aminoferrocene groups and an AB_2 Fréchet-type, aromatic ether dendron (from zero to third generation of growth, **F0**−**F3**). The structures of these triazine-cored dendrimers are shown in Figure 1. In this report, we describe the synthesis, characterization, and some electrochemical properties of these dendrimers, as well as preliminary data on their hydrogen bonding interactions with glutarimide.

The synthetic strategy for the preparation of these compounds takes into consideration that the attachment of electron-rich residues to the triazine nucleus deactivates it for subsequent nucleophilic substitutions. Therefore, the attachment of the two aminoferrocenyl residues was accomplished in a single step at the end. Initially, trichlorotriazine (cyanuric chloride) was reacted, as reported already,[3] with the benzylic alcohol form of the corresponding Fréchet dendron to produce the dendronized dichlorotriazine derivatives (**F0TCl2**−**F3TCl2**, see Scheme 1) in 40−60% yields. The dichlorotriazine intermediates were reacted with 2.0 equiv of aminoferrocene[6] in dry THF at room temperature, using diisopropylethylamine (DIPEA) as the base. After 4 h an additional 2.0 equiv of aminoferrocene was added and the solution was transferred to an autoclave, which was closed and heated in an oil bath at 80−90 °C overnight. After column chromatography, the target compounds (**F0TFc2**−**F3TFc2**) were isolated in moderate yields (20−40%) and fully characterized by using ^{1}H and ^{13}C NMR spectroscopic and FAB or MALDI-TOF mass spectrometric data (see the Supporting Information).

The anodic electrochemical behavior of these dendrimers is dominated by the one-electron oxidation of the ferrocenyl residues. In dichloromethane solution, using 0.1 M tetrabutylammonium hexafluorophosphate ($TBA^+PF_6^-$) as supporting electrolyte, the electrochemical oxidation of the two ferrocenyl units takes place in a single anodic wave (Figure 2A). This finding suggests that the ferrocene centers behave independently, as identical redox centers, with no significant electronic communication between them. The voltammetric behavior was similar regardless of the size of the Fréchet dendron connected to the triazine core. Recently, the noncoordinating character of the PF_6^- anion in nonpolar media, such as dichloromethane, has been questioned. Geiger and co-workers have demonstrated that, in low-polarity solvents, replacement of hexafluorophosphate by tetrakis(pentafluorophenyl)borate, $B(C_6F_5)_4^-$, may have a pronounced effect on the voltammetric behavior observed for compounds that contain two or more equivalent, oxidizable centers.[7,8] In agreement with these arguments, the voltammetric behavior of dendrimers **F0TFc2** to **F3TFc2** in 0.1 M $TBA^+B(C_6F_5)_4^-$/

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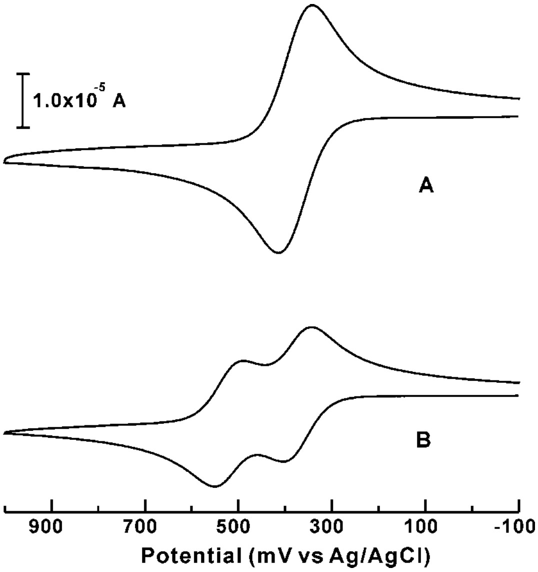

Figure 2. Cyclic voltammetric behavior on glassy carbon (0.071 cm^2) of 1 mM **F2TFc2** in dichloromethane solution also containing (A) 0.1 M $TBA^+PF_6^-$ and (B) 0.1 M $TBA^+B(C_6F_5)_4^-$. Scan rate: 0.1 V s^{-1}.

CH_2Cl_2 solution exhibits two perfectly resolved, reversible anodic waves (Figure 2B). Clearly, the $B(C_6F_5)_4^-$ anion has a substantially lower coordinating or ion pairing ability (as compared to the PF_6^- anion) and allows the formation of essentially "naked" positive charges upon electrochemical oxidation of the ferrocene centers, which exert increased electrostatic effects on their vicinity, leading to a split of the two successive oxidation potentials in these dendrimers.

The half-wave potentials ($E_{1/2}$) recorded for all the dendrimers are given in Table 1 along with their calculated molecular weights and diffusion coefficients (D_o), as measured using Pulse Gradient Stimulated Echo (PGSE) NMR techniques.[9] All the half-wave potentials show a slight tendency to shift to more positive values with increasing dendron size. However, as is usually the case with Fréchet dendrons, the trend is not quite pronounced and amounts to a total change of 30−50 mV in going from the smallest (**F0TFc2**) to the largest (**F3TFc2**) dendrimer. The small anodic potential shifts observed indicate that the aromatic ether nature of the dendrons does not provide significant stabilization to the positively charged, oxidized ferrocene centers and, in fact, they afford a slight differential stabilization to the reduced ferrocene centers. In the presence of $B(C_6F_5)_4^-$ as the supporting electrolyte, the difference between the $E_{1/2}$ values for the two anodic waves observed is essentially constant within experimental error. In this medium, the comproportionation constant[10] (K_c), defined for the equilibrium **FnTFc2** + **FnTFc2^{2+}** $\rightleftarrows$ 2 **FnTFc2$^+$**, can be obtained as $\exp(F\Delta E_{1/2}/RT)$ and is approximately equal to $(3.0 \pm 0.3) \times 10^2$. Therefore, the mixed valence (**FnTFc2$^+$**) species is reasonably stable in all these dendrimers when using a noncoordinating supporting electrolyte anion. Finally, the measured diffusion coefficients were found to decrease monotonically with increasing molecular weight, as anticipated.

Table 1. Molecular Weights, Diffusion Coefficients, and Half-Wave Potentials for Dendrimers **F0TFc2**−**F3TFc2** in Dichloromethane Solution at 23 °C

	F0TFc2	**F1TFc2**	**F2TFc2**	**F3TFc2**
MW	585	797	1222	2071
D_o ($\times 10^6$ cm^2 s^{-1})^a	11.9	10.3	7.6	5.5
$E_{1/2}$ (V vs Ag/AgCl)^b	0.370	0.378	0.377	0.416
$(E_{1/2})^1$ (V vs Ag/AgCl)^c	0.371	0.375	0.375	0.403
$(E_{1/2})^2$ (V vs Ag/AgCl)^c	0.516	0.519	0.520	0.552
$\Delta E_{1/2}$ (mV)^c	145	144	145	149

[a] Measured in CD_2Cl_2 solution. Error margin: $<0.1 \times 10^{-6}$ cm^2 s^{-1}. [b] Measured in 0.1 M $TBA^+PF_6^-$. Error margin: ±0.005 V. [c] Measured in 0.1 M $TBA^+B(C_6F_5)_4^-$. Error margin: ±0.005 V.

It is well-known that triazine derivatives containing at least one pendant amine residue may exist as rotamers at room temperature due to the partial double bond character of the covalent bond between the amine nitrogen and the carbon atom on the triazine nucleus.[11] However, rotamer interconversions are relatively facile and we anticipated that the two NH's connected to the ferrocenyl residues and the intermediate nitrogen on the triazine nucleus may form a donor−acceptor−donor (DAD) hydrogen bonding array, which may be useful to bind to a complementary ADA sequence (Figure 3). To test this idea, we selected glutarimide as the possible guest, because it has a well-defined ADA hydrogen bonding array and its interactions with aminotriazines have been previously reported.[12]

Addition of glutarimide to a solution containing dendrimer **F1TFc2** results in a series of changes in the ^{1}H NMR spectra that are consistent with the anticipated hydrogen bonding interactions. At low values of the [glutarimide]/[dendrimer] challenge ratio, the glutarimide NH proton (H_b in Figure 3) resonates at $\delta > 8.5$ ppm, as expected when engaged in hydrogen bonding to the dendrimer. As the concentration of glutarimide increases, while the dendrimer concentration remains constant, the fraction of unbound glutarimide in solution increases and its NH proton shifts upfield (toward the value found for unbound glutarimide). On the other hand the NH protons on the dendrimer (H_a in Figure 3) shift downfield monotonically, as the increasing concentration of glutarimide shifts the equilibrium further toward the hydrogen bonded complex. The variation of the chemical shift of

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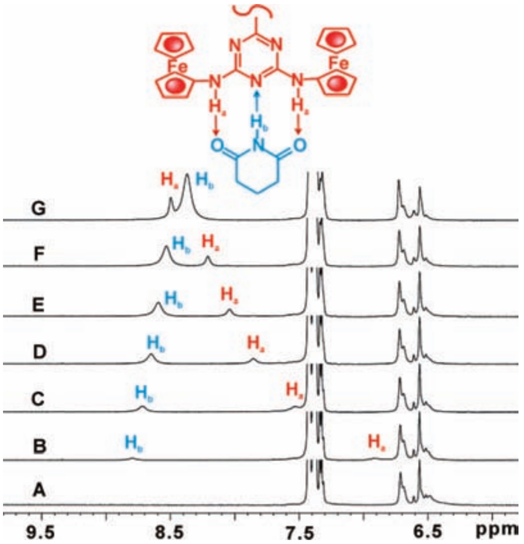

Figure 3. Partial ^{1}H NMR spectra (500 MHz, CD_2Cl_2) of 5.0 mM **F1TFc2** (A) in the absence and in the presence of glutarimide: (B) 0.2, (C) 0.6, (D) 1.0, (E) 1.4, (F) 2.0, and (G) 3.0 equiv. H_a labels the two NH protons on the dendrimer and H_b is the NH proton on glutarimide.

these two equivalent protons as a function of glutarimide concentration can be fitted to a 1:1 binding isotherm (see the Supporting Information). From the optimization of the fit we extracted the equilibrium association constant (K), which was found to be equal to 850 M^{-1}. This value is rather modest, but falls within the anticipated range for binding interactions between DAD−ADA hydrogen bonding partners.[13] Similar results were obtained with the remaining dendrimers.

The voltammetric behavior of any of the dendrimers is also affected by the presence of glutarimide. In general terms, the anodic waves for the oxidation of the ferrocenyl residues shift to more negative values as the concentration of glutarimide increases. The glutarimide-induced potential shifts are similar for the single anodic wave observed in 0.1 M $TBA^+PF_6^-/CH_2Cl_2$ or for the two anodic waves detected in 0.1 M $TBA^+B(C_6F_5)_4^-/CH_2Cl_2$, reflecting that hydrogen bonding engagement by the NH's next to the ferrocenyl units increases the electronic density on the redox centers and leads to less positive half-wave potentials for their oxidation. We observed a modest cathodic shift of 22 mV in the $E_{1/2}$ value for oxidation of **F2TFc2** upon addition of 10 equiv of guest. As was the case with the NMR experiments the glutarimide-induced changes in the voltammetric parameters are essentially the same, regardless of the dendron size attached to the triazine core.

In summary, this work demonstrates that the triazine core can be utilized as a useful framework for the preparation of dendrimers containing two identical aminoferrocene centers, which exhibit a reasonable level of electronic communication in 0.1 M $TBA^+B(C_6F_5)_4^-/CH_2Cl_2$ solution. These dendrimers contain a DAD hydrogen bonding array and their resulting binding interactions to ADA-type guests were illustrated with glutarimide, using ^{1}H NMR spectroscopic and voltammetric data. These compounds constitute our first step in the development of structurally more complex macromolecules containing redox active or fluorescent reporter groups and designed to bind simple guests, such as glutarimide. We intend to continue the synthetic elaboration of these molecules to make similar binding interactions possible in more polar solvents.

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Supporting Information Available: Synthetic details for all new compounds and additional NMR spectroscopic and voltammetric data as mentioned in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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