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ÉCOLE DOCTORALE DES SCIENCES CHIMIQUES DE BORDEAUX

POUR OBTENIR LE GRADE DE :

DOCTEUR

SPÉCIALITÉ: CHIMIE

Par

Jérémy CAMPONOVO

Thèse dirigée par Pr. Didier ASTRUC
ISM, Groupe Nanosciences et Catalyse, Université Bordeaux 1

Titre de la thèse :

SYNTHÈSE DE NANOARCHITECTURES À VOCATION BIOCHIMIQUE

Soutenue le 12 Juillet 2010 devant la commission d'Examen

COMPOSITION DU JURY :

Mme. Sandrine BOUQUILLON,	Professeur (Université de Reims Champagne-Ardenne),	**Rapporteur**
M. Sébastien TILLOY,	Professeur (Université d'Artois)	**Rapporteur**
M. Laurent DJAKOVITCH,	Chargé de Recherche CNRS (Université Lyon 1)	
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« La connaissance s'acquiert par l'expérience,
tout le reste n'est que de l'information »

Albert Einstein

À ma fille

Je dédie cette thèse à ma fille Rose, qui m'a apporté par sa naissance le plus grand bonheur qu'un homme puisse attendre.

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Introduction Générale

Introduction Générale

À la fin des années 70, les premières itérations dendritiques[1] ont ouvert la voie à une nouvelle classe de molécule : les dendrimères. Ce sont des molécules arborescentes, parfaitement définies, dont les premiers exemples sont apparus au début des années 80 avec les dendrimères PAMAM de Tomalia,[2] et les arborols de Newkome.[3] Par la suite, la chimie des dendrimères[4] n'a cessé de s'enrichir tant au niveau des synthèses que des propriétés avec notamment les dendrimères polypropyleneimine (PPI) de Meijer,[5] ou les dendrimères polyéther de Fréchet.[6]

Aujourd'hui, grâce à l'ingénierie moléculaire, il est possible d'adapter les dendrimères commerciaux pour obtenir un large choix de fonctionnalisations[7]. Il est également possible de synthétiser et d'optimiser une série dendritique pour une fonction précise. Ainsi, l'utilisation des dendrimères peut servir pour de nombreuses applications dont la reconnaissance moléculaire,[8] la catalyse[9] ou encore la nanomédecine.[10]

Pour les applications biologiques, il convient de revenir sur l'organisation spatiale des dendrimères. Leur forme dans l'espace est globulaire[11] au-delà d'une certaine génération (4ème génération dans le cas des dendrimères PAMAM). De plus, l'encombrement stérique à la périphérie augmente avec la génération. Le modèle bien connu de de Gennes,[12] qui fit référence pendant près de 20 ans, prédisait une génération limite impossible à dépasser lors de la synthèse de dendrimères, due à la congestion à la surface des molécules.

Bien que ceci reste vrai dans le cas de molécules rigides, une approche différente, apparue en 1990, semble mieux convenir aux dendrimères plus flexibles: c'est le modèle de cœur dense.[13] Ce modèle prend en compte le fait que les fins de chaînes dendritiques peuvent se tourner vers le cœur du dendrimère jusqu'à occuper tout le volume disponible. Celles-ci restent tout de même un peu accessibles lors de réactions chimiques car ce phénomène est dynamique : au court du temps, ce ne sont pas toujours les mêmes branches qui sont tournées vers le cœur.

Notre groupe a réalisé la synthèse de dendrimères géants,[14] très au-delà de la limite imaginée par de Gennes. On peut donc voir le dendrimère comme une surface périphérique relativement sphérique comportant une densité importante de fonctions chimiques, sous laquelle des cavités sont disponibles. La densité de fonctions chimiques, l'encombrement stérique périphérique ainsi que la taille des cavités peuvent être adaptés par la génération dendritique ou l'emploi d'un espaceur entre deux générations par exemple.

Cette organisation particulière et le grand nombre de fonctions périphériques ont fait germer l'idée de transporter certaines molécules, dont des médicaments, à l'aide de dendrimères.[15] Différentes stratégies ont été imaginées.[16]

Il est tout d'abord possible de lier le médicament par liaison covalente à la surface du dendrimère.[17] La grande densité de branches périphériques du vecteur permet d'en transporter un grand nombre et d'améliorer l'entrée du médicament dans les cellules. Cependant, ce genre d'architectures nuit souvent à la solubilité dans l'eau du vecteur obtenu. De plus, l'impact sur l'activité du médicament n'est pas bien prévisible (effet dendritique positif, négatif, ou présentant un maximum).

Il est également possible de réaliser un « complexe » dendrimère médicament par liaison électrostatique à la périphérie ou par interaction supramoléculaire au niveau des cavités dendritiques.[18] En effet, il a été montré que les dendrimères peuvent encapsuler un grand nombre de molécules. C'est le concept de boite moléculaire imaginé par Meijer.[4] Le problème lié à ce genre d'architectures vient du fait qu'elles relarguent progressivement le médicament même avant d'avoir atteint la cible souhaitée. Ces deux types de vecteurs peuvent permettre tout de même d'améliorer la biodistribution, le temps de circulation dans le sang, l'entrée dans les cellules, ou encore le ciblage.

Dans cette étude, nous avons opté pour la stratégie d'encapsulation. Ainsi, les structures dendritiques obtenues pourront être utilisées avec un large choix de médicaments. De plus, en utilisant cette stratégie, le dendrimère est alors une entité unique qui peut être considéré comme un nouvel agent de formulation pour des médicaments déjà autorisés. Dans le cas de liaisons covalentes par exemple entre le dendrimère et le médicament, il s'agit d'une nouvelle entité chimique qui nécessitera de repartir à zéro pour tous les tests biologiques, et ce, à chaque modification de l'organe cible ou du médicament comme s'il s'agissait d'un médicament nouveau.

Nous avons également décidé d'inclure sur nos branches dendritiques le motif 1,2,3-triazole. Il s'agit tout d'abord d'un formidable outil de synthèse car obtenu par chimie « click »,[19] qui est rapide, efficace et déjà employé avec succès pour la fonctionnalisation de dendrimères. Ensuite, ce motif comporte des atomes d'azote, qui se comportent comme des accepteurs de liaison hydrogène très disponibles. Ceci permet d'améliorer la stabilisation intradendritique pour une grande variété de molécules, sans présenter de charge positive à pH neutre comme dans le cas des amines.

Un autre facteur très important est la solubilité des vecteurs. Dans le cadre de la nanomédecine, le vecteur utilisé doit présenter une solubilité dans l'eau suffisante. La majorité des principes actifs présente une solubilité dans l'eau faible. Ainsi il est souvent nécessaire, lors de la formulation d'un médicament, d'ajouter d'autres molécules pour améliorer la solubilité du principe actif dans l'eau.

Il est possible, dans le cas des dendrimères, d'obtenir des molécules solubles dans l'eau comportant un cœur hydrophobe. En effet, leur solubilité générale est essentiellement celle conférée par la fin des branches, la composition du cœur n'ayant qu'un effet mineur. Les cavités hydrophobes internes permettent alors une interaction supramoléculaire avec les molécules encapsulées: c'est le concept de micelle unimoléculaire développé par Newkome.[3]

Il convient également de parler de la toxicité générale des dendrimères.[20] Il est assez difficile de faire ressortir une tendance car finalement assez peu d'études ont été réalisées sur ce sujet. Les dendrimères les plus étudiés dans ce domaines sont bien sûr issus des dendrimères commerciaux PAMAM et PPI. Globalement, les dendrimères chargés positivement sont plus toxiques que les dendrimères neutres et anioniques. Les charges internes jouent un rôle moins important pour la toxicité de l'ensemble que les charges portées à la surface, mais celui-ci n'est tout de même pas négligeable. Cette toxicité peut être diminuée par le greffage de molécules neutres comme les chaînes polyéthylène glycol (PEG) à la périphérie du vecteur.

Ainsi, pour nous permettre de réaliser des dendrimères solubles dans l'eau, nous avons décidé de greffer des molécules neutres à la périphérie des dendrimères. Au laboratoire, nous

nous sommes d'abord orientés vers l'utilisation de chaînes polyéthylène glycol.[21] Dans le cas des médicaments à visée antitumorale, l'effet EPR qu'elles confèrent au vecteur améliore le ciblage des cellules malades, en plus de le rendre biocompatible. Enfin, elles ont un côté pratique lors des synthèses, car elles autorisent la solubilisation du vecteur à la fois dans l'eau et dans certains solvants organiques.

Nous avons ensuite entrepris la synthèse de glycodendrimères,[22] une famille largement utilisée en nanomédecine. En effet, il a été montré qu'ils sont non immunogènes[23] et présentent toutes les caractéristiques nécessaires d'un bon vecteur. Nous avons visé pour cela l'utilisation du xylose et de l'arabinose, des pentoses issus de la biomasse. Ceux-ci sont peu coûteux, non toxiques, présentent une bonne solubilité dans l'eau, et leur utilisation permettrait de valoriser toute une série de déchets agricoles. Nous avons donc développé une série dendritique comportant 27, 81 et 243 fonctions alcynes périphériques, modifié les sucres pour introduire la fonction azoture et enfin réalisé le greffage terminal par chimie « click ».

Les cyclodextrines[24] sont une famille de polysaccharides cycliques naturels composés de sous-unités D-glucopyranoses liés en alpha-(1,4). Elles présentent une solubilité dans l'eau variable (très forte pour l'α- et la γ-cyclodextrine et moyenne dans le cas de la β-cyclodextrine) qui peut être modifiée par fonctionnalisation chimique.[25] Elles ont la propriété de comporter une cavité hydrophobe de taille définie et de présenter vers l'extérieur des groupements hydrophiles. Ceci ajouté à leur toxicité négligeable (LD50 de 18800 mg/kg par voie orale chez le rat pour la β-CD), on comprend leur large utilisation dans le domaine de l'agroalimentaire (additif E459), la cosmétique ou encore la formulation pharmaceutique (excipient de formulation).

Les nanoobjets comportant plusieurs cyclodextrines périphériques[26] sont connus pour améliorer les propriétés de complexation des cyclodextrines. En effet, les espaceurs reliant plusieurs cyclodextrines agissent comme des pseudo-cavités supplémentaires. L'interaction avec la molécule encapsulée est alors supérieure à la somme de celles dues aux cyclodextrines seules. Ainsi, l'utilisation de polycylodextrines pourrait permettre le même genre d'applications que celles qui existent déjà pour les cyclodextrines natives, mais pour le transport de molécules plus grosses ou pour la complexation d'un plus grand nombre de petites molécules. Nous avons donc envisagé la synthèse de dendrimères comportant plusieurs motifs cyclodextrines périphériques pour des applications en nanomédecine et en catalyse.

La synthèse de tels vecteurs solubles dans l'eau est une thématique très proche de la catalyse, une autre spécialité de notre groupe de recherche, car ils peuvent également servir de nanoréacteurs en phase aqueuse, à la synthèse et à la stabilisation de nanoparticules,[27] ou encore à réaliser des catalyses biphasiques.[28]

Le plan de ce mémoire de thèse, réalisée dans le groupe de Didier Astruc à Talence à l'Université Bordeaux 1, s'articule sous forme de mémoires en anglais publiés ou en attente dont la liste suit. Chaque mémoire est précédé d'une introduction en Français situant le contexte de la contribution du mémoire à l'ensemble. La conclusion générale en Français fera le bilan et situera les perspectives futures pour les objets dendritiques présentés.

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Chapitre 1

Synthèse de dendrimères polyalcynes comportant 27, 81 et 243 branches, fonctionnalisation par des ferrocènes et reconnaissance de molécules d'intérêt biologique

Chapitre 1 : Synthèse de dendrimères polyalcynes comportant 27, 81 et 243 branches, fonctionnalisation par des ferrocènes et reconnaissance de molécules d'intérêt biologique

Ce travail est basé sur l'utilisation des cœurs dendritiques classiques du laboratoire comportant 9, 27 ou 81 iodomethyl périphériques. Ces cœurs sont obtenus en utilisant les complexes d'aromatiques avec le greffon activant $(\eta^5\text{-}C_5H_5)Fe^+$ noté $CpFe^+$ pour réaliser les réactions de perallylation.

La perallylation du mésitylène conduit au cœur dendritique de génération 0, comportant neuf branches : le nonaallyle. L'autre brique essentielle est le dendron phénoltriallyle, utilisé pour construire les générations supérieures. Il peut être obtenu en trois étapes à partir du p-chlorotoluène en utilisant le même greffon $CpFe^+$.

La montée en génération s'effectue grâce à une réaction d'hydrosilylation régiosélective, permettant d'introduire le chloromethyldimethylsilane en bout de chaîne. Une réaction quantitative d'échange d'halogénure est réalisée pour substituer l'atome de chlore terminal par un atome d'iode. La génération supérieure est obtenue par une réaction de Williamson. L'absence d'hydrogène en béta du groupe partant interdit, dans ce cas, la réaction d'élimination.

Pour tirer parti de ces synthèses dendritiques bien maîtrisées, il a ensuite été mis au point un dendron trialcyne comportant une fonction phénol au point focal. Celui-ci peut être obtenu en grande quantité (plusieurs grammes) avec un bon rendement global, et à partir de réactifs bon marché. L'analogie avec le dendron phénoltriallyl, nous a permis d'adapter facilement les conditions du couplage de Williamson pour obtenir des dendrimères contenant respectivement 27, 81 et 243 fonctions alcynes périphériques.

Des ferrocènes ont ensuite été greffés par chimie « click » à la périphérie, donnant à l'ensemble une structure d'exorécepteur. Les investigations réalisées par voltamétrie cyclique nous ont permis de montrer l'interaction entre les cycles 1,2,3-triazoles et certains oxo-anions (dont l'ATP d'intérêt biologique) d'une part et certains cations métalliques d'autre part (Pd^{2+}). Ceci confirme donc l'hypothèse de départ : ce cycle présent à l'intérieur du dendrimère va nous permettre de mieux stabiliser les molécules encapsulées (comme le cis-platine par exemple).

Des dosages de ces oxo-anions ont pu être réalisés. Ceux-ci montrent une stoechiométrie d'un oxo-anion par branche dans le cas de molécules monochargées et d'un oxo-anion pour deux branches dans le cas de l'ATP dichargé.

Il est également intéressant de noter que les résultats obtenus en reconnaissance moléculaire sont du même ordre de grandeur que le ferrocène soit conjugué (travaux précédents du groupe) ou non au cycle 1,2,3-triazole.

L’effet dendritique sur la reconnaissance est relativement faible ici. L’augmentation de la génération permet cependant d’améliorer les propriétés d’adsorption du dendrimère et ainsi d’obtenir des électrodes de platine modifiées plus robustes et recyclables.

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New Polyalkynyl Dendrons and Dendrimers: "Click" Chemistry with Azidomethylferrocene and Specific Anion and Cation Electrochemical Sensing Properties of the 1,2,3-Triazole-Containing Dendrimers

Jérémy Camponovo,[a] Jaime Ruiz,[a] Eric Cloutet,[b] and Didier Astruc*[a]

Abstract: The synthesis and use of the new tris-alkynyl dendrons **2** to **5** are reported, including the Williamson reaction of **5** with 9-iodo (**9**), 27-iodo (**11**), and 81-iodo (**12**) dendritic cores to yield 27-alkynyl (**13**), 81-alkynyl (**14**), and 243-alkynyl (**15**) dendrimers. So-called "click" reactions of these three dendrimers with azidomethylferrocene (**20**) give 27-ferrocenyl (**16**), 81-ferrocenyl (**17**), and 243-ferrocenyl (**18**) dendrimers. Electrochemical recognition of oxo-anions ($H_2PO_4^-$ and ATP^{2-}) and Pd^{2+} cation has been compared using the three polyferrocenyl dendrimers. Derivatization of Pt electrodes with the dendrimers for recognition becomes more facile with increasing size of the dendrimer. This first "click" dendrimer bearing 243-ferrocenyl groups is the best one in the series to obtain robust, recyclable modified Pt electrodes, whereas previous "click" ferrocenyl dendrimers have not been suitable for this purpose.

Keywords: alkynes · click chemistry · dendrimers · ferrocenes · redox chemistry

Introduction

The multifaceted supramolecular properties of dendrimers[1] can be applied to various fields of nanoscience, such as vectors,[2] sensors,[3] and green catalysts.[4] The terminal alkyne function has high potential for chemical properties[5] (as exemplified by the recently reported catalysis of 1,3-dipolar cycloadditions by "click" reaction).[6] Alkynyl functions have previously been used by Newkome et al.[7] and Moore et al.[8] for dendritic construction. Various syntheses of dendrimers with alkynyl termini have also been reported.[9] We have now synthesized the new dendrons **2** to **5** containing three propargyl groups, and have used **5** to open the way to a set of larger polyalkynyl dendrimers containing 27, 81, and 243 alkynyl termini. Indeed, polyiodomethyl dendrimers, used here as dendritic cores, are known for up to nine generations (more than 10^5 branches).[10]

The good overall yield of the synthesis reported here and the easily performed steps used to obtain this Percec-type dendron[11] make it a good tool for obtaining dendronized polyalkynyl molecules. The phenol function located at the focal point of the dendron also allows its introduction onto materials using the classical Williamson reaction.

The reactivity of the three alkynyl dendrimers **13**, **14**, and **15** has now been tested in the "click" reaction with azidomethylferrocene (**20**), a substrate that has not previously been used for this reaction. Our previous "click" dendrimer synthesis involved azido-terminated dendrimers and terminal alkyne substrates. We now report "inverse click" reactions, that is, click dendrimer synthesis in which the terminal alkyne is located on the dendrimer branch termini.[9d,e] Finally, electrochemical recognition of ATP^{2-}, $H_2PO_4^-$, and Pd^{2+} has been probed using the new ferrocenyl dendrimers **16**, **17**, and **18** (containing 27, 81, and 243 ferrocenyl groups, respectively).[12] We recently reported[12d] syntheses of polyferrocenyl dendrimers, along with their redox recognition abilities. We now describe "inverse click" reactions using polyalkynyl cores. The resulting "inverse click" dendrimers display electrochemical properties that differ from those of the previously reported "normal click" dendrimer series. The large size of the dendrimers synthesized here has allowed the preparation of modified Pt electrodes that could not be ob-

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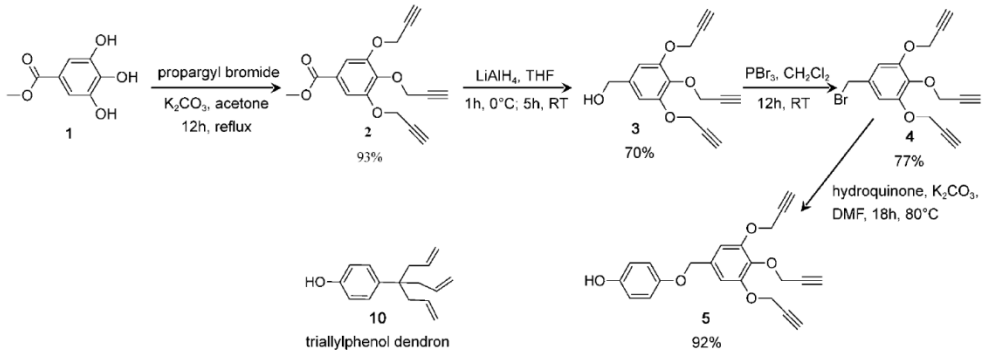
tained with the previously reported "normal click" dendrimers. The resulting dendritic effects are discussed.

Results and Discussion

Dendrimer synthesis: The tris-alkynyl dendron **5** was synthesized from commercially available methyl 3,4,5-trihydroxybenzoate **1** (Scheme 1). Four classical organic chemistry steps were performed to obtain the desired dendron **5** in 45% overall yield. This synthesis only requires a purification step at the end of the process. The three first steps could be easily accomplished on a wide range of scales (from 100 mg to 10 g). The last step proved to be very sensitive to the dilution and addition time, and it was important to remove DMF prior to column chromatographic work-up. The dendron **5** was characterized by classical spectroscopic and analytical means, including mass spectrometry (molecular peak + Na^+ at m/z 385.1050, calcd for $[M+Na]^+$ 385.1046; see the Supporting Information).

The known nona-allylation of $[FeCp(\eta^6\text{-mesitylene})][PF_6]$ **6** ($Cp=\eta^5\text{-}C_5H_5$) quantitatively furnished the 9-allyl dendritic core, **7**, on a large scale after visible-light photolysis to remove the metal moiety (Scheme 2).[10] Hydrosilylation of the terminal olefinic bonds of **7**, a reaction pioneered in dendrimer synthesis by van Leeuwen et al.,[13] was carried out as previously reported, using $HSiMe_2(CH_2Cl)$ and the Karsted catalyst, to regioselectively afford the known 9-chloromethyl(dimethyl)silyl intermediate **8**. Compound **8** was then stirred for 5 h with sodium iodide in refluxing butanone, which quantitatively afforded the known 9-iodomethyl(dimethyl)silyl dendritic core **9** (Scheme 2). Williamson reaction of **9** with the known triallyl-phenol dendron, **10**, has previously been reported to give the polyallyl dendritic core of the next higher generation. Repetition of the hydrosilylation and halogen-exchange steps is known to



Scheme 1. Tris-alkynyl and tris-allyl dendrons.

Abstract in French: *Nous reportons ici la synthèse et l'utilisation de nouveaux dendrons tris-alcynes (composés **2** à **5**). La réaction de Williamson entre **5** et les cœurs dendritiques polyiodés comportant 9, 27 ou 81 branches (composés **9**, **11** et **12**) conduit aux dendrimères poly-alcynes à 27, 81 et 243 branches respectivement (composés **13** à **15**). La réaction "click" de ces dendrimères avec l'azidométhylferrocène (**20**) permet d'obtenir des dendrimères polyferrocéniques à 27, 81 et 243 branches (composés **16** à **18**). La reconnaissance électrochimique d'oxo-anions ($H_2PO_4^-$ et ATP^{2-}) et du cation Pd^{2+} est comparée avec trois dendrimères polyferrocéniques, et l'obtention d'électrodes de Pt modifiées à l'aide de ces dendrimères pour cette reconnaissance est de plus en plus facile lorsque la taille du dendrimère augmente. Le premier dendrimère "click" comportant 243 ferrocènes est le meilleur de la série pour la modification d'électrodes de Pt. Ces électrodes sont robustes et recyclables avec ce dendrimère, alors que les dendrimères "click" précédemment publiés n'étaient pas utilisables pour cette fonction.*

yield the 27-iodo dendritic core, **11**, and the last three steps have previously been used on the latter to yield the 81-iodo dendritic core **12**.[10b]

Coupling between the phenol dendron **5** and the dendritic core, using either of two methods, proceeded with similar yields. The first method involved reaction between the 9-iodomethyl(dimethyl)silyl dendritic core **9** and the phenol dendron **5** in the presence of K_2CO_3 (Scheme 2). The second involved the 9-chloromethyl(dimethyl)silyl dendritic core **8**, together with a stoichiometric amount of NaI, the phenol dendron **5**, and K_2CO_3. Both methods gave the 27-propargyl dendrimer **13** in 65–70% yield. The MALDI-TOF mass spectrum showed the $[M+Na]^+$ peak at m/z 4415.1 (calcd for $[M+Na]^+$ 4415.7; see the Supporting Information). The first method was used with the 27-iodo dendritic core **11** to yield the 81-alkynyl dendrimer **14** (Scheme 3), and with the 81-iodo dendritic core **12** to yield the 243-alkynyl dendrimer **15** (Scheme 4). The only difference was in the reaction time, which was higher for each added generation. This set of dendrimers was characterized by dynamic light scattering (DLS) for the two larger dendrimers (6.2 ± 0.2 nm for **14**

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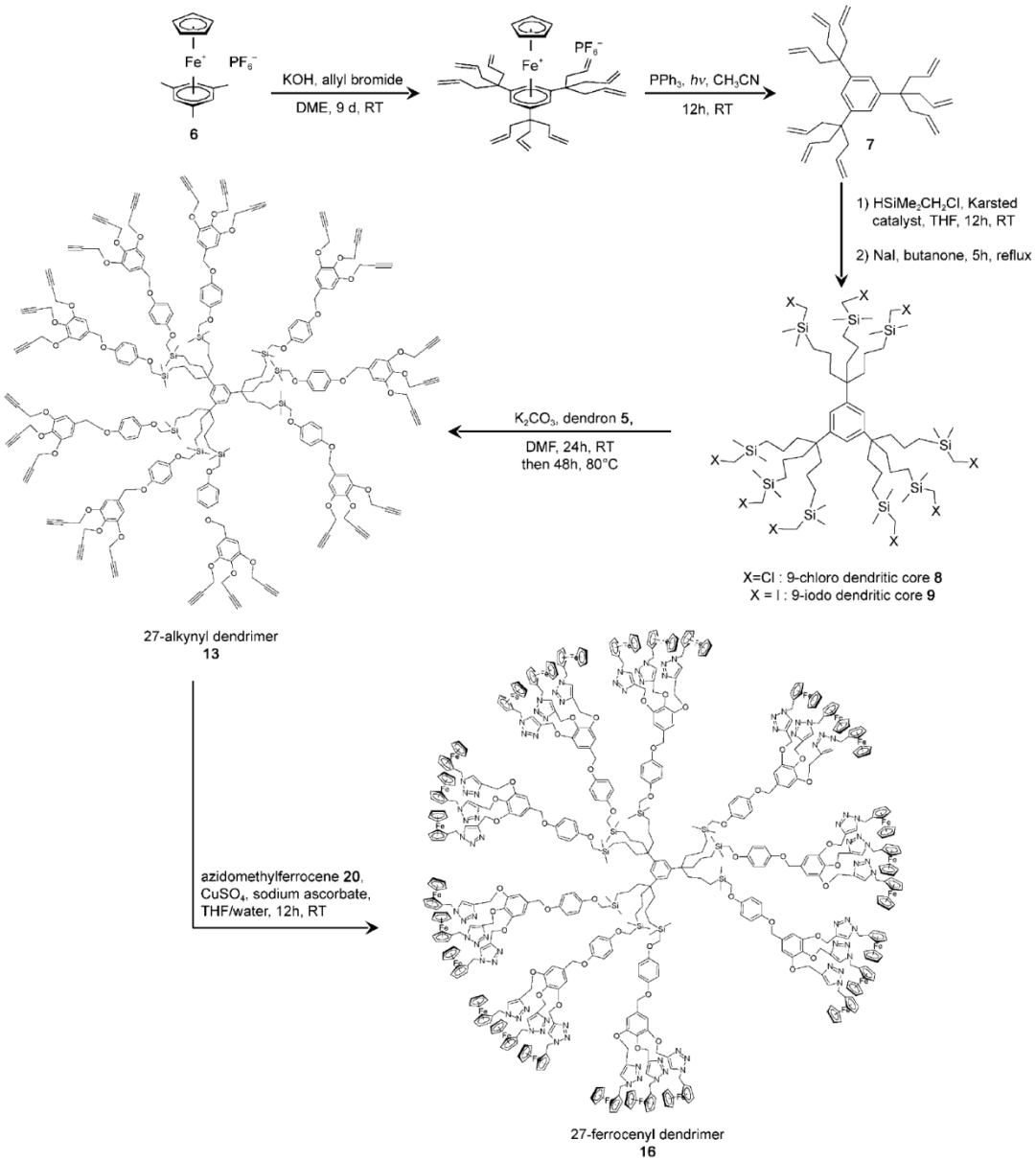

Scheme 2. Synthesis of the 27-alkynyl dendrimer **13** and 27-ferrocenyl dendrimer **16**. For the synthesis of **9**, see ref. [10].

and 6.6 ± 0.2 nm for **15**), ^{1}H, ^{13}C, ^{29}Si, and DOSY NMR, IR, and elemental analysis (see the Experimental Section). Size-exclusion chromatography (SEC) showed the size progression from **13** to **15** (retention times of 20.53, 18.70, and 17.67 min, respectively) and the low polydispersities (1.02 for each compound). The size progression was also shown by the DOSY NMR data (4.1, 4.8, and 4.9 nm, respectively).

Huisgen 1,3-dipolar cycloaddition reactions of **13**, **14**, and **15** with azidomethylferrocene, **20**, were "catalyzed" by Cu^{I} (used in stoichiometric amount)[12d] in a homogeneous THF/water medium yielding the 27-ferrocenyl dendrimer **16** (Scheme 2), the 81-ferrocenyl dendrimer **17** (Scheme 3), and the 243-ferrocenyl dendrimer **18** (Scheme 4), under the same reaction conditions (Scheme 5).[14] These functionalized dendrimers were characterized by DLS for the largest (5.3 ± 1.0 nm for **18**), SEC, ^{1}H, ^{13}C, ^{29}Si, and DOSY NMR, IR, and cyclic voltammetry (see the Experimental Section and the Supporting Information). SEC showed the size pro-

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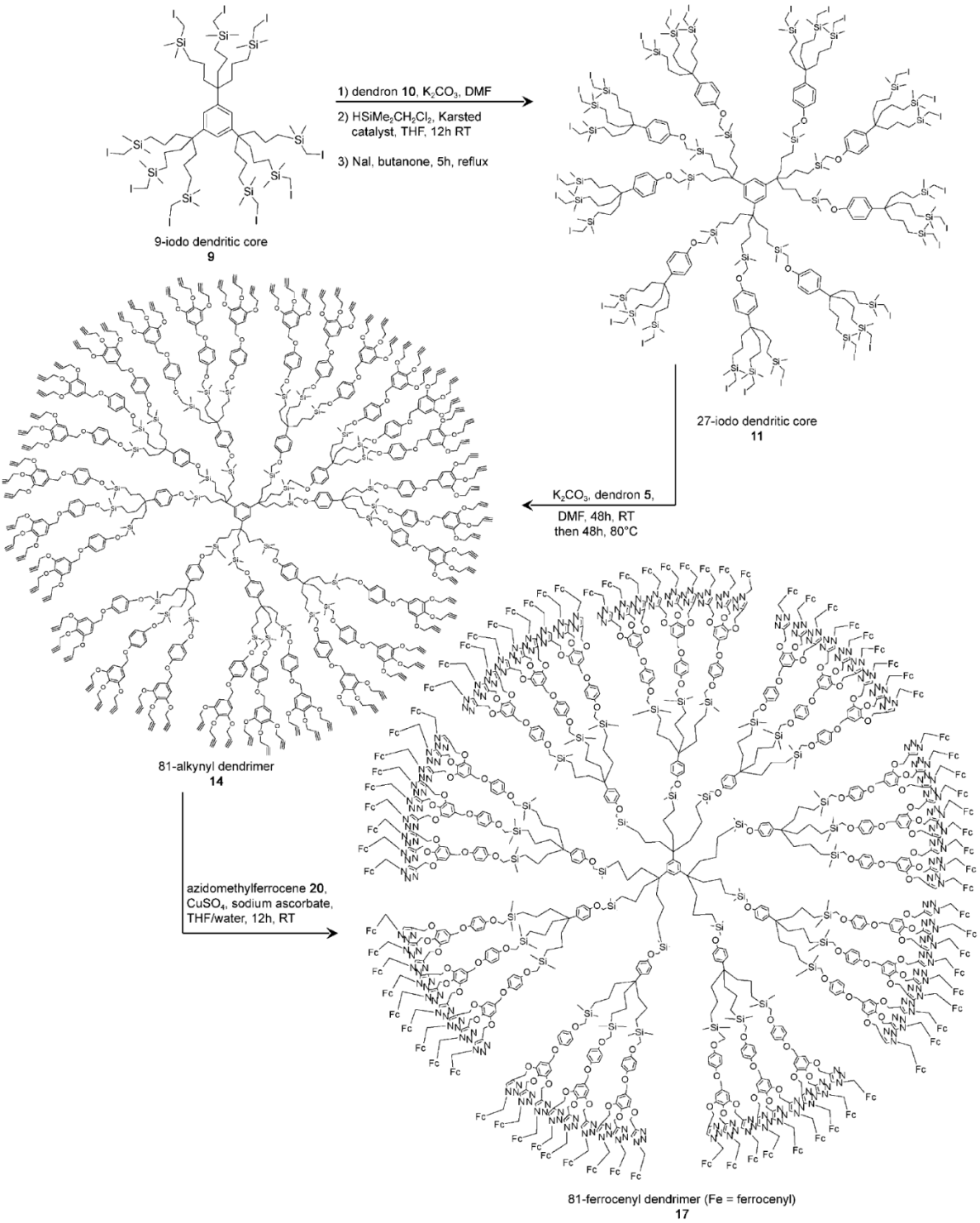

Scheme 3. Synthesis of the 81-alkynyl dendrimer **14** and 81-ferrocenyl dendrimer **17**. For the synthesis of **11**, see ref. [10].

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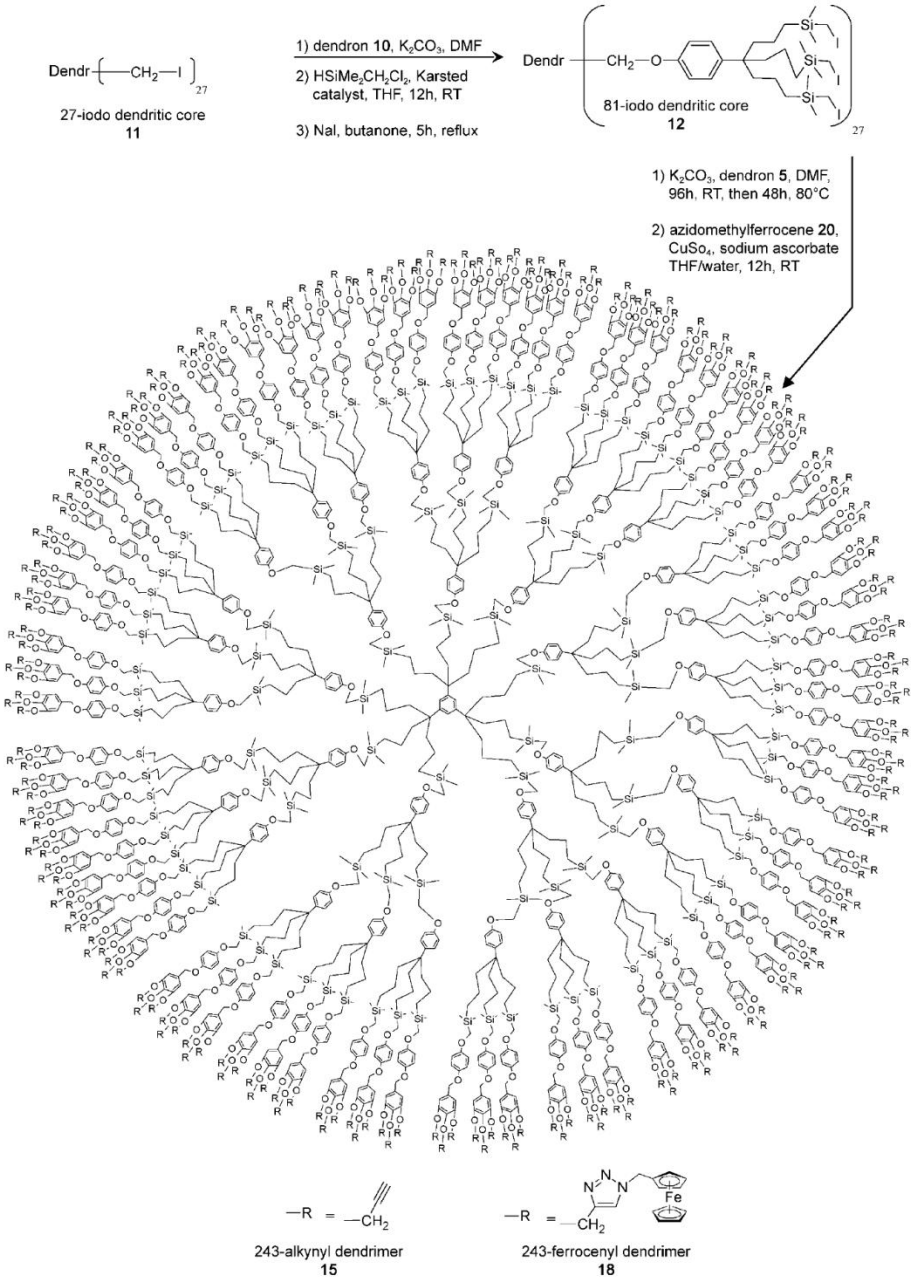

Scheme 4. Synthesis of the 243-alkynyl dendrimer **15** and 243-ferrocenyl dendrimer **18**. For the synthesis of **12**, see ref. [10].

gression from **16** to **18** (retention times of 20.18, 18.70, and 17.82 min, respectively) and the low polydispersities (1.01 to 1.03). The size progression was also shown by the DOSY NMR data (3.2, 3.8, and 4.2 nm, respectively).

Cyclic voltammetry and electrochemical sensing: The cyclic voltammogram of **16** shows a single reversible wave at 0.61 V versus the internal reference redox system $[Fe(\eta^5\text{-}C_5Me_5)_2]^{+/0}$ (Table 1).[15] This wave corresponds to the oxido-reduction of the ferrocenyl group and shows that all of the ferrocenyl groups of the dendrimer are equivalent and independent on the electrochemical time scale. The number of ferrocenyl units was determined to be 30 ± 3 for the 27-ferrocenyl dendrimer **16**, using the Bard–Anson

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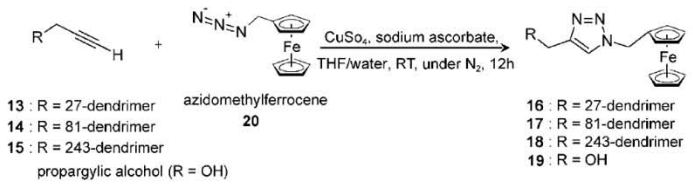

Scheme 5. "Click" reactions with azidomethylferrocene **20**.

Table 1. Electrochemical properties of the ferrocenyl CV waves for the three polyferrocenyl dendrimers **16**, **17**, and **18**.

	$E_{1/2}$ vs Fc*[a]	$E_{pa} - E_{pc}$ [mV]	I_{pc}/I_{pa}
27-Fc **16**[b]	0.610	30	3.80
81-Fc **17**[b]	0.600	0	1.90
243-Fc **18**[b]	0.595	0	2.00

[a] $E_{1/2}$ in V vs Fc* = $[Fe(\eta^5\text{-}C_5Me_5)_2]^{+/0}$ (average of the cathodic and anodic CV peaks). [b] Degassed solutions of the metallodendrimers in CH_2Cl_2; concentrations: 1.7×10^{-5} M for **16**, 5.8×10^{-6} M for **17**, and 1.9×10^{-6} M for **18**.

equation.[3b,16,17] This kind of calculation is precluded for compounds **17** and **18** by the adsorption of the dendrimers onto the electrode surface, because it yields excessively high results. Electrochemical recognition of both $H_2PO_4^-$ and ATP^{2-} was investigated. The interaction with HSO_4^- is much weaker than that with $H_2PO_4^-$, but the titration of HSO_4^- was nevertheless possible.[1]

Numerous studies by Beer et al. with endoreceptors[18] bearing one or more ferrocenyl groups have paved the way for the recognition of oxo-anions. Addition of $[n\text{Bu}_4\text{N}][H_2PO_4]$ to an electrochemical cell containing a solution of polyferrocenyl dendrimer (**16**, **17**, or **18**) in CH_2Cl_2 led to the appearance of a new wave at a potential less positive than the initial wave, the intensity of which decreased while that of the new wave increased (Figure 1). The equivalence point was reached when the initial wave was completely replaced by the new wave, as has previously been established for endoreceptors[18] and other ferrocenyl dendrimer structures.[12] Analysis of the CV waves using the square scheme has been rationalized by Echegoyen and Kaifer in a seminal article.[19]

We used this analysis to determine the ratio of apparent equilibrium constants $K_{(+)}$ and $K_{(0)}$ related to the strong interaction of the anion with the cationic ferrocenium form of the redox system, as well as with the neutral ferrocenyl form ($K \gg 1$). Only a rough estimate of $K_{(+)}/K_{(0)}$ and $K_{(+)}$ values could be obtained, because of the irreversible behaviour of the CVs of the dendrimers in the presence of $[n\text{Bu}_4\text{N}][H_2PO_4]$ and $[n\text{Bu}_4\text{N}]_2[ATP]$.

The electrochemical irreversibility is characterized by ($E_{pc}-E_{pa}$) values of 0.140 ± 0.010 V for compound **16**, under the conditions of Figure 2 at the end of the titration. This slow heterogeneous electron transfer between the electrode and the dendrimer redox sites is due to the very substantial structural transformation of the $H_2PO_4^-$/redox site ensemble in the course of electron transfer (in particular, tight ion pairs or

[1] A slightly positive dendritic effect (i.e., the variation in $E_{1/2}$ is larger for the dendrimer than for the monomer) is observed for the electrochemical recognition of the three oxo-anions by the dendrimer as compared to their recognition by the ferrocenyl monomer **19**.

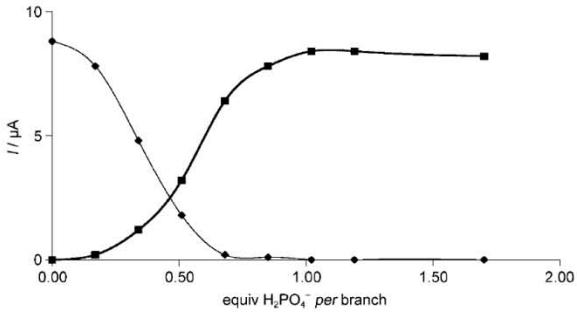

Figure 1. Titration of $[n\text{Bu}_4\text{N}][H_2PO_4]$ with the 81-alkynyl dendrimer **17** in CH_2Cl_2 at 20 °C by adding the salt of the ion to the dendrimer solution. Decrease of the intensity of the initial CV wave and increase of the intensity of the new CV wave vs. the number of equivalents of $[n\text{Bu}_4\text{N}][H_2PO_4]$ added per ferrocenyl branch. (See the supporting information for other titration curves).

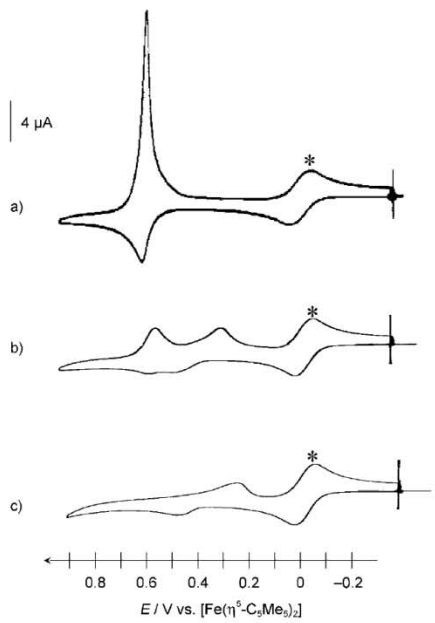

Figure 2. Cyclic voltammograms for the titration of $[n\text{Bu}_4\text{N}]_2[ATP]$ with the 27-ferrocenyl dendrimer **16** in CH_2Cl_2 at 20 °C by adding the salt of the ion to the dendrimer solution: a) before addition of $[n\text{Bu}_4\text{N}]_2[ATP]$, b) during titration of $[n\text{Bu}_4\text{N}]_2[ATP]$, and c) after addition of excess $[n\text{Bu}_4\text{N}]_2[ATP]$; * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

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aggregates are formed at the redox sites upon anodic oxidation in CH_2Cl_2; vide infra). The difference in $E_{1/2}$ values between the initial and the new wave (determined after addition of 0.5 equiv of $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$, in order to observe both waves at the same time) was found to be 0.210 ± 0.010 V. This corresponds to a ratio of apparent association constants ($K_{(+)}/K_{(0)}$) of 4200 ± 400 according to the Echegoyen–Kaifer model.[19]

$$\log(K_{(+)}/K_{(0)}) = \Delta E_{1/2}/0.058 \text{ at } 20\,^{\circ}\mathrm{C}$$

For ATP^{2-}, electrochemical recognition was also studied in CH_2Cl_2, and the observed trends closely followed those found for $H_2PO_4^-$. The addition of $[n\mathrm{Bu_4N}]_2[\mathrm{ATP}]$ to an electrochemical cell containing a solution of the 27-ferrocenyl dendrimer **16** in CH_2Cl_2 caused, as in the case of $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$, the appearance of a new wave at a potential less positive than the initial one. Indeed, the interaction of the anions with redox groups releases electron density, rendering oxidation of the ferrocene group easier. The intensity of the initial wave decreased, while that of the new wave increased (Figures 2 and 3). Thus, this is a case of a strong-

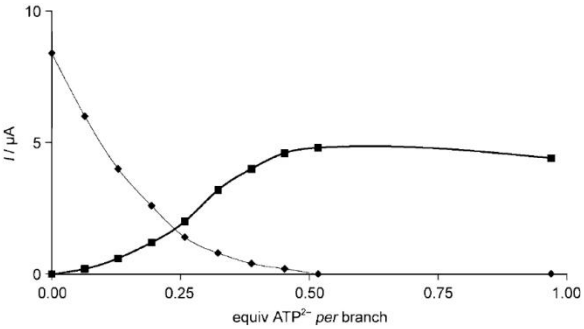

Figure 3. Titration of $[n\mathrm{Bu_4N}]_2[\mathrm{ATP}]$ with the 81-ferrocenyl dendrimer **17** in CH_2Cl_2 at 20 °C by adding the salt of the ion to the dendrimer solution. Decrease of the intensity of the initial CV wave and increase of the intensity of the new CV wave vs. the number of equivalents of $[n\mathrm{Bu_4N}]_2[\mathrm{ATP}]$ added per ferrocenyl branch (see Supporting Information for other titration curves).

type interaction that can be treated using the square scheme,[19] as with $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$. The difference in ferrocenyl redox potential between the initial wave and the new wave is of the same order of magnitude as with $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$, but slightly lower than for the latter (0.180 ± 0.010 V, i.e., 30 mV less than with $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$). The corresponding ratio of apparent association constants is $K_{(+)}/K_{(0)} = 1300 \pm 150$. The equivalence point is reached when 0.5 equiv of $[n\mathrm{Bu_4N}]_2[\mathrm{ATP}]$ has been added, which is in accord with the double negative charge of this anion. These strong interactions seen with $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$ and $[n\mathrm{Bu_4N}]_2[\mathrm{ATP}]$ are all the more remarkable as there is no conjugation between the triazole ring and the ferrocenyl group.

For $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$ in CH_2Cl_2, the interaction with the 27-ferrocenyl dendrimer **16** was indeed weak, but the titration and the recognition could nevertheless be carried out. The addition of $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$ to an electrochemical cell containing a solution of the dendrimer **16** in CH_2Cl_2 did not, however, lead to the appearance of a new wave, and only a shift of the CV wave towards a less positive potential was observed (Figures 4 and 5). The maximum shifts of 75 mV

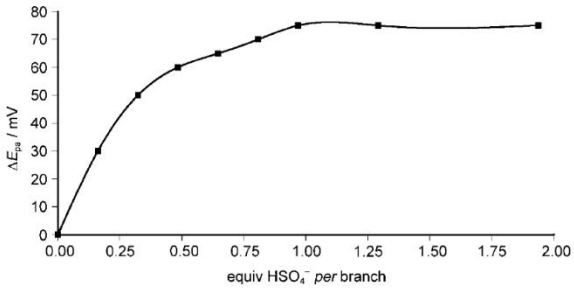

Figure 4. Titration of $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$ with the 27-ferrocenyl dendrimer **16** in CH_2Cl_2 at 20 °C by adding the salt of the ion to the dendrimer solution: shift of E_{pa} toward less positive potentials recorded by CV as a function of the number of equivalents of $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$ added per ferrocenyl branch.

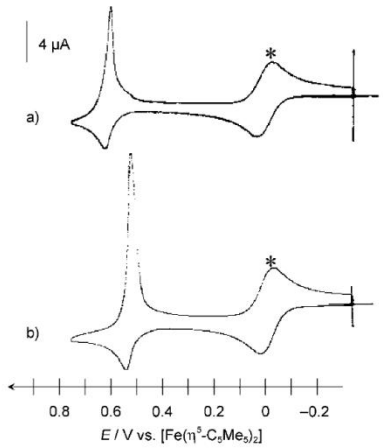

Figure 5. Cyclic voltammograms for the titration of $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$ with the 27-ferrocenyl dendrimer **16** in CH_2Cl_2 at 20 °C by adding the salt of the ion to the dendrimer solution: a) before addition of $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$, b) after addition of excess $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$; * internal reference: $[\mathrm{Fe}(\eta^5\text{-}\mathrm{C_5Me_5})_2]$.

for the anodic wave potential and 70 mV for the cathodic one were reached around the equivalence point, which allowed the titration of $[n\mathrm{Bu_4N}][\mathrm{HSO_4}]$. A further noteworthy feature was that a rather strong adsorption was observed throughout the titration. With $[n\mathrm{Bu_4N}][\mathrm{H_2PO_4}]$ and $[n\mathrm{Bu_4N}]_2[\mathrm{ATP}]$, the wave was clearly electrochemically irreversible during the titration. The absolute apparent associa-

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tion constant $K_{(+)}$ between compound **16** and the anion HSO_4^- could then be defined by:

$$\log K_{(+)}c = \Delta E_{1/2}/0.058 \text{ at } 20\,^{\circ}\text{C}$$

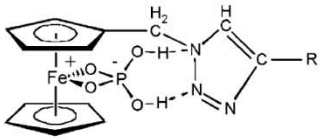
giving $K_{(+)} = (4 \pm 0.4) \times 10^4\ \text{L mol}^{-1}$. The same analyses with ATP^{2-} and $H_2PO_4^-$ were performed for the 81-ferrocenyl dendrimer **17** and for the 243-ferrocenyl dendrimer **18**. A slightly positive dendritic effect (i.e., an increase in the potential difference with increasing dendritic generation) was observed for $H_2PO_4^-$. The results are summarized in Table 2.

Table 2. Results of the electrochemical recognition of the oxo-anions using the three ferrocenyl dendrimers **16**, **17**, and **18** and the three modified Pt electrodes.

	$H_2PO_4^-$			ATP^{2-}		
	$E_{1/2}$[a] ($E_{pa}-E_{pc}$)	$\Delta E_{1/2}$[b]	$K_{(+)}/K_{(0)}$	$E_{1/2}$[a] ($E_{pa}-E_{pc}$)	$\Delta E_{1/2}$[b]	$K_{(+)}/K_{(0)}$
27-Fc **16** on Pt	–	–	–	0.410 (100)	0.200	2800
27-Fc **16**[c]	0.400 (140)	0.210	4200	0.430 (215)	0.180	1300
81-Fc **17** on Pt	–	–	–	0.390 (135)	0.210	4200
81-Fc **17**[c]	0.350 (75)	0.250	20400	0.420 (115)	0.180	1300
243-Fc **18** on Pt	–	–	–	0.375 (170)	0.220	6200
243-Fc **18**[c]	0.340 (85)	0.255	24900	0.415 (120)	0.180	1300

[a] $E_{1/2}$ in V vs $[Fe(\eta^5\text{-}C_5Me_5)_2]^{+/0}$ (average of the cathodic and anodic CV peaks), ($E_{pa}-E_{pc}$) in mV. [b] $\Delta E_{1/2}$ in V. [c] Degassed solutions of the metallodendrimers in CH_2Cl_2; concentrations: 1.7×10^{-5} M for **16**, 5.8×10^{-6} M for **17**, and 1.9×10^{-6} M for **18**.

It is important to notice that the recognition is as good here when the ferrocenyl unit is not conjugated with the triazolyl ring as when there is conjugation.[12d] A possible explanation is that the chelation of the positively charged iron atom in the oxidized ferrocenium form by the two $P-O^{-1/2}$ bonds of $H_2PO_4^-$ is stabilized by the chelating double H-bonding of the two dihydrogenphosphate $O-H^{\delta+}$ bonds with two neighboring nitrogen atoms of the triazole ring (see below). This discards the direct intramolecular ferrocenyl–triazole electronic interaction as being the most



important factor of the oxo-anion–ferrocenium interaction in the case of the "normal click" ferrocenyl dendrimers.[12d] This chelating double H-bonding does not exist in the case of HSO_4^-, which is responsible for the difference in strength of the interactions with $H_2PO_4^-$ and HSO_4^-, and this difference is larger in the presence of the nearby triazole ring than in its absence.[3b]

Fabrication of electrodes modified with the "click" dendrimers: The accessibility of modified electrodes[20] has also been explored. Each generation of polyferrocenyl dendrimer allows the fabrication of Pt electrodes with adsorbed dendrimer, but the capacity for strong adsorption on a Pt electrode increases with increasing generation (Tables 3 and 4). The first-generation dendrimer with 27 ferrocenyl groups does not adsorb well, whereas that with 243 ferrocenyl groups adsorbs very strongly and is resistant to washing the salt of ATP^{2-} or Pd^{2+} with CH_2Cl_2 (Table 4 and Figure 6).

The modified electrodes were compared after 50 adsorption cycles and after 200 adsorption cycles (see the Experimental Section for details of the experimental procedure). The intensity obtained, the stability at various scan rates (Figure 6), and the recognition of $[Pd(MeCN)_4](BF_4)_2$[2] (Figure 7) and $[nBu_4N]_2[ATP]$ (Figure 8) were explored (Table 2 and Table 3). The robustness of the various modified electrodes was tested by measuring the intensity before and after operation for 30 min (about 200 cycles) with a fresh solution of 0.1 M $[nBu_4N][PF_6]$ in CH_2Cl_2 (Table 4). The electrode modified with **18** proved to be an excellent, re-usable redox sensor.

Table 3. Results of the electrochemical recognition of Pd^{2+} using the three ferrocenyl dendrimers **16**, **17**, and **18** and the three modified Pt electrodes.

	$E_{1/2}$ ($E_{pa}-E_{pc}$)[a] Before addition of Pd^{2+}	$E_{1/2}$ ($E_{pa}-E_{pc}$)[a] After addition of excess Pd^{2+}	$\Delta E_{1/2}$ [mV]	$K_{(+)}$
27-Fc **16** on Pt	0.610 (0)	0.645 (30)	−35	–
27-Fc **16**[b]	0.610 (30)	0.650 (35)	−40[c]	10700
81-Fc **17** on Pt	0.600 (0)	0.650 (30)	−50	–
81-Fc **17**[b]	0.600 (0)	0.650 (20)	−50	15500
243-Fc **18** on Pt	0.595 (0)	0.660 (40)	−65	–
243-Fc **18**[b]	0.595 (0)	0.660 (0)	−65	28600

[a] $E_{1/2}$ in V vs $[Fe(\eta^5\text{-}C_5Me_5)_2]^{+/0}$ (average of the cathodic and anodic CV peaks), ($E_{pa}-E_{pc}$) in mV. [b] Degassed solutions of the metallodendrimers in CH_2Cl_2; concentrations: 1.7×10^{-5} M for **16**, 5.8×10^{-6} M for **17**, and 1.9×10^{-6} M for **18**. [c] Shift of 40 mV toward more positive potential, in contrast to what is observed for $[nBu_4N][HSO_4]$ (shift toward less positive potential).

Finally, electrochemical recognition of $[Pd(MeCN)_4][BF_4]_2$ by the dendrimers (Figure 9) was also found to be possible but, as with $[nBu_4N][HSO_4]$, was weak with only a CV wave shift rather than the appearance of a new wave. Moreover, the CV waves remained fully chemically and electrochemi-

[2] The addition of $[Pd(MeCN)_4](BF_4)_2$ to both the dendrimer solution and the modified Pt electrode provokes only a shift of the CV wave.

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Table 4. Robustness of the various modified Pt electrodes.

	I [μA] after 200 cycles adsorption	I [μA] after 200 cycles in CH_2Cl_2[a]	I [μA] after 50 cycles adsorption	I [μA] after recycling[b]
27-Fc **16** on Pt	11.6	7.8	6.4	1.7
81-Fc **17** on Pt	26.6	18.5	11.6	7.4
243-Fc **18** on Pt	40.2	22.6	11.8	8.2

[a] On the modified Pt electrode obtained after 200 adsorption cycles (see Experimental Section). [b] Intensity obtained for the electrode after 50 adsorption cycles (see the Experimental Section) after titrating ATP^{2-} and washing with CH_2Cl_2.

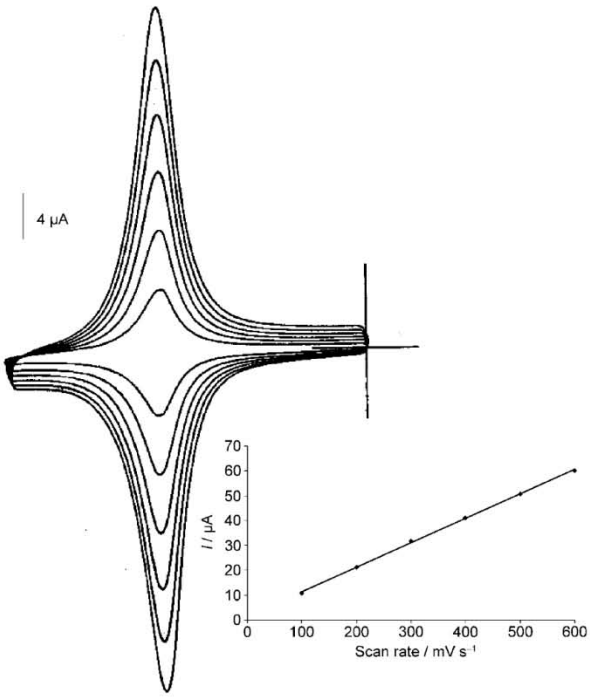

Figure 6. Stability of the Pt electrode with adsorbed 243-ferrocenyl dendrimer **18** for various scan rates (from smaller to larger at 100, 200, 300, 400, 500, and 600 mV s^{-1}) observed by cyclic voltammetry.

cally reversible without adsorption. This is most likely indicative of a weak ionic interaction. Interestingly, this is in sharp contrast with the previously reported "normal click" ferrocenyl dendrimers, which provided a strong interaction. This is obviously due to the fact that the previous click ferrocenyl dendrimers were conjugated whereas the present ones are not.

Conclusion

New, easily prepared tris-alkynyl dendrons have been synthesized from commercial precursors. The use of these dendrons in dendrimer synthesis has been exemplified by their efficient Williamson reactions with three polyiodo dendritic cores yielding a 27-alkynyl, an 81-alkynyl, and a 243-alkynyl dendrimer.

The "click" reaction of these dendrimers with azidomethylferrocene yields the new 27-ferrocenyl, 81-ferrocenyl, and 243-ferrocenyl dendrimers, which are capable of electrochemically recognizing oxo-anions such as HSO_4^-, $H_2PO_4^-$, and ATP^{2-} as well as the Pd^{2+} cation.

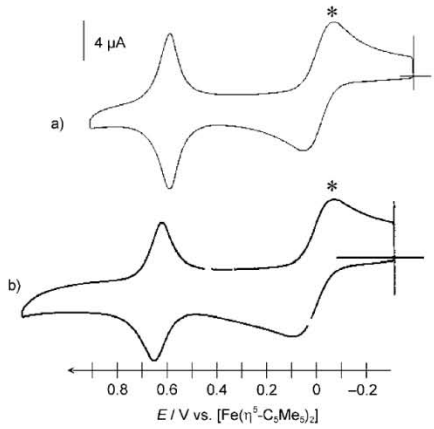

Figure 7. Cyclic voltammograms for the recognition of Pd^{2+} by the modified Pt electrode with adsorbed 243-ferrocenyl dendrimer **18** in CH_2Cl_2 at 20 °C: a) before addition of $[Pd(MeCN)_4](BF_4)_2$, b) after addition of excess $[Pd(MeCN)_4](BF_4)_2$; * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$. Note the flattening of the CV of the internal reference (for discussion, see ref. [15b]).

Recognition of the phosphorus-containing oxo-anions results from a strong interaction with the ferrocenyl redox system that is accentuated by the presence of the triazole ring, probably due to double H-bonding to the N atoms. On the other hand, the interactions with HSO_4^- and Pd^{2+} are weak, but nevertheless allow titrations.

These three dendrimers form modified Pt electrodes, which are increasingly robust with increasing size of the dendrimer and allow the sensing of ATP^{2-} better than in solution. A positive dendritic effect is obtained with the modified electrodes, whereas this is not the case in solution. The described access to such large "click" dendrimers represents a significant advance, since it allows the preparation of modified electrodes that could not be prepared with the previous series of "click" ferrocenyl dendrimers.

Prospective uses include the possibility of applying this Williamson reaction to our larger polyiodo dendrimers and of using the 1,2,3-triazole dendritic rings as ligands for supramolecular catalysis applications using dendrimer-stabilized nanoparticles.

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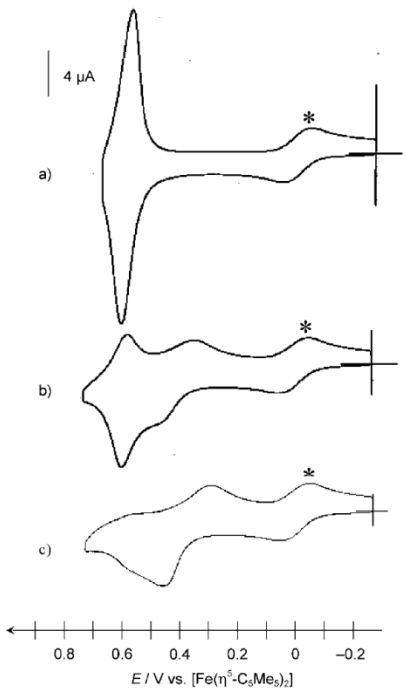

Figure 8. Cyclic voltammograms for the titration of $[n\mathrm{Bu}_4\mathrm{N}]_2[\mathrm{ATP}]$ by the modified Pt electrode with adsorbed 243-ferrocenyl dendrimer **18** in CH_2Cl_2 at 20 °C: a) before addition of $[n\mathrm{Bu}_4\mathrm{N}]_2[\mathrm{ATP}]$, b) during titration of $[n\mathrm{Bu}_4\mathrm{N}]_2[\mathrm{ATP}]$, and c) after addition of excess $[n\mathrm{Bu}_4\mathrm{N}]_2[\mathrm{ATP}]$; * internal reference: $[\mathrm{Fe}(\eta^5\text{-}C_5Me_5)_2]$.

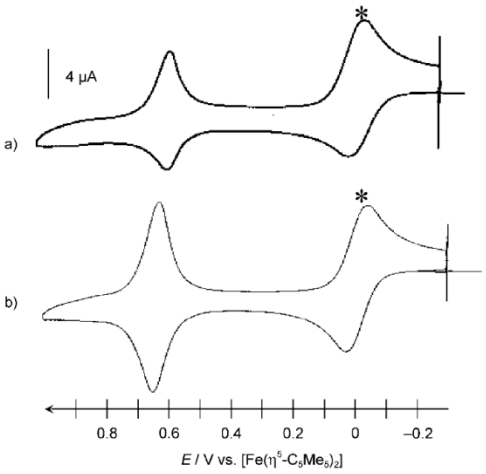

Figure 9. Cyclic voltammograms for the titration of $[\mathrm{Pd(MeCN)_4}](BF_4)_2$ with the 81-ferrocenyl dendrimer **17** in CH_2Cl_2 at 20 °C by adding the salt of the ion to the dendrimer solution: a) before addition of $[\mathrm{Pd(MeCN)_4}](BF_4)_2$, b) after addition of excess $[\mathrm{Pd(MeCN)_4}](BF_4)_2$; * internal reference: $[\mathrm{Fe}(\eta^5\text{-}C_5Me_5)_2]$.

Experimental Section

General: All operations were performed under nitrogen atmosphere using standard Schlenk techniques. Prior to use, THF was dried over sodium benzophenone ketyl and freshly distilled under a nitrogen atmosphere. Whenever mentioned, CH_2Cl_2 was dried over calcium hydride and freshly distilled under a nitrogen atmosphere. All other reagents were obtained from commercial sources and were used without further purification. All glassware was previously dried in an oven and cooled under a nitrogen flow.

Physical measurements: ^{1}H NMR spectra were recorded at 25 °C on a Bruker AC 250 (250 MHz), a Bruker Advance 300 (300 MHz), or a Bruker DPX 400 (400 MHz) spectrometer. ^{13}C NMR spectra were recorded in pulse FT mode on a Bruker AC 300 spectrometer at 75.50 MHz. ^{29}Si NMR spectra were recorded on a Bruker AC 300 spectrometer at 59.6 MHz. All chemical shifts are reported in parts per million (δ, ppm) with reference to $SiMe_4$ (TMS). Mass spectra were obtained at the CESAMO, Université Bordeaux I, on a PerSeptive Biosystems Voyager Elite (Framingham, MA) time-of-flight mass spectrometer. This instrument is equipped with a nitrogen laser (337 nm), a delayed extraction, and a reflector. It was operated at an accelerating potential of 20 kV in both linear and reflection modes. The mass spectra shown represent an average over 256 consecutive laser shots (3 Hz repetition rate). Peptides were used to calibrate the mass scale using the two-points calibration software 3.07.1 from PerSeptive Biosystems. Elemental analyses were performed at the Center of microanalysis of the CNRS, Lyon Villeurbanne, France. All electrochemical measurements were performed in degassed CH_2Cl_2 at 20 °C. Supporting electrolyte: 0.1 M $[n\mathrm{Bu}_4\mathrm{N}][PF_6]$; working and counter electrode: Pt; quasi-reference electrode: Ag; internal reference: $[\mathrm{Fe}(\eta^5\text{-}C_5Me_5)_2]^{+/0}$;[15] scan rate: 0.200 V s^{-1}.

Modification of Pt electrodes with polyferrocenyl dendrimers 16, 17, and 18: A platinum electrode (Sodimel, Pt 30) was immersed in 10 % aqueous HNO_3 for 3 h, then rinsed with distilled water, dried in air, and polished using cerium oxide powder (5 MU). The dendrimers **16**, **17**, and **18** were electrodeposited onto such platinum-disk electrodes (A = 0.0078 cm^2) from degassed solutions of metallodendrimer (1.7×10^{-5} M (**16**), 5.8×10^{-6} M (**17**), and 1.9×10^{-6} M (**18**), in order to obtain the same concentration in ferrocenyl groups) and $[n\mathrm{Bu}_4\mathrm{N}][PF_6]$ (0.1 M) in CH_2Cl_2 by continuous scanning (0.20 V s^{-1}) up to 50 cycles or up to 200 cycles between 0.0 and 0.9 V versus $[\mathrm{Fe}(\eta^5\text{-}C_5Me_5)_2]^{+/0}$. The coated electrodes were washed with CH_2Cl_2 in order to remove the solution of material and dried in air. The modified electrodes were characterized by CV in freshly distilled CH_2Cl_2 containing only the supporting electrolyte. They showed a single symmetrical CV wave, and the linear relationship between the peak current and the potential sweep rate was verified. The surface coverage Γ (mol cm^{-2}) by the ferrocenyl dendrimers **16**, **17**, and **18** was determined from the integrated charge of the CV wave, $\Gamma = Q/nFA$, where Q is the charge, n is the number of electrons transferred, F is the Faraday constant, and A is the area. For example, the surface coverage for the electrode modified with **16** was 3.62×10^{-9} mol cm^{-2} (ferrocenyl sites), corresponding to 1.34×10^{-10} mol cm^{-2} of **16** after 50 adsorption cycles, and 6.23×10^{-9} mol cm^{-2} (ferrocenyl sites), corresponding to 2.31×10^{-10} mol cm^{-2} of **16** after 200 cycles (Table 5).

Synthesis of methyl 3,4,5-tris(prop-2-yn-1-yloxy)benzoate (2): A mixture of methyl 3,4,5-trihydroxybenzoate **1** (10 g, 0.0543 mol) and propargyl bromide (80 % in toluene) (21 mL, 0.19 mol) was stirred for 10 min in degassed acetone. K_2CO_3 (50 g, 0.362 mol) was then added, and the reaction was carried out overnight under reflux. Thereafter, the solvent was removed from the resulting brown solution by rotary evaporation. The solid was redissolved in CH_2Cl_2 (200 mL), and this solution was dried over anhydrous magnesium sulfate and filtered. The solvent was removed by rotary evaporation. The product **2** was obtained as a slightly yellow oil that recrystallized (15.1 g, 93 %). M.p. 89.4 °C; ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS): δ = 7.44 (s, 2 H; H_{Ar}), 4.80 (d, ^4J(H,H) = 2.3 Hz, 2 H; p-O-CH_2-C≡C), 4.78 (d, ^4J(H,H) = 2.3 Hz, 4 H; m-O-CH_2-C≡C), 3.89 (s, 3 H; CH_3-O), 2.53 (t, ^4J(H,H) = 2.3 Hz, 2 H; C≡C-H), 2.45 ppm (t, ^4J(H,H) = 2.3 Hz, 1 H; C≡C-H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C, TMS): δ = 166.23, 151.27, 141.07, 125.74 (quat. C_{Ar}), 109.84 (C_{Ar}-H), 78.68, 77.94,

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Table 5. Electrode surface coverage (Γ in mol cm^{-2}) for the various modified Pt electrodes.

	Γ [mol cm^{-2}][a] (ferrocenyl sites)	Γ [mol cm^{-2}][a]	Γ [mol cm^{-2}][b] (ferrocenyl sites)	Γ [mol cm^{-2}][b]
27-Fc **16** on Pt	3.62×10^{-9}	1.34×10^{-10}	6.23×10^{-9}	2.31×10^{-10}
81-Fc **17** on Pt	6.56×10^{-9}	8.10×10^{-11}	2.13×10^{-8}	2.63×10^{-10}
243-Fc **18** on Pt	7.46×10^{-9}	3.07×10^{-11}	3.75×10^{-8}	1.54×10^{-10}

[a] On the modified Pt electrode obtained after 50 adsorption cycles. [b] On the modified Pt electrode obtained after 200 adsorption cycles.

76.22, 75.60 (*C*≡C-H, C≡*C*-H), 60.30, 57.05 (O-*C*H$_2$-C≡C-H), 52.35 ppm (O-*C*H$_3$); IR: $\tilde{\nu}=1724$ (C=O), 2121 (C≡C), 3274 cm^{-1} (C≡C-H); MS: *m/z*: 619 [2*M*+Na$^+$], 321 [*M*+Na$^+$], 299 [*M*+H$^+$].

Synthesis of [3,4,5-tris(prop-2-yn-1-yloxy)phenyl]methanol (3): LiAlH$_4$ (19.3 g, 0.508 mol) was added to dry THF and this suspension was cooled to 0°C. A solution of methyl 3,4,5-tris(prop-2-yn-1-yloxy)benzoate **2** (15.1 g, 0.0507 mol) in dry THF was then added dropwise. The mixture was stirred at 0°C for 1 h, then at room temperature for a further 5 h. Thereafter, excess LiAlH$_4$ was quenched with water, and the solution was concentrated by rotary evaporation. The concentrate was extracted with CH$_2$Cl$_2$ (3×200 mL), and the combined organic layers were dried over anhydrous magnesium sulfate and filtered. The solvent was removed by rotary evaporation. The product **3** was obtained as a white powder (9.6 g, 70%). M.p. 103.0°C; ^{1}H NMR (300 MHz, CDCl$_3$, 25°C, TMS): $\delta=$ 6.78 (s, 2H; H_{Ar}), 4.76 (d, ^4J(H,H)=2.4 Hz, 4H; *m*-O-C*H*$_2$-C≡C), 4.72 (d, ^4J(H,H)=2.1 Hz, 2H; *p*-O-C*H*$_2$-C≡C), 4.65 (s, ^3J(H,H)=6.1 Hz, 2H; HO-C*H*$_2$-C$_{Ar}$), 2.51 (t, ^4J(H,H)=2.4 Hz, 2H; C≡C-*H*), 2.46 (t, ^4J(H,H)= 2.1 Hz, 1H; C≡C-*H*), 1.73 ppm (t, ^3J(H,H)=6.1 Hz, 1H; O*H*); ^{13}C NMR (75 MHz, CDCl$_3$, 25°C, TMS): $\delta=$151.59, 145.31, 137.38 (quat. C_{Ar}), 106.88 (C_{Ar}-H), 79.17, 78.51, 75.91, 75.29 (*C*≡C-H, C≡*C*-H), 64.93 (HO-*C*H$_2$), 60.27, 56.94 ppm (O-*C*H$_2$-C≡C-H); IR: $\tilde{\nu}=2121$ (C≡C), 3294 (C≡C-H), 3538 cm^{-1} (O-H); MS: *m/z*: 563 [2*M*+Na$^+$], 293 [*M*+Na$^+$], 271 [*M*+H$^+$].

Synthesis of 5-(bromomethyl)-1,2,3-tris(prop-2-yn-1-yloxy)benzene (4): Compound **3** (9.6 g, 0.0356 mol) and PBr$_3$ (3.35 mL, 0.0356 mol) were stirred together in CH$_2$Cl$_2$ (dried over calcium hydride and freshly distilled) for 12 h at room temperature. Water was then added to quench the excess PBr$_3$. The mixture was concentrated by rotary evaporation and extracted with CH$_2$Cl$_2$ (3×200 mL). The combined organic layers were then dried over anhydrous magnesium sulfate and filtered. The solvent was removed by rotary evaporation to give compound **4** as a slightly yellow oil that recrystallized (9.2 g, 77%). M.p. 63.7°C; ^{1}H NMR (300 MHz, CDCl$_3$, 25°C, TMS): $\delta=6.75$ (s, 2H; H_{Ar}), 4.71 (d, ^4J(H,H)= 2.6 Hz, 4H; *m*-O-C*H*$_2$-C≡C), 4.67 (d, ^4J(H,H)=2.2 Hz, 2H; *p*-O-C*H*$_2$-C≡C), 4.41 (s, 2H; Br-C*H*$_2$-C$_{Ar}$), 2.52 (t, ^4J(H,H)=2.6 Hz, 2H; C≡C-*H*), 2.45 ppm (t, ^4J(H,H)=2.2 Hz, 1H; C≡C-*H*); ^{13}C NMR (75 MHz, CDCl$_3$, 25°C, TMS): $\delta=150.54$, 136.16, 132.75 (quat. C_{Ar}), 108.42 (C_{Ar}-H), 78.06, 77.26, 75.19, 74.45 (*C*≡C-H, C≡*C*-H), 59.31, 56.04 (O-*C*H$_2$-C≡C-H), 52.61 ppm (*C*H$_2$-Br); IR: $\tilde{\nu}=2120$ cm^{-1} (C≡C), 3290.6 cm^{-1} (C≡C-H); MS: *m/z*: 355, 357 [*M*+Na$^+$], 333, 335 [*M*+H$^+$].

Synthesis of the "trialkyne-phenol" dendron 4-{[3,4,5-tris(prop-2-yn-1-yloxy)benzyl]oxy}phenol (5): Hydroquinone (0.99 g, 9 mmol) and K$_2$CO$_3$ (0.89 g, 6.5 mmol) were stirred together at 80°C in dry dimethylformamide (DMF; 250 mL), and then a solution of compound **4** (0.5 g, 1.5 mmol) in DMF (100 mL) was added dropwise over a period of 1 h. The reaction was carried out for 18 h at 80°C. The DMF was then removed in vacuo and the residue was partitioned between water and CH$_2$Cl$_2$. The organic layer was concentrated in vacuo and chromatographed on silica gel, eluting first with CH$_2$Cl$_2$ and then with CH$_2$Cl$_2$/MeOH 9:1. The obtained oil was dissolved in the minimum volume of CH$_2$Cl$_2$ and precipitated using excess pentane. The "trialkyne-phenol" dendron **5** was obtained as an off-white powder (0.5 g, 92%). M.p. 76.5°C; ^{1}H NMR (300 MHz, CDCl$_3$, 25°C, TMS): $\delta=6.87$–6.74 (m, 6H; H_{Ar}), 4.95 (s, 2H; O-C*H*$_2$-C$_{Ar}$), 4.76 (d, ^4J(H,H)=1.9 Hz, 4H; *m*-O-C*H*$_2$-C≡C), 4.73 (d, ^4J(H,H)=1.9 Hz, 2H; *p*-O-C*H*$_2$-C≡C), 2.50–2.45 ppm (m, 3H; C≡C-*H*); ^{13}C NMR (75 MHz, CDCl$_3$, 25°C, TMS): $\delta=152.67$, 151.67, 149.92, 136.63, 133.53 (quat. C_{Ar}), 116.14, 116.08, 107.74 (C_{Ar}-H), 79.14, 78.37, 75.98, 75.34 (*C*≡C-H, C≡*C*-H), 70.65 (C$_{Ar}$-*C*H$_2$-O), 60.36, 57.04 ppm (O-*C*H$_2$-C≡C-H); IR: $\tilde{\nu}=$ 2123 (C≡C), 3283 (C≡C-H), 3500 cm^{-1} (O-H); MS: *m/z*: 747 [2*M*+Na$^+$], 385 [*M*+Na$^+$]; elemental analysis calcd (%) for C$_{22}$H$_{18}$O$_5$: C 72.91, H 5.01, O 22.08; found: C 72.39, H 4.99, O 22.25.

General procedure for the synthesis of the polyalkynyl dendrimers: A mixture of poly-iodomethyl(dimethyl)silyl dendritic core (1 equiv), phenol dendron **5** (2 equiv per branch), and K$_2$CO$_3$ (5 equiv per branch) was stirred in dry DMF at room temperature (1 d for the 27-iodo, 2 d for the 81-iodo, and 4 d for the 243-iodo dendritic core) under nitrogen atmosphere. The mixture was then stirred for a further 48 h at 80°C. Thereafter, the solvent was removed in vacuo, and the residue was redissolved in CH$_2$Cl$_2$. This solution was filtered through silica and concentrated by rotary evaporation. The product was precipitated by treating the concentrated solution with excess MeOH three times to give the desired polyalkynyl dendrimer as an off-white gum in yields of 67, 61, and 59%, respectively.

27-Alkynyl dendrimer 13: C$_{261}$H$_{282}$O$_{45}$Si$_9$; M_W 4391.89 g mol^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$, 25°C, TMS): $\delta=7.00$–6.80 (m, 57H; H_{Ar}), 4.88 (s, 18H; O-C*H*$_2$-C$_{Ar}$), 4.74 (s, 54H; O-C*H*$_2$-C≡C), 3.46 (s, 18H; Si-C*H*$_2$-O), 2.49 (s, 18H; C≡C-*H*), 2.47 (s, 27H; C≡C-*H*), 1.66 (s, 18H; C*H*$_2$-CH$_2$-CH$_2$-Si), 1.15 (s, 18H; CH$_2$-C*H*$_2$-CH$_2$-Si), 0.60 (s, 18H; CH$_2$-CH$_2$-C*H*$_2$-Si), 0.05 ppm (s, 54H, Si-C*H*$_3$); ^{13}C NMR (63 MHz, CDCl$_3$, 25°C, TMS): $\delta=$ 156.46, 152.85, 152.03, 146.19, 136.98, 133.91 (quat. C_{Ar}), 116.45, 116.08, 115.14, 108.04 (C_{Ar}-H), 79.55, 78.83, 76.34, 75.69 (*C*≡C-H, C≡*C*-H), 70.91 (C$_{Ar}$-*C*H$_2$-O), 61.25 (Si-*C*H$_2$-O), 60.72, 57.37 (O-*C*H$_2$-C≡C-H), 44.29 (quat. *C*), 42.36 (*C*H$_2$-CH$_2$-CH$_2$-Si), 18.24 (CH$_2$-*C*H$_2$-CH$_2$-Si), 14.98 (CH$_2$-CH$_2$-*C*H$_2$-Si), −4.08 ppm (Si-*C*H$_3$); ^{29}Si NMR (60 MHz, CDCl$_3$, 25°C, TMS): the spectrum showed only one peak at $\delta=0.85$ ppm (all the branches had reacted); IR: $\tilde{\nu}=2122$ (C≡C), 3291 cm^{-1} (C≡C-H); MALDI-TOF: *m/z*: calcd for 4415.7; found: 4415.1 [*M*+Na$^+$]; elemental analysis calcd (%) for C$_{261}$H$_{282}$O$_{45}$Si$_9$: C 71.38, H 6.47; found: C 70.41, H 6.30; DOSY NMR gave $D=2.77\times10^{-10}$ m^2 s^{-1} in chloroform at 25°C, which corresponds to a size of 4.1 nm; SEC showed the low polydispersity (1.02) and the size progression for the three alkynyl dendrimers.

81-Alkynyl dendrimer 14: C$_{882}$H$_{1002}$O$_{144}$Si$_{36}$; M_W 14918.46 g mol^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$, 25°C, TMS): $\delta=7.20$–6.80 (m, 201H; H_{Ar}), 4.90 (s, 54H; O-C*H*$_2$-C$_{Ar}$), 4.74 (s, 162H; O-C*H*$_2$-C≡C), 3.57 (s, 18H; inner Si-C*H*$_2$-O), 3.48 (s, 54H; outer Si-C*H*$_2$-O), 2.50 (s, 81H; C≡C-*H*), 1.65 (s, 72H; C*H*$_2$-CH$_2$-CH$_2$-Si), 1.16 (s, 72H; CH$_2$-C*H*$_2$-CH$_2$-Si), 0.59 (s, 72H; CH$_2$-CH$_2$-C*H*$_2$-Si), 0.12 (s, 54H; inner Si-C*H*$_3$), 0.05 ppm (s, 162H; outer Si-C*H*$_3$); ^{13}C NMR (75 MHz, CDCl$_3$, 25°C, TMS): $\delta=158.00$, 155.04, 151.41, 150.60, 144.76, 138.26, 135.58, 132.53 (quat. C_{Ar}), 126.14, 117.01, 114.70, 113.76, 112.38, 106.68 (C_{Ar}-H), 78.17, 77.44, 74.98, 74.34 (*C*≡C-H, C≡*C*-H), 69.50 (C$_{Ar}$-*C*H$_2$-O), 59.89, 59.27, 59.07, 55.98 (O-*C*H$_2$-C≡C-H, Si-*C*H$_2$-O), 42.00 (C_{quat}), 40.98 (*C*H$_2$-CH$_2$-CH$_2$-Si), 16.61 (CH$_2$-*C*H$_2$-CH$_2$-Si), 13.53 (CH$_2$-CH$_2$-*C*H$_2$-Si), −5.44, −5.60 ppm (Si-*C*H$_3$); ^{29}Si NMR (60 MHz, CDCl$_3$, 25°C, TMS): the spectrum showed only one peak at $\delta=0.793$ ppm (all the branches had reacted); IR: $\tilde{\nu}=2122$ (C≡C), 3292 cm^{-1} (C≡C-H); elemental analysis calcd (%) for C$_{882}$H$_{1002}$O$_{144}$Si$_{36}$: C 71.01, H 6.77; found: C 70.51, H 7.28; DOSY NMR gave $D=2.41\times10^{-10}$ m^2 s^{-1} in chloroform at 25°C, which corresponds to a size of 4.8 nm; DLS was indicative of only one population at a size of 6.2±0.2 nm; SEC showed the low polydispersity (1.02) and the size progression for the three alkynyl dendrimers.

243-Alkynyl dendrimer 15: C$_{2745}$H$_{3162}$O$_{441}$Si$_{117}$; M_W 46498.43 g mol^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$, 25°C, TMS): $\delta=7.14$–6.75 (m, 633H; H_{Ar}) 4.84 (s, 162H; O-C*H*$_2$-C$_{Ar}$), 4.69 (s, 486H; O-C*H*$_2$-C≡C), 3.50 (s, 72H; inner Si-C*H*$_2$-O), 3.42 (s, 162H; outer Si-C*H*$_2$-O), 2.47–2.43 (m, 243H; C≡C-*H*), 1.61 (s, 234H; C*H*$_2$-CH$_2$-CH$_2$-Si), 1.11 (s, 234H; CH$_2$-C*H*$_2$-CH$_2$-Si), 0.54 (s, 234H; CH$_2$-CH$_2$-C*H*$_2$-Si), 0.06 (s, 216H; inner Si-C*H*$_3$), 0.01 ppm (s, 486H; outer Si-C*H*$_3$); ^{13}C NMR (75.5 MHz, CDCl$_3$, 25°C,

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TMS): $\delta = 159.05$, 156.10, 152.49, 151.69, 139.33, 136.69, 133.58 (quat. C_{Ar}), 127.21, 115.57, 114.83, 113.46, 107.76 (C_{Ar}-H), 79.24, 78.51, 76.04, 75.37 (*C*≡C-H, C≡*C*-H), 70.55 (C_{Ar}-*C*H$_2$-O), 60.92, 60.35, 60.15, 57.06 (O-*C*H$_2$-C≡C-H, Si-*C*H$_2$-O), 43.06 (quat. *C*), 42.09 (*C*H$_2$-CH$_2$-CH$_2$-Si), 17.71 (CH$_2$-*C*H$_2$-CH$_2$-Si), 14.62 (CH$_2$-CH$_2$-*C*H$_2$-Si), −4.51 ppm (Si-*C*H$_3$); ^{29}Si NMR (59.6 MHz, $CDCl_3$, 25 °C, TMS): the spectrum showed only one peak at $\delta = 0.792$ ppm (all the branches have reacted); IR: $\tilde{\nu} = 2122$ (C≡C), 3293 cm^{-1} (C≡C-H); DOSY NMR gave $D = 2.35 \times 10^{-10}$ m^{2}s^{-1} in chloroform at 25 °C, which corresponds to a size of 4.9 nm; DLS was indicative of only one population at a size of 6.6 ± 0.2 nm; SEC showed the low polydispersity (1.02) and the size progression for the three alkynyl dendrimers.

Second procedure for the synthesis of the 27-alkynyl dendrimer 13: The nona-chloromethyl(dimethyl)silyl dendrimer **8** (0.1 g, 0.069 mmol), sodium iodide (0.1 g, 0.67 mmol), and the phenol dendron **5** (0.45 g, 1.24 mmol) were stirred in DMF at 80 °C for two days and then for a further day at room temperature. The DMF was then removed in vacuo. The residue was redissolved in CH_2Cl_2 and the product was precipitated with excess MeOH to give the 27-propargyl dendrimer, **10**, as an off-white gum (0.21 g, 70 %). The spectroscopic data were identical to those obtained in the first synthesis (vide supra).

General procedure for the "click" coupling: The polyalkynyl dendrimer (1 equiv) and azidomethylferrocene **20** (2 equiv per branch) were dissolved in THF (30 mL). Copper(II) sulfate pentahydrate (4 equiv per branch) was then added with a small amount of water (20 mL), and the mixture was stirred and heated until complete dissolution. Sodium ascorbate (8 equiv per branch) was dissolved in water (10 mL) and this solution was added dropwise to the mixture. The resulting mixture was stirred overnight at room temperature under a nitrogen atmosphere. It was then concentrated by rotary evaporation and the residue was partitioned between CH_2Cl_2 and aqueous ammonia solution. The organic layer was washed with water, dried over anhydrous magnesium sulfate, filtered, and concentrated by rotary evaporation. The residue was purified by flash column chromatography, eluting first with CH_2Cl_2 and then with CH_2Cl_2/MeOH 9:1, to yield the desired dendrimers as yellow powders in yields of 72, 70, and 69 %, respectively.

27-Ferrocenyl dendrimer 16: $C_{558}Fe_{27}H_{579}N_{81}O_{45}Si_9$; MW 10 900.88 g mol^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS): $\delta = 7.62$, 7.60 (s, 27 H; $H_{triazole}$), 7.12–6.66 (m, 57 H; H_{Ar}), 5.24–5.05 (m, 108 H; $C_{triazole}$-C*H*$_2$-$C_{ferrocene}$, $C_{triazole}$-C*H*$_2$-O), 4.72 (s, 18 H; C_{Ar}-C*H*$_2$-O), 4.27–4.13 (m, 243 H; $C_{ferrocene}$-*H*), 3.48 (s, 18 H; Si-C*H*$_2$-O), 1.68 (s, 18 H; C*H*$_2$-CH$_2$-CH$_2$-Si), 1.15 (s, 18 H; CH$_2$-C*H*$_2$-CH$_2$-Si), 0.60 (s, 18 H; CH$_2$-CH$_2$-C*H*$_2$-Si), 0.05 ppm (s, 54 H; Si-C*H*$_3$); ^{13}C NMR (63 MHz, $CDCl_3$, 25 °C, TMS): $\delta =$ 156.44, 152.82, 152.58 (quat. C_{Ar}), 146.62 (core quat. C_{Ar}), 144.72, 143.98 (quat. $C_{triazole}$), 137.10, 133.84 (quat. C_{Ar}), 123.77, 123.28 ($C_{triazole}$-H), 116.38, 115.88 (C_{Ar}-H), 115.19 (core C_{Ar}-H), 107.26 (C_{Ar}-H), 81.80, 81.48 (quat. $C_{ferrocene}$), 72.58, 70.73, 69.30, 69.14, 66.67, 66.01 ($C_{ferrocene}$-H), 63.41, 63.36 ($C_{triazole}$-*C*H$_2$-O), 61.27 (Si-*C*H$_2$-O), 50.40, 50.24 ($C_{ferrocene}$-*C*H$_2$-N), 44.31 (C_{quat}), 42.35 (*C*H$_2$-CH$_2$-CH$_2$-Si), 18.24 (CH$_2$-*C*H$_2$-CH$_2$-Si), 14.95 (CH$_2$-CH$_2$-*C*H$_2$-Si), −4.04 ppm (Si-*C*H$_3$); ^{29}Si NMR: the spectrum showed only one peak at $\delta = -0.388$ ppm; no azide or alkyne absorption was visible in the IR spectrum; MALDI-TOF MS: *m*/*z*: calcd for 10 924 [*M*+Na$^+$]; found: 10 927, side peaks: 10 686 [*M*−ferrocenyl$^+$], 10 444 [*M*−2 ferrocenyl$^+$], 9866 [*M*−dendron$^+$], 9632 [*M*−dendron−ferrocenyl$^+$]; DOSY NMR gave $D = 3.65 \times 10^{-10}$ m^{2}s^{-1} in chloroform, which corresponds to a size of 3.2 nm; SEC showed the low polydispersity (1.03) and the size progression for the three ferrocenyl dendrimers. Some signals appeared as doublets in the NMR spectra due to the difference between *meta* and *para* substituents (such as for the 81-ferrocenyl and the 243-ferrocenyl dendrimers).

81-Ferrocenyl dendrimer 17: $C_{1773}Fe_{81}H_{1893}N_{243}O_{144}Si_{36}$; M_W 34 445.72 g mol^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS): $\delta = 7.62$, 7.59 (s, 81 H; $H_{triazole}$), 7.16–6.66 (m, 201 H; H_{Ar}), 5.20–5.02 (m, 324 H; $C_{triazole}$-C*H*$_2$-$C_{ferrocene}$, $C_{triazole}$-C*H*$_2$-O), 4.71 (s, 54 H; C_{Ar}-C*H*$_2$-O), 4.25–4.11 (m, 729 H; $C_{ferrocene}$-*H*), 3.54 (s, 18 H; inner Si-C*H*$_2$-O), 3.44 (s, 54 H; outer Si-C*H*$_2$-O), 1.63 (s, 72 H; C*H*$_2$-CH$_2$-CH$_2$-Si), 1.12 (s, 72 H; CH$_2$-C*H*$_2$-CH$_2$-Si), 0.56 (s, 72 H; CH$_2$-CH$_2$-C*H*$_2$-Si), 0.12 (s, 54 H; inner Si-C*H*$_3$), 0.02 ppm (s, 162 H; outer Si-C*H*$_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25 °C, TMS): $\delta =$ 159.07 (inner quat. C_{Ar}), 156.10, 152.46, 152.22 (outer quat. C_{Ar}), 144.33, 143.60 (quat. $C_{triazole}$), 139.26 (inner quat. C_{Ar}), 136.84, 133.51 (outer quat. C_{Ar}), 127.18 (inner C_{Ar}-H), 123.48, 123.00 ($C_{triazole}$-H), 116.07, 115.56 (outer C_{Ar}-H), 114.87 (inner C_{Ar}-H), 107.00 (outer C_{Ar}-H), 81.49, 81.21 (quat. $C_{ferrocene}$), 72.02, 70.41, 68.93, 68.75, 66.30, 65.94 ($C_{ferrocene}$-H), 63.04 ($C_{triazole}$-*C*H$_2$-O), 60.97 (Si-*C*H$_2$-O), 50.02, 49.88 ($C_{ferrocene}$-*C*H$_2$-N), 43.06 (C_{quat}), 42.00 (*C*H$_2$-CH$_2$-CH$_2$-Si), 17.62 (CH$_2$-*C*H$_2$-CH$_2$-Si), 14.57 (CH$_2$-CH$_2$-*C*H$_2$-Si), −4.49 ppm (Si-*C*H$_3$); ^{29}Si NMR: the spectrum showed only one peak at $\delta = -0.412$ ppm; no azide or alkyne absorption was visible in the IR spectrum; DOSY NMR gave $D = 3.02 \times 10^{-10}$ m^{2}s^{-1} in chloroform, which corresponds to a size of 3.8 nm; SEC showed the low polydispersity (1.01) and the size progression for the three ferrocenyl dendrimers.

243-Ferrocenyl dendrimer 18: $C_{5418}Fe_{243}H_{5835}N_{729}O_{441}Si_{117}$; M_W 105 080.24 g mol^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS): $\delta = 7.61$, 7.59 (s, 243 H; $H_{triazole}$), 7.16–6.64 (m, 633 H; H_{Ar}), 5.15–5.01 (m, 972 H; $C_{triazole}$-C*H*$_2$-$C_{ferrocene}$, $C_{triazole}$-C*H*$_2$-O), 4.70 (s, 162 H; C_{Ar}-C*H*$_2$-O), 4.22–4.08 (m, 2187 H; $C_{ferrocene}$-*H*), 3.51 (s, 72 H; inner Si-C*H*$_2$-O), 3.43 (s, 162 H; outer Si-C*H*$_2$-O), 1.60 (s, 234 H; C*H*$_2$-CH$_2$-CH$_2$-Si), 1.10 (s, 234 H; CH$_2$-C*H*$_2$-CH$_2$-Si), 0.55 (s, 234 H; CH$_2$-CH$_2$-C*H*$_2$-Si), 0.07 (s, 216 H; inner Si-C*H*$_3$), 0.02 ppm (s, 486 H; outer Si-C*H*$_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25 °C, TMS): $\delta = 159.09$ (inner quat. C_{Ar}), 156.08, 152.46, 152.22 (outer quat. C_{Ar}), 144.33, 143.60 (quat. $C_{triazole}$), 138.92 (inner quat. C_{Ar}), 136.81, 133.48 (outer quat. C_{Ar}), 128.85, 127.17 (inner C_{Ar}-H), 123.42, 122.97 ($C_{triazole}$-H), 115.82, 115.55 (outer C_{Ar}-H), 114.87 (inner C_{Ar}-H), 106.99 (outer C_{Ar}-H), 81.56, 81.24 (quat. $C_{ferrocene}$), 72.07, 70.41, 68.93, 68.61, 66.34, 65.94 ($C_{ferrocene}$-H), 63.08 ($C_{triazole}$-*C*H$_2$-O), 60.95 (Si-*C*H$_2$-O), 50.02, 49.87 ($C_{ferrocene}$-*C*H$_2$-N), 43.06 (C_{quat}), 42.54 (*C*H$_2$-CH$_2$-CH$_2$-Si), 17.62 (CH$_2$-*C*H$_2$-CH$_2$-Si), 14.66 (CH$_2$-CH$_2$-*C*H$_2$-Si), −4.44 ppm (Si-*C*H$_3$); ^{29}Si NMR: the spectrum showed only one peak at $\delta = -0.425$ ppm; no azide or alkynyl absorption was visible in the IR spectrum. DOSY NMR gave $D = 2.74 \times 10^{-10}$ m^{2}s^{-1} in chloroform, which corresponds to a size of 4.2 nm. DLS was indicative of only one population with a size of 5.3 ± 1.0 nm. SEC showed the low polydispersity (1.1) and the size progression for the three ferrocenyl dendrimers.

Synthesis of the triazolylferrocenyl monomer 19: Propargyl alcohol (50 µL, 0.86 mol) and azidomethylferrocene **20** (0.1 g, 0.42 mmol) were dissolved in THF (20 mL). Copper(II) sulfate pentahydrate (0.42 g, 1.7 mmol) was then added with a small amount of water (15 mL), and the mixture was stirred and heated until complete dissolution. Sodium ascorbate (0.66 g, 3.3 mmol) was dissolved in water (5 mL) and this solution was added dropwise to the mixture. The resulting mixture was stirred at room temperature overnight. It was then concentrated by rotary evaporation and the residue was partitioned between CH_2Cl_2 and aqueous ammonia solution. The organic layer was washed with water, dried over anhydrous magnesium sulfate, filtered, and concentrated by rotary evaporation. The desired click-ferrocenyl monomer was precipitated with excess pentane. It was recovered in quantitative yield as a yellow powder (0.12 g). M.p. 161.2 °C; ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS): $\delta = 7.42$ (s, 1 H; $H_{triazole}$), 5.29 (s, 2 H; N-C*H*$_2$-$C_{ferrocene}$), 4.74 (d, ^3J(H,H) = 6.1 Hz, 2 H; $C_{triazole}$-C*H*$_2$-OH), 4.29–4.19 (m, 9 H; $C_{ferrocene}$-*H*), 2.31 ppm (t, ^3J(H,H) = 6.1 Hz, 1 H; O-*H*); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25 °C, TMS): $\delta = 147.43$ (quat. $C_{triazole}$), 120.91 ($C_{triazole}$-H), 80.65 (quat. $C_{ferrocene}$), 69.12, 68.95, 68.91 ($C_{ferrocene}$-H), 56.70 ($C_{ferrocene}$-CH$_2$-N), 50.09 ppm (*C*H$_2$-OH); IR: no alkyne or azide absorption was visible; MS: *m*/*z*: 617 [2*M*+Na$^+$], 320.05 [*M*+Na$^+$], 298 [*M*+H$^+$]; elemental analysis calcd (%) for $C_{14}H_{15}ON_3Fe$: C 56.59, H 5.09; found: C 56.82, H 5.34.

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Supporting Information

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New polyalkynyl dendrons and dendrimers, "click" chemistry with azidomethylferrocene and specific anion and cation electrochemical sensing properties of the 1,2,3-triazole-containing dendrimers

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Spectroscopic characterizations including ^{1}H, ^{13}C and ^{29}Si NMR, IR spectra, MALDI-TOF mass spectra and cyclic voltammetry.

NMR Spectroscopy:
^{1}H NMR spectra were recorded at 25°C with a Bruker DPX 400 (400 MHz), a Bruker Advance 300 (300 MHz) or with a Bruker AC 250 (250 MHz) spectrometer. ^{13}C NMR spectra were obtained in the pulse FT mode at 75.0 MHz with a Bruker AC 300 spectrometer and ^{29}Si NMR spectra were obtained in at 59.6 MHz with a Bruker AC 300 spectrometer. All chemical shifts are reported in parts per million (δ, ppm) with reference to $SiMe_4$ (TMS). DOSY NMR spectra were recorded at 25°C with a Bruker DPX 400 spectrometer.

MALDI-TOF mass spectrometry:
The mass spectra reported in this Supplementary Information are MALDI TOF mass spectra. MALDI mass spectra were recorded with a PerSeptive Biosystems Voyager Elite (Framingham, MA) time-of-flight mass spectrometer. This instrument is equipped with a nitrogen laser (337 nm), a delayed extraction, and a reflector. It was operated at an accelerating potential of 20 kV in both linear and reflection modes. The mass spectra shown represent an average over 256 consecutive laser shots (3 Hz repetition rate). Peptides were used to calibrate the mass scale using the two points calibration software 3.07.1 from PerSeptive Biosystems. Mentioned m/z values correspond to monoisotopic masses. The dendrimer solutions (10^{-3} M) were prepared in tetrahydrofuran (THF). Matrix compounds were from Sigma (France) and used without further purification. The matrices, 2-5-dihydroxybenzoic acid (2.5-DHB), 1,8-dihydroxy-9[10H]-anthracenone (dithranol), 6-azathiothymine, 2,4,6-trihydroxyacetophenon, 7-hydroxycoumarin, or 2-anthramine, were also dissolved in THF (10 $g.L^{-1}$). One microliter of dendrimer solution was mixed with 50 microliter of matrix solution. Ten microliters of alkali iodide (LiI, NaI) solutions (5 $g.L^{-1}$ in THF) were added in some experiments to induce cationization. One microliter of the final solution was dissolved onto the sample stage and allowed to dry in air.

The cyclic voltammetry measurements:
All electrochemical measurements were recorded in degassed CH_2Cl_2 at 20°C. Supporting electrolyte: [*n*-Bu_4N][PF_6] 0.1 M; working and counter electrode: Pt; reference electrode: Ag; internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]^{+/0}$; scan rate = 0.200 $V.s^{-1}$.

Modified Pt electrodes
A platinum electrode (Sodimel, Pt 30) was dipped into 10% aq HNO_3 for 3h, then rinsed with distillated water, dried in air, and polished using cerium oxide pulver (5 MU). The dendrimers **16**, **17** and **18** were electrodeposited onto such platinum-disk electrodes (A = 0.078 cm^2) from degassed CH_2Cl_2 solutions of metallodendrimer (10^{-6} M) and [*n*-Bu_4N][PF_6] (0.1 M) by continuous scanning (0.20 $V.s^{-1}$) up to 50 cycles and up to 200 cycles between 0.0 and 0.9 V vs. $[Fe(\eta^5\text{-}C_5Me_5)_2]^{+/0}$. The coated electrode was washed with CH_2Cl_2 in order to remove the solution of material and dried to air. This modified electrode was characterized by CV in freshly distilled CH_2Cl_2 as containing only the supporting electrolyte. It showed a single symmetrical CV wave, and the linear relationship of the peak current with potential sweep rate was verified. The surface coverage Γ ($mol.cm^{-2}$) by the ferrocenyl dendrimers **16**, **17** and **18** was determined from integrated charge of the CV wave. $\Gamma = Q/nFA$, where Q is the charge, n is the number of electrons transferred, F is the Faraday constant, and A is the area.

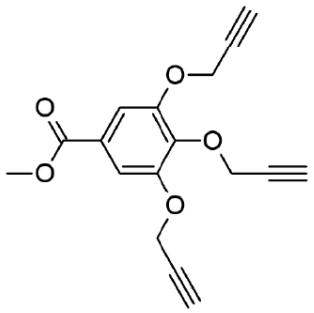
Table 5. Γ (mol.cm^{-2}) for the various modified Pt electrodes

	Γ (mol.cm^{-2}) [a] (ferrocenyl sites)	Γ (mol.cm^{-2}) [a]	Γ (mol.cm^{-2}) [b] (ferrocenyl sites)	Γ (mol.cm^{-2}) [b]
16	3.62×10^{-9}	1.34×10^{-10}	6.23×10^{-9}	2.31×10^{-10}
17	6.56×10^{-9}	8.10×10^{-11}	2.13×10^{-8}	2.63×10^{-10}
18	7.46×10^{-9}	3.07×10^{-11}	3.75×10^{-8}	1.54×10^{-10}

[a] on the modified Pt electrode obtained after 50 cycles adsorption, [b] on the modified Pt electrode obtained after 200 cycles adsorption

Elemental analysis:
Elemental analyses were performed by the center of Microanalysis of the CNRS at Lyon Villeurbanne, France.

Compound **2:** 3,4,5-tris(prop-2-yn-1-yloxy)benzoate



m.p. 89.4°C; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=7.44 ppm (s, 2H, $\underline{H}_{Ar}$), 4.80 ppm (d, ^{4}J(H,H) = 2.3 Hz, 2H, para-O-C$\underline{H}_2$-C≡C), 4.78 ppm (d, ^{4}J(H,H) = 2.3 Hz, 4H, meta-O-C$\underline{H}_2$-C≡C), 3.89 (s, 3H, C$\underline{H}_3$-O), 2.53 ppm (t, ^{4}J(H,H) = 2.3 Hz, 2H, C≡C-$\underline{H}$), 2.45 ppm (t, ^{4}J(H,H) = 2.3 Hz, 1H, C≡C-$\underline{H}$) ; ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ=166.23, 151.27, 141.07 and 125.74 ppm (quat. C_{Ar}), 109.84 ppm (C_{Ar}-H), 78.68, 77.94, 76.22 and 75.60 ppm (*C*≡C-H and C≡*C*-H), 60.30 and 57.05 ppm (O-*C*H_2-C≡C-H), 52.35 ppm (O-*C*H_3) ; IR: ν=1724 cm^{-1} (C=O), 2121 cm^{-1} (C≡C) and 3274 cm^{-1} (C≡C-H) ; MS: *m/z*: 619 [NaM_2^+], 321 [NaM^+], 299 [HM^+].

Figure S.I.1. ^{1}H NMR spectrum of **2** (250 MHz $CDCl_3$)

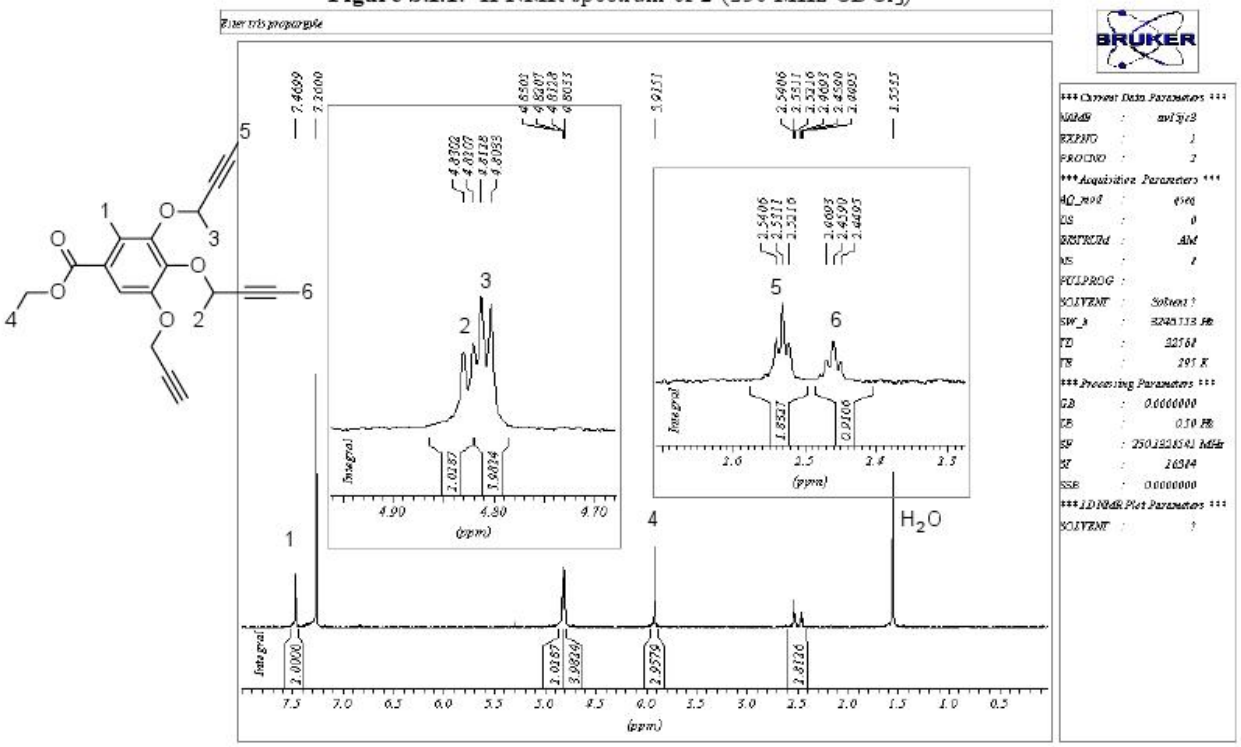


Figure S.I.2. ^{13}C NMR spectrum of **2** (75.5 MHz $CDCl_3$)

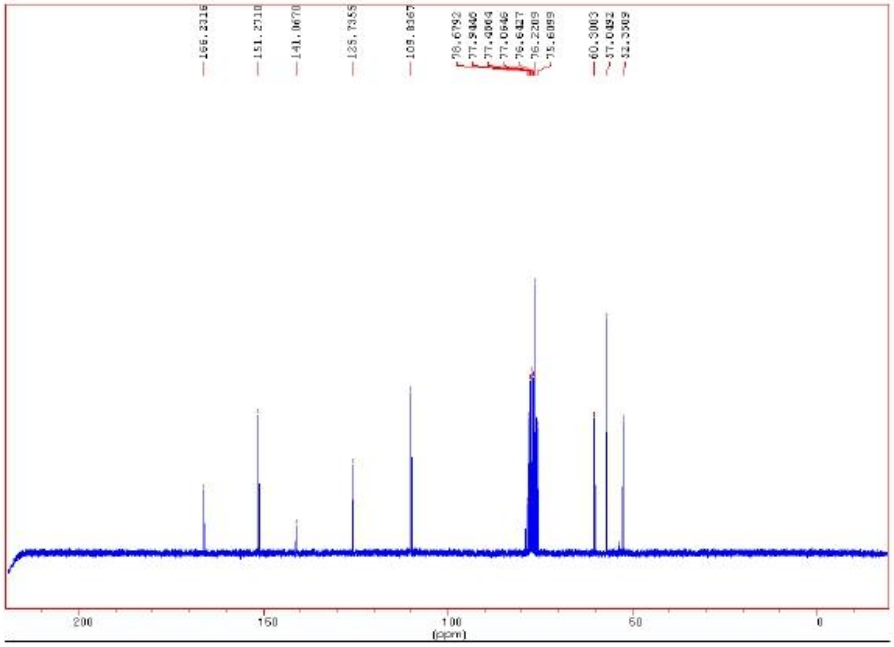


Figure S.I.3. ^{13}C DEPT 135 NMR spectrum of **2** (75.5 MHz $CDCl_3$)

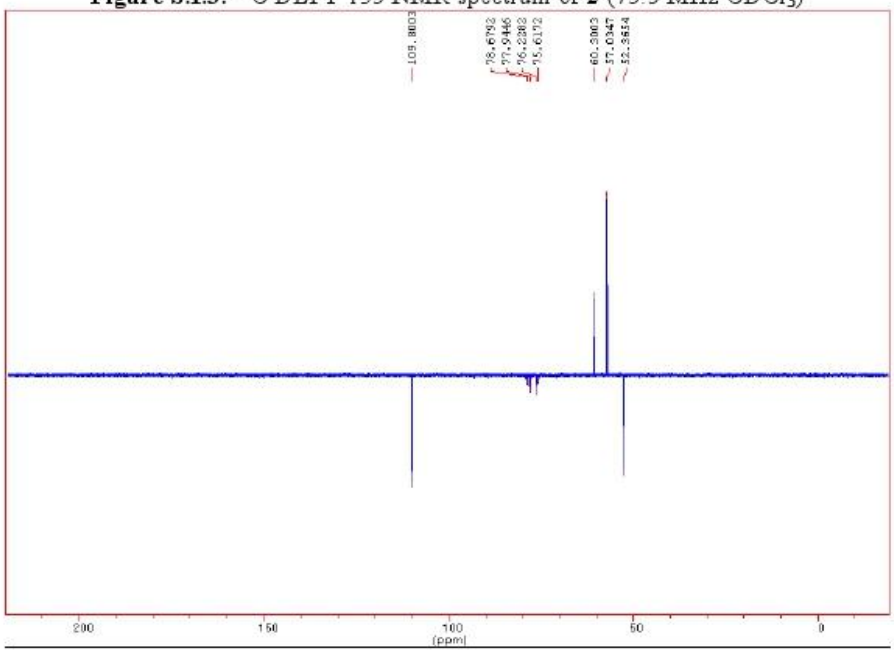
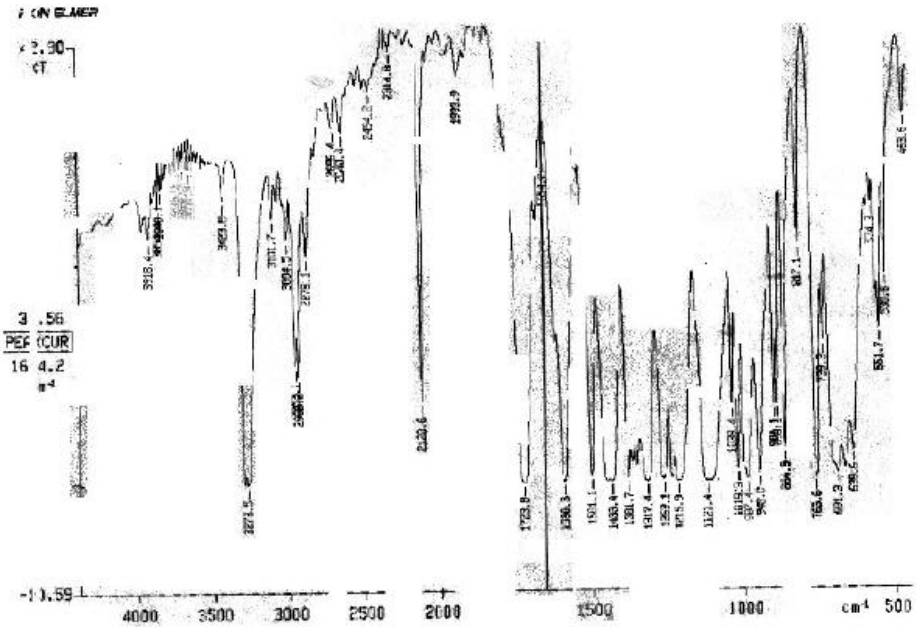


Figure S.I.4. IR spectrum of **2**



SI7

Figure S.I.5. Mass spectrum of **2** (1/2)

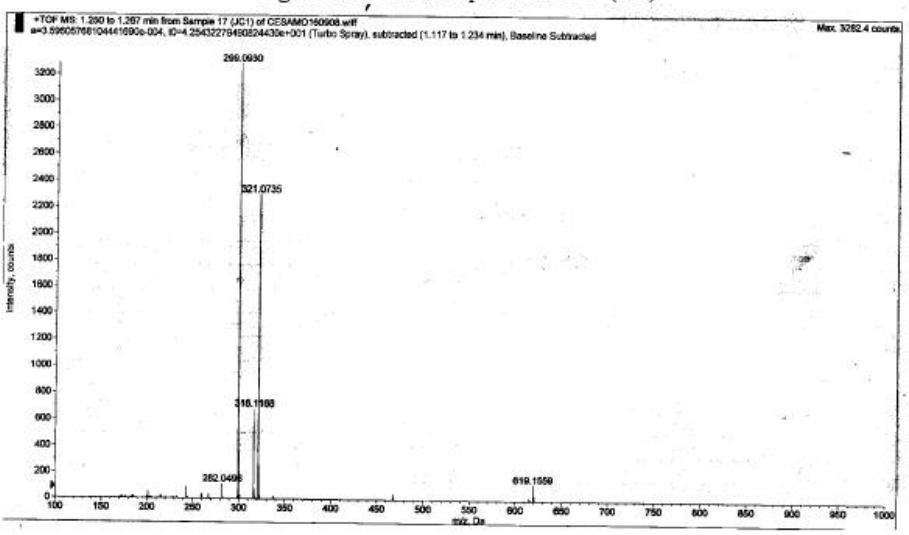


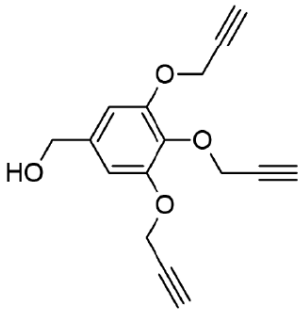
Figure S.I.6. Mass spectrum of **2** (2/2)

	Elements	Min Number	Max Number
11	Na	0	1
12	O	1	5
13	P	0	0
14	S	0	0
15	Si	0	0
16	Sn	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C17 H14 O5 Na	321.0733	0.1551	0.4831	10.5

SI8

Compound **3:** [3,4,5-tris(prop-2-yn-1-yloxy)phenyl]methanol



m.p. 103.0°C; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=6.78 ppm (s, 2H, $\underline{H}_{Ar}$), 4.76 ppm (d, ^{4}J(H,H) = 2.4 Hz, 4H, meta-O-C$\underline{H}_2$-C≡C), 4.72 ppm (d, ^{4}J(H,H) = 2.1 Hz, 2H, para-O-C$\underline{H}_2$-C≡C), 4.65 ppm (s, ^{3}J(H,H) = 6.1 Hz, 2H, HO-C$\underline{H}_2$-C_{Ar}), 2.51 ppm (t, ^{4}J(H,H) = 2.4 Hz, 2H, C≡C-$\underline{H}$), 2.46 ppm (t, ^{4}J(H,H) = 2.1 Hz, 1H, C≡C-$\underline{H}$), 1.73 ppm (t, ^{3}J(H,H) = 6.1 Hz, 1H, O$\underline{H}$) ; ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ=151.59, 145.31 and 137.38 ppm (quat. C_{Ar}), 106.88 ppm (C_{Ar}-H), 79.17, 78.51, 75.91 and 75.29 ppm (*C*≡C-H and C≡*C*-H), 64.93 ppm (HO-*C*H_2), 60.27 and 56.94 ppm (O-*C*H_2-C≡C-H) ; IR: ν=2121 cm^{-1} (C≡C), 3294 cm^{-1} (C≡C-H) and 3538 cm^{-1} (O-H) ; MS: *m/z*: 563 [NaM_2^+], 293 [NaM^+], 271 [HM^+].

Figure S.I.7. ^{1}H NMR spectrum of **3** (250 MHz $CDCl_3$)

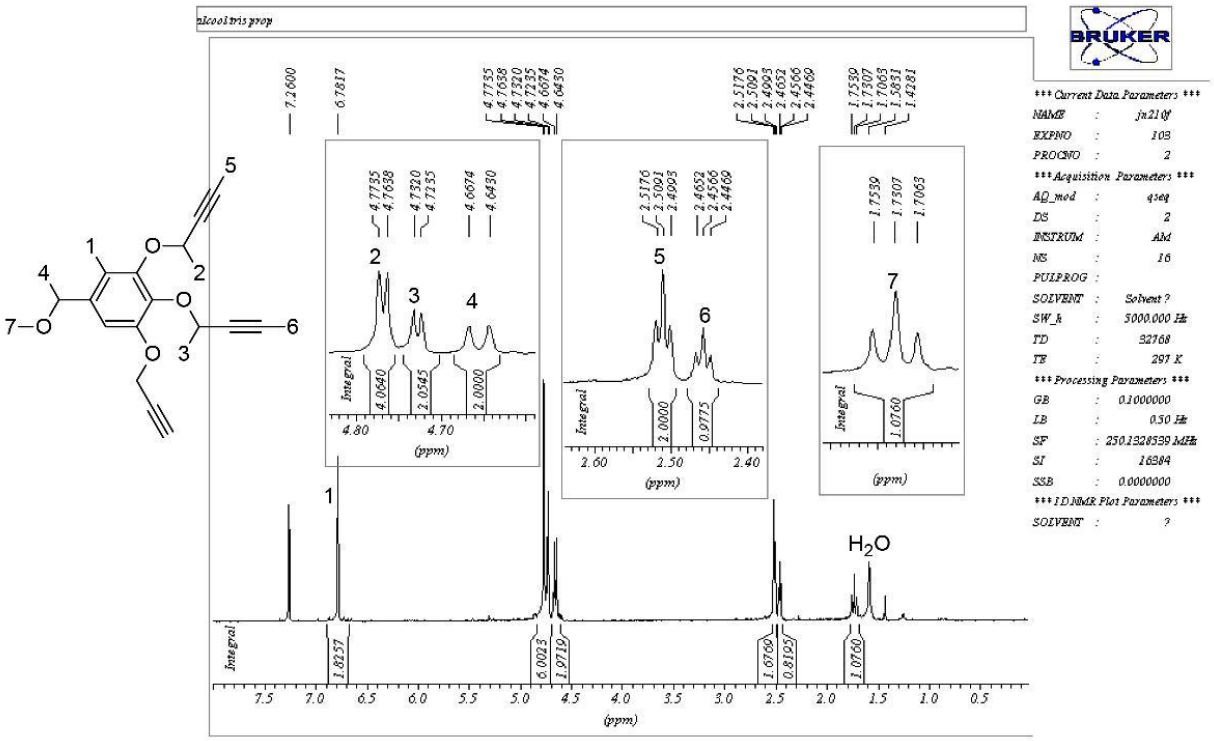
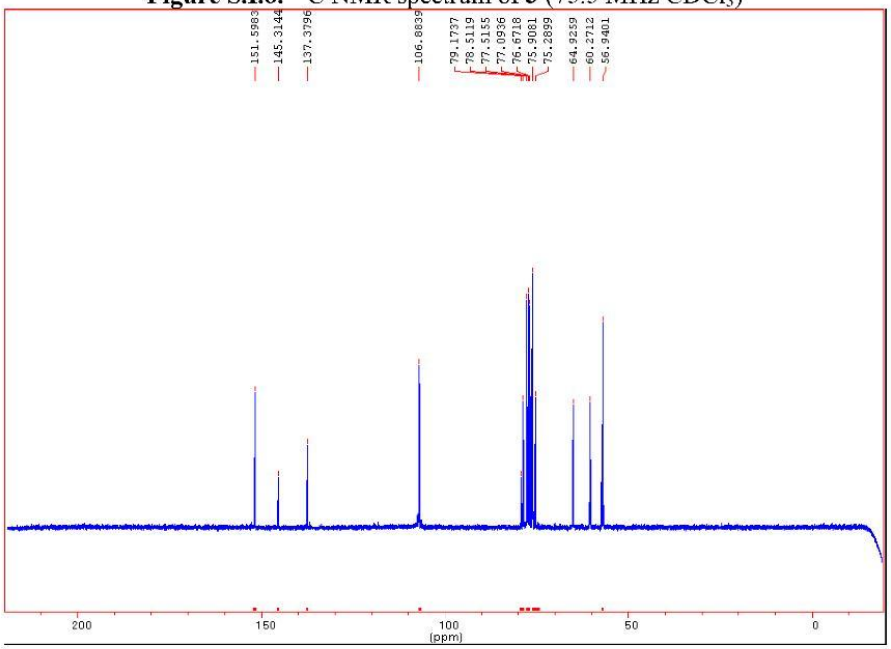


Figure S.I.8. ^{13}C NMR spectrum of **3** (75.5 MHz $CDCl_3$)



SI10

Figure S.I.9. ^{13}C DEPT 135 NMR spectrum of **3** (75.5 MHz $CDCl_3$)

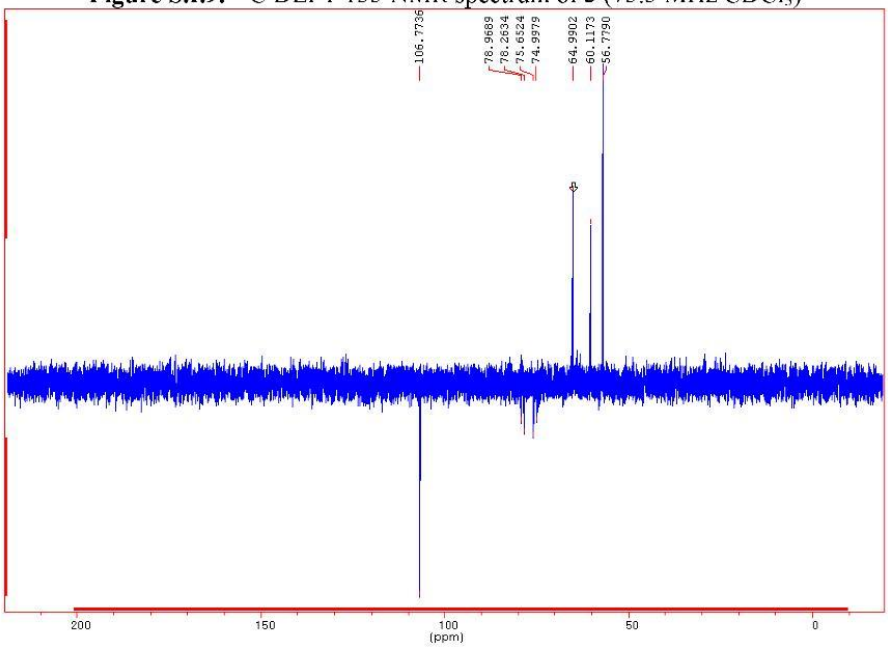
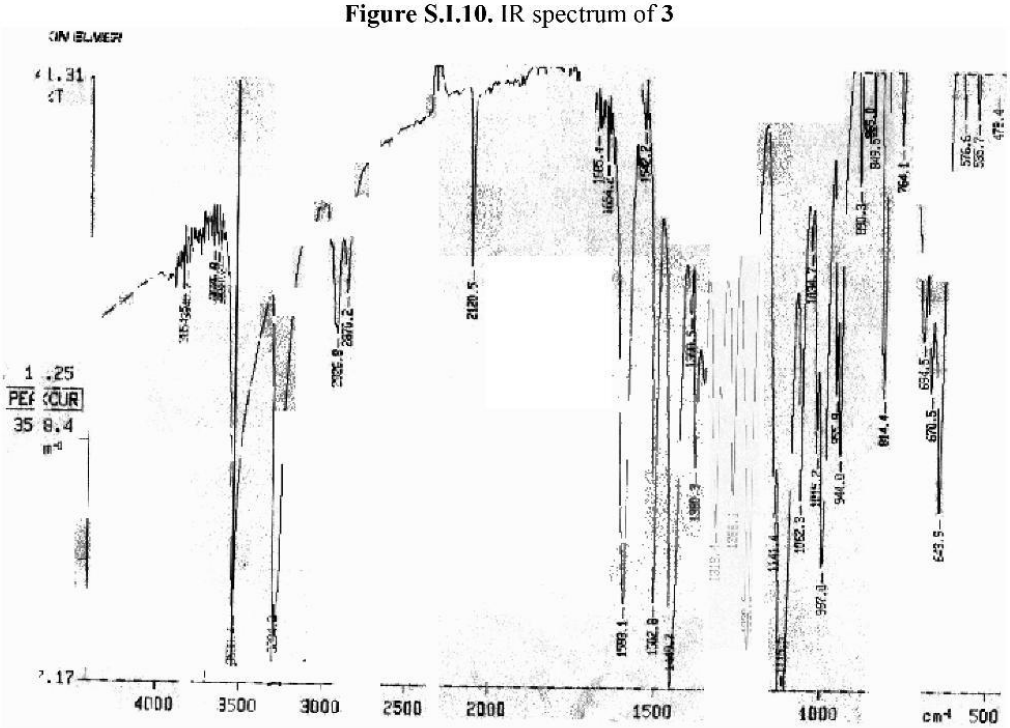


Figure S.I.10. IR spectrum of **3**



SI11

Figure S.I.11. Mass spectrum of **3** (1/2)

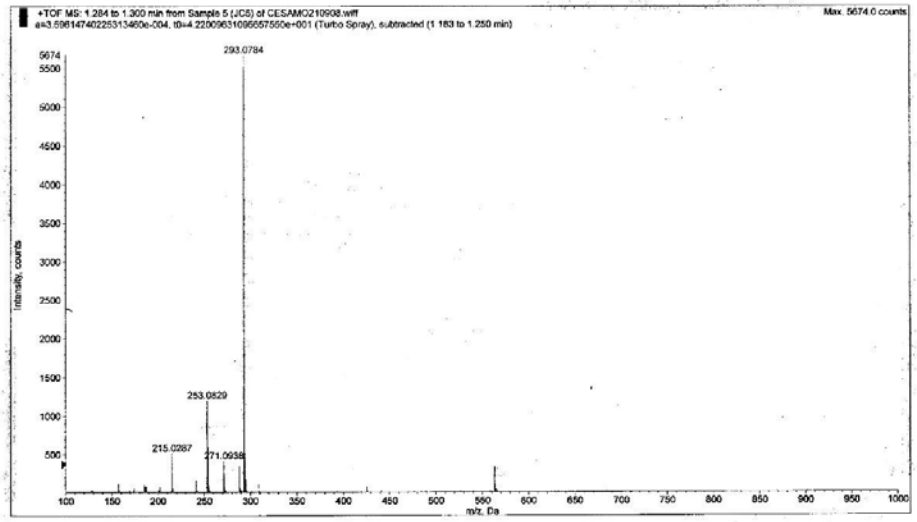


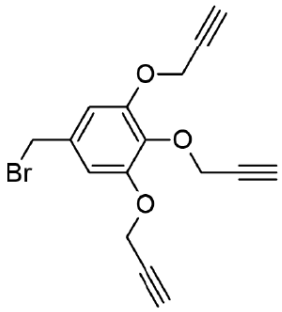
Figure S.I.12. Mass spectrum of **3** (2/2)

	Elements	Min Number	Max Number
11	Na	0	1
12	O	2	8
13	P	0	0
14	S	0	0
15	Se	0	0
16	Si	0	0
17	Sn	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C16 H14 O4 Na	293.0784	-0.0302	-0.1031	9.5

SI12

Compound **4**: 5-bromomethyl-1,2,3-tris(prop-2-yn-1-yloxy)benzene



m.p. 63.7°C; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=6.75 ppm (s, 2H, $\underline{H}_{Ar}$), 4.71 ppm (d, ^{4}J(H,H) = 2.6 Hz, 4H, meta-O-C$\underline{H}_2$-C≡C), 4.67 ppm (d, ^{4}J(H,H) = 2.2 Hz, 2H, para-O-C$\underline{H}_2$-C≡C), 4.41 ppm (s, 2H, Br-C$\underline{H}_2$-C_{Ar}), 2.52 ppm (t, ^{4}J(H,H) = 2.6 Hz, 2H, C≡C-$\underline{H}$), 2.45 ppm (t, ^{4}J(H,H) = 2.2 Hz, 1H, C≡C-$\underline{H}$) ; ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ=150.54, 136.16 and 132.75 ppm (quat. C_{Ar}), 108.42 ppm (C_{Ar}-H), 78.06, 77.26, 75.19 and 74.45 ppm (*C*≡C-H and C≡*C*-H), 59.31 and 56.04 ppm (O-*C*H_2-C≡C-H), 52.61ppm (*C*H_2-Br) ; IR: ν=2120 cm^{-1} (C≡C) and 3290.6 cm^{-1} (C≡C-H) ; MS: *m/z*: 355 and 357 [NaM^{+}], 333 and 335 [HM^{+}].

Figure S.I.13. ^{1}H NMR spectrum of **4** (250 MHz $CDCl_3$)

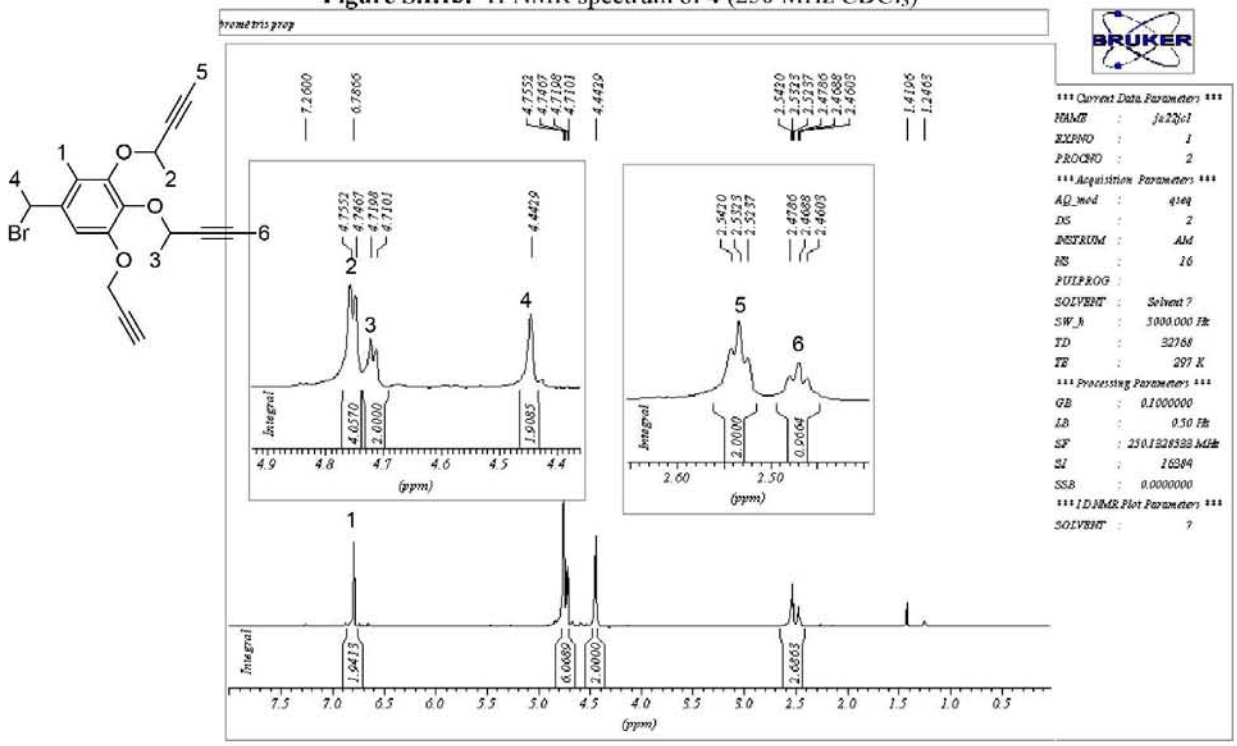
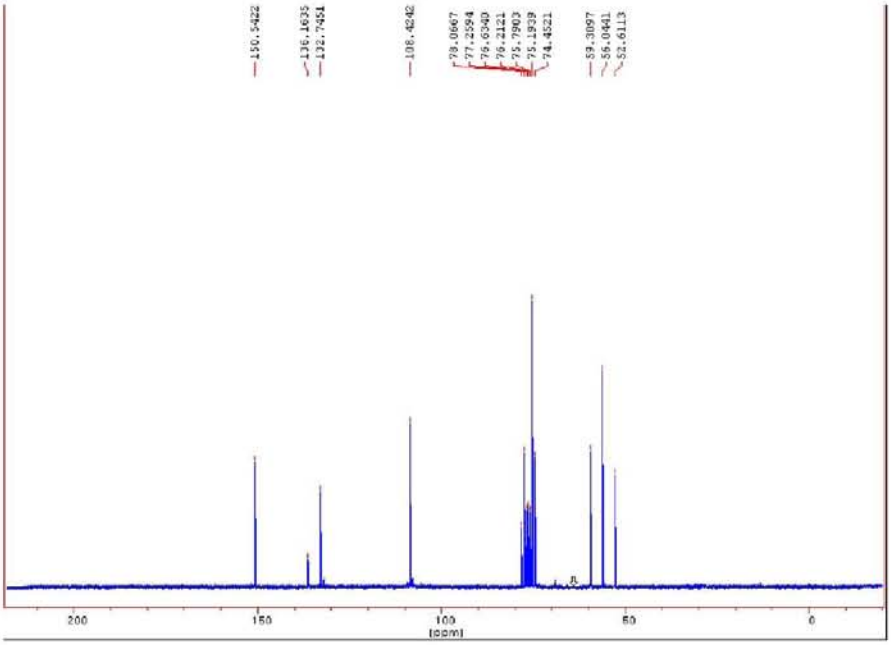


Figure S.I.14. ^{13}C NMR spectrum of **4** (75.5 MHz $CDCl_3$)



SI14

Figure S.I.15. ^{13}C DEPT 135 NMR spectrum of **4** (75.5 MHz $CDCl_3$)

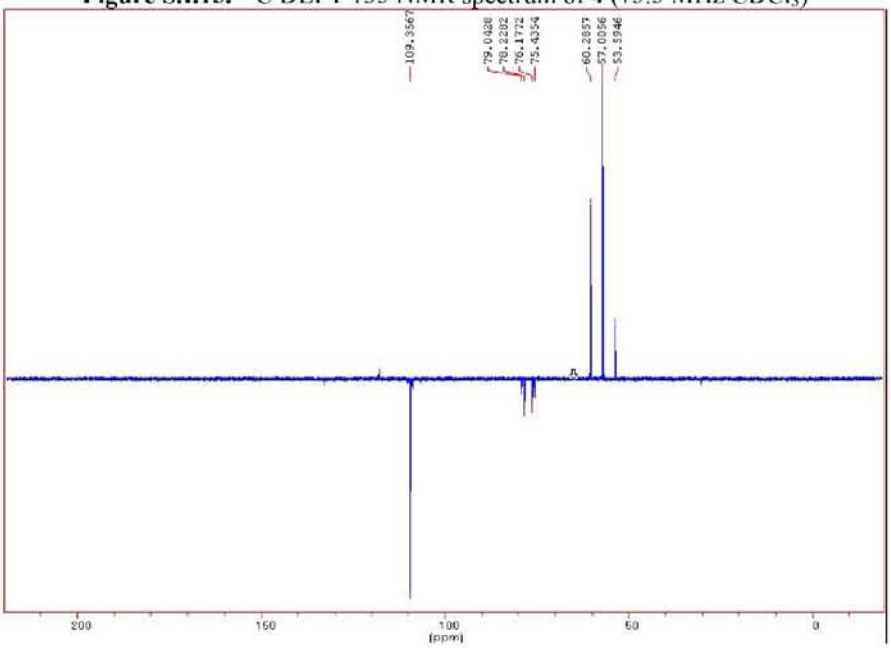
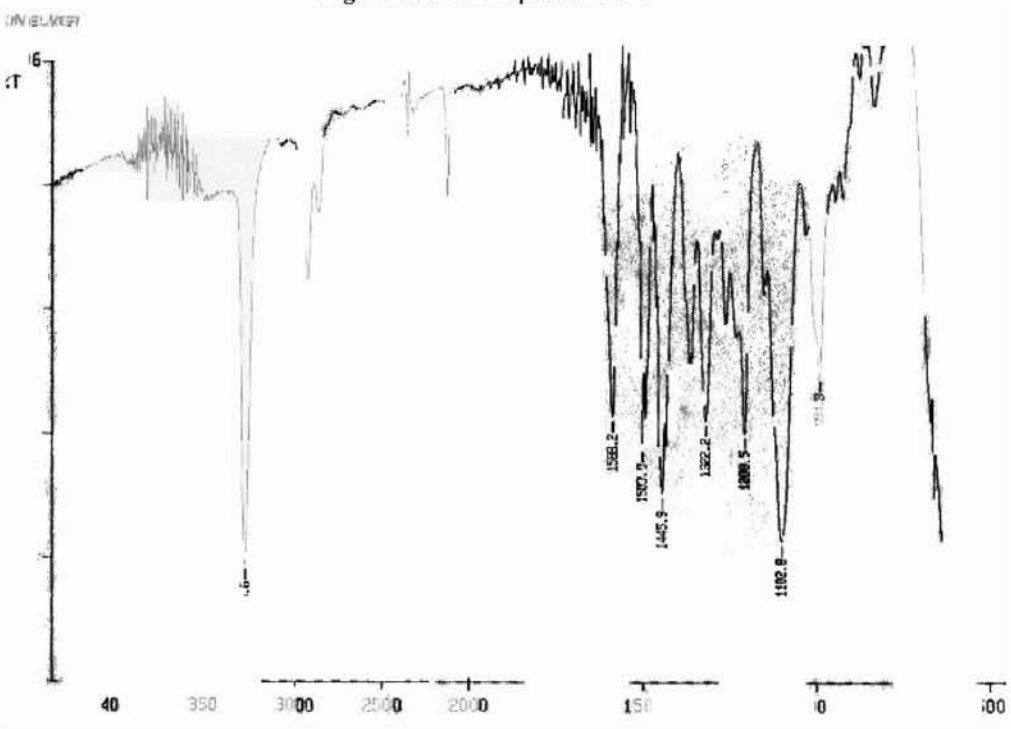


Figure S.I.16. IR spectrum of **4**



SI15

Figure S.I.17. Mass spectrum of **4** (1/3)

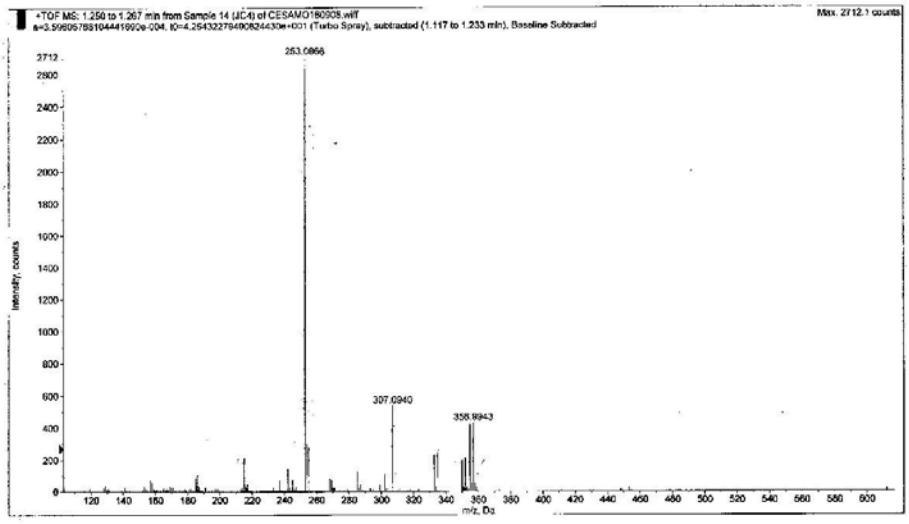
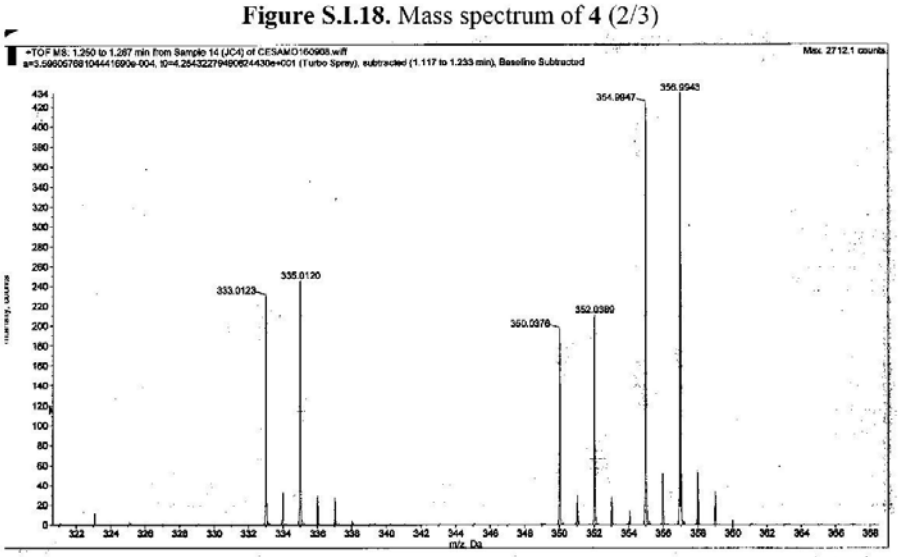


Figure S.I.18. Mass spectrum of **4** (2/3)



SI16

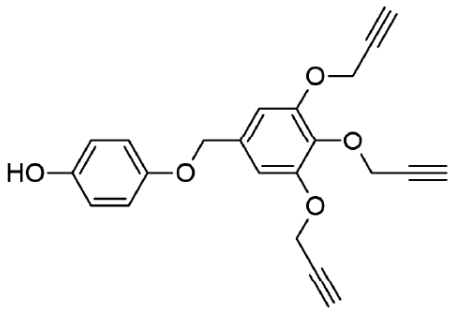
Figure S.I.19. Mass spectrum of **4** (3/3)

	Elements	Min Number	Max Number
11	Na	0	0
12	O	1	3
13	P	0	0
14	S	0	0
15	Si	0	0
16	Sn	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C16 H14 O3 Br	333.0120	0.2179	0.6546	9.5

SI17

Compound **5**: tris-alkynyl phenol dendron, 4-{[3,4,5-tris(prop-2-yn-1-yloxy)benzyl]oxy}phenol



m.p. 76.5°C; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=6.87 to 6.74 ppm (m, 6H, $\underline{H}_{Ar}$), 4.95 ppm (s, 2H, O-C$\underline{H}_2$-C_{Ar}), 4.76 ppm (d, ^{4}J(H,H) = 1.9 Hz, 4H, meta-O-C$\underline{H}_2$-C≡C), 4.73 ppm (d, ^{4}J(H,H) = 1.9 Hz, 2H, para-O-C$\underline{H}_2$-C≡C), 2.50 to 2.45 ppm (m, 3H, C≡C-$\underline{H}$); ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ=152.67, 151.67, 149.92, 136.63 and 133.53 ppm (quat. C_{Ar}), 116.14, 116.08 and 107.74 ppm (C_{Ar}-H), 79.14, 78.37, 75.98 and 75.34 ppm (*C*≡C-H and C≡*C*-H), 70.65 ppm (C_{Ar}-*C*H_2-O), 60.36 and 57.04 (O-*C*H_2-C≡C-H); IR: ν=2123 cm^{-1} (C≡C), 3283 cm^{-1} (C≡C-H) and 3500 cm^{-1} (O-H); MS: *m/z*: 747 [NaM_2^+], 385 [NaM^+]; Elemental analysis calcd (%) for $C_{22}H_{18}O_5$: C 72.91, H 5.01, O 22.08; found: C 72.39, H 4.99, O 22.25.

Figure S.I.20. ^{1}H NMR spectrum of **5** (300 MHz $CDCl_3$)

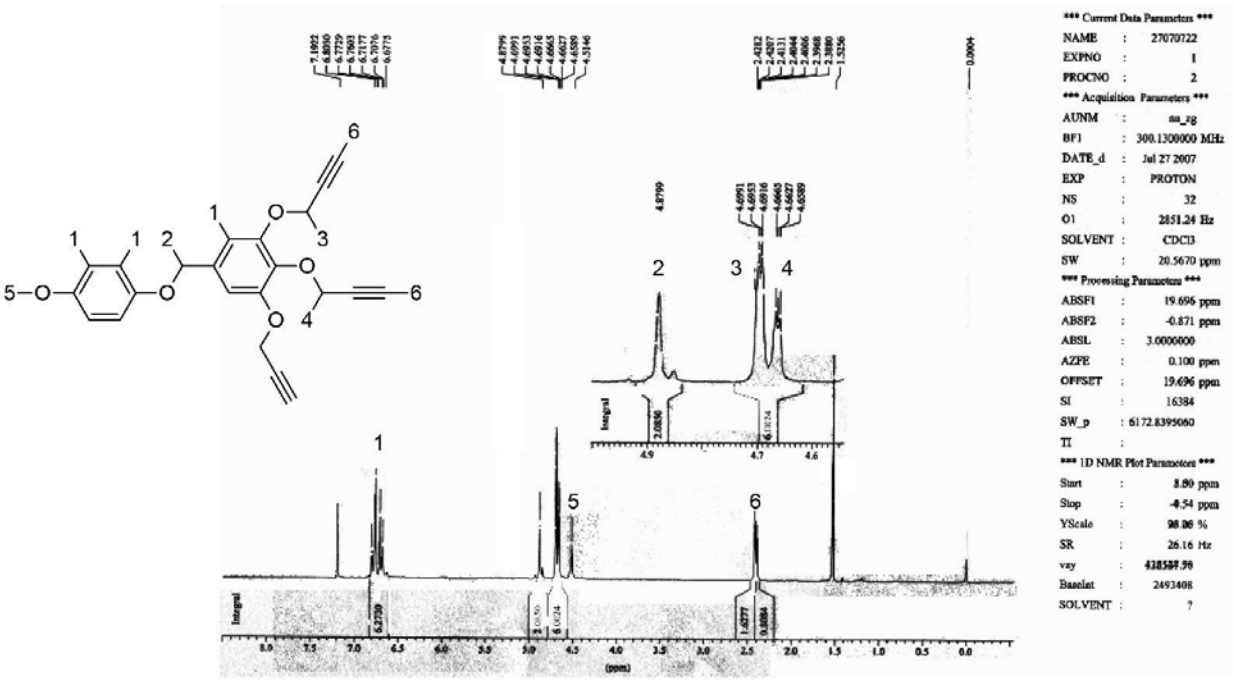


Figure S.I.21. ^{13}C NMR spectrum of **5** (75.5 MHz $CDCl_3$)

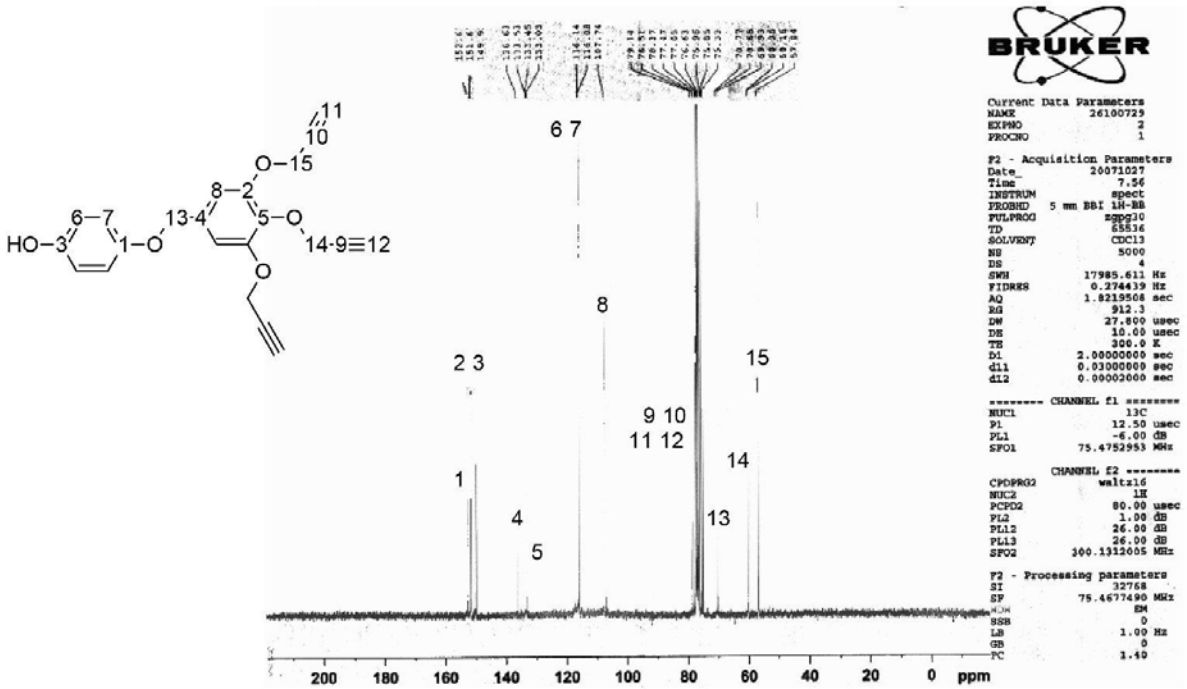


Figure S.I.22. ^{13}C DEPT 135 NMR spectrum of **5** (75.5 MHz $CDCl_3$)

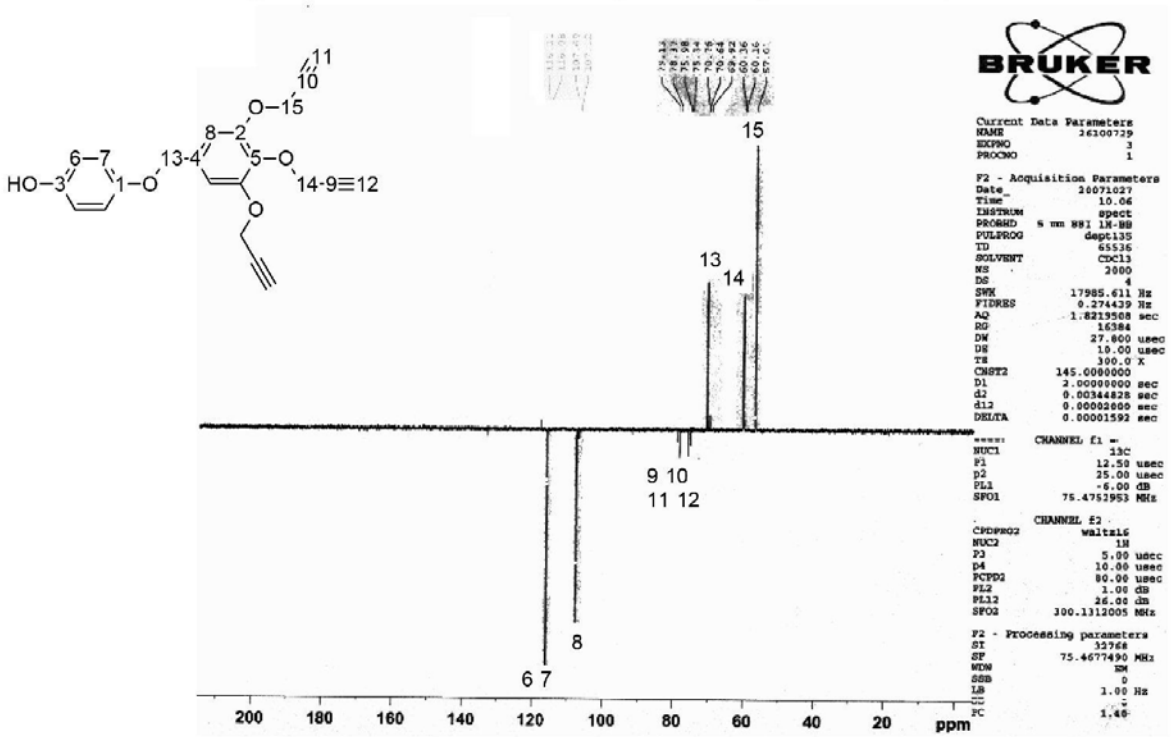


Figure S.I.23. IR spectrum of **5**

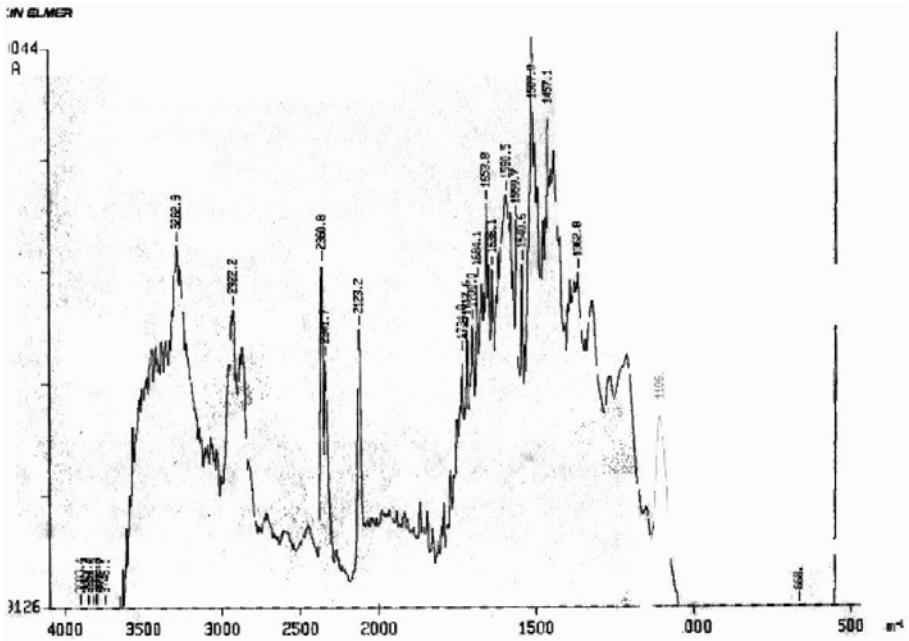


Figure S.I.24. Mass spectrum of **5** (1/2)

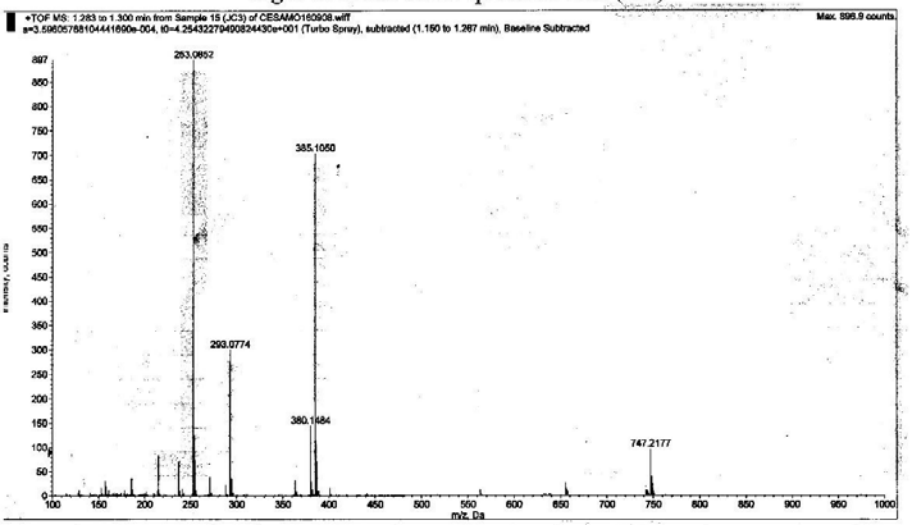


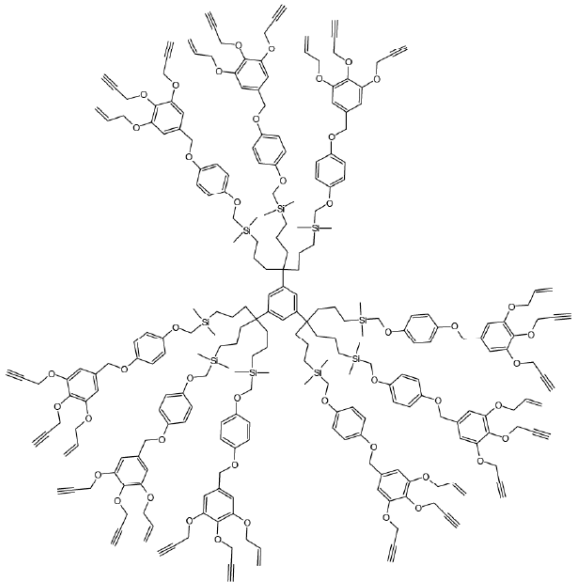
Figure S.I.25. Mass spectrum of **5** (2/2)

	Elements	Min Number	Max Number
11	Na	0	1
12	O	1	5
13	P	0	0
14	S	0	0
15	Si	0	0
16	Sn	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C22 H18 O5 Na	385.1046	0.3549	0.9217	13.5

SI21

Compound **13**: 27-alkynyl dendrimer



$C_{261}H_{282}O_{45}Si_9$; MW 4391.89 g.mol^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=7.00 to 6.80 ppm (m, 57H, $\underline{H}_{Ar}$), 4.88 ppm (s, 18H, O-C$\underline{H}_2$-C_{Ar}), 4.74 ppm (s, 54H, O-C$\underline{H}_2$-C≡C), 3.46 ppm (s, 18H, Si-C$\underline{H}_2$-O), 2.49 ppm (s, 18H, C≡C-$\underline{H}$), 2.47 ppm (s, 27H, C≡C-$\underline{H}$), 1.66 ppm (s, 18H, C$\underline{H}_2$-CH_2-CH_2-Si), 1.15 ppm (s, 18H, CH_2-C$\underline{H}_2$-CH_2-Si), 0.60 ppm (s, 18H, CH_2-CH_2-C$\underline{H}_2$-Si), 0.05 ppm (s, 54H, Si-C$\underline{H}_3$); ^{13}C NMR (63 MHz, $CDCl_3$, 25°C, TMS): δ=156.46, 152.85, 152.03, 146.19, 136.98 and 133.91 ppm (quat. C_{Ar}), 116.45, 116.08, 115.14 and 108.04 ppm (C_{Ar}-H), 79.55, 78.83, 76.34 and 75.69 ppm (*C*≡C-H and C≡*C*-H), 70.91 ppm (C_{Ar}-*C*H_2-O), 61.25 ppm (Si-*C*H_2-O), 60.72 and 57.37 ppm (O-*C*H_2-C≡C-H), 44.29 ppm (quat. *C*), 42.36 ppm (*C*H_2-CH_2-CH_2-Si), 18.24 ppm (CH_2-*C*H_2-CH_2-Si), 14.98 ppm (CH_2-CH_2-*C*H_2-Si), -4.08 ppm (Si-*C*H_3); ^{29}Si NMR (60 MHz, $CDCl_3$, 25°C, TMS) shows only one peak at 0.85 ppm (all the branches have reacted); IR: ν=2122 cm^{-1} (C≡C) and 3291 cm^{-1} (C≡C-H); MALDI-TOF mass spectrum: molecular peak observed at m/z = 4415.1 (calcd for NaM^+ 4415.7); Elemental analysis calcd (%) for $C_{261}H_{282}O_{45}Si_9$: C 71.38, H 6.47; found: C 70.41, H 6.30; DOSY NMR gives D = 2.77.10^{-10} m².s^{-1} in chloroform at 25°C which corresponds to a size of 4.1 nm; Size exclusion chromatography (SEC) shows the low polydispersity (1.02) and the size progression for the three alkynyl dendrimers.

Figure S.I.26. ^{1}H NMR spectrum of **13** (300 MHz $CDCl_3$)

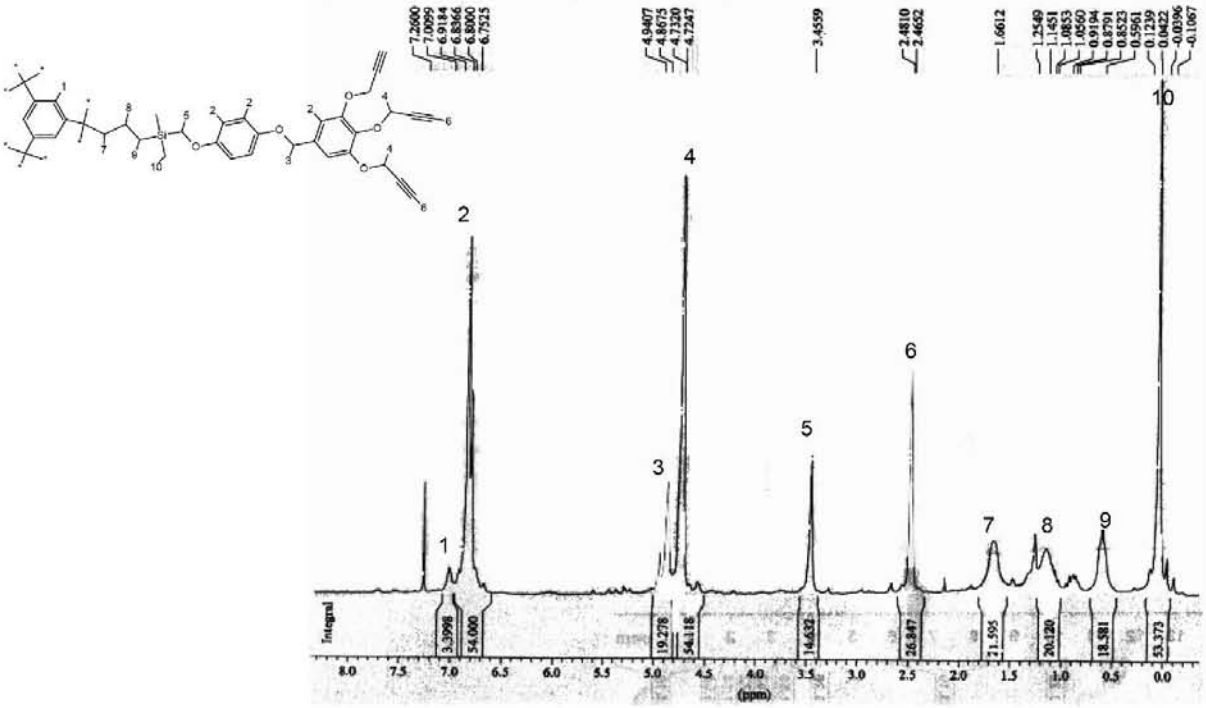
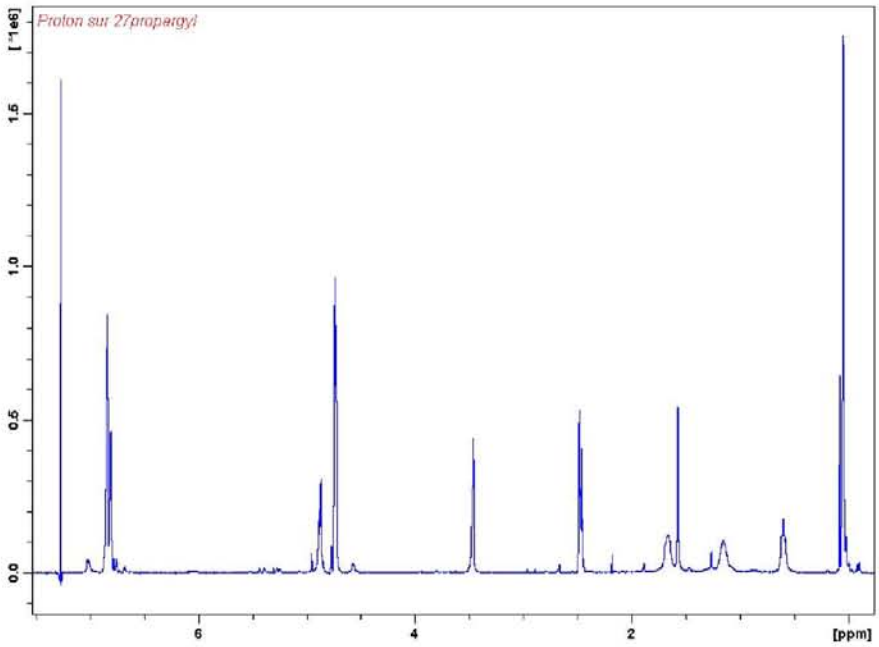


Figure S.I.27. ^{1}H NMR spectrum of **13** (400 MHz $CDCl_3$)



SI23

Figure S.I.28. ^{13}C NMR spectrum of **13** (62.9 MHz $CDCl_3$)

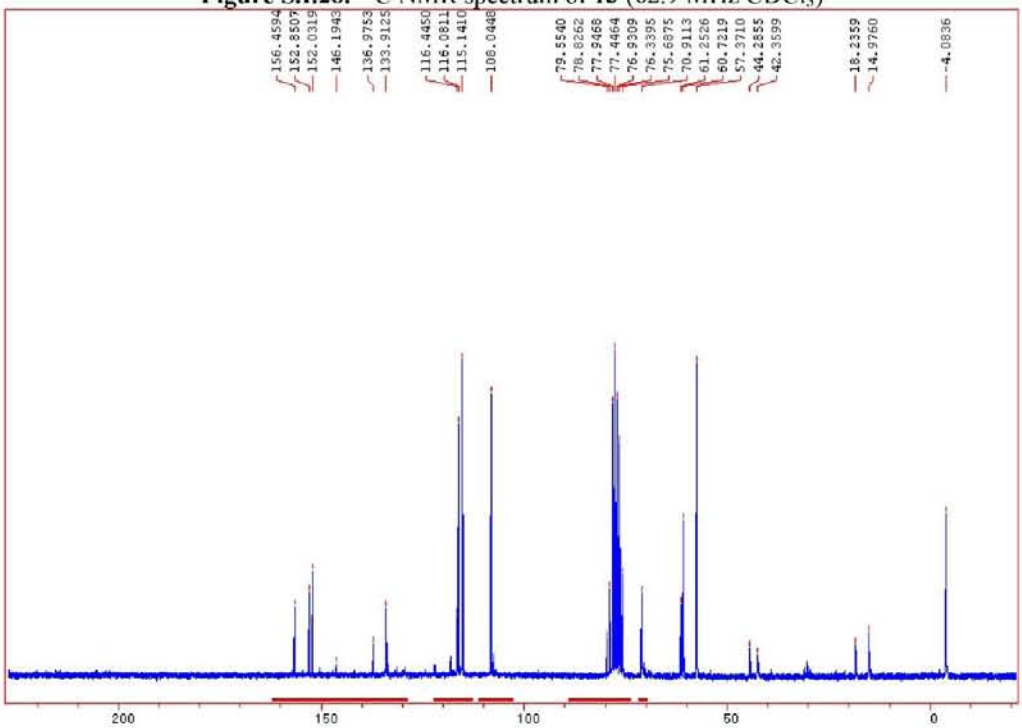
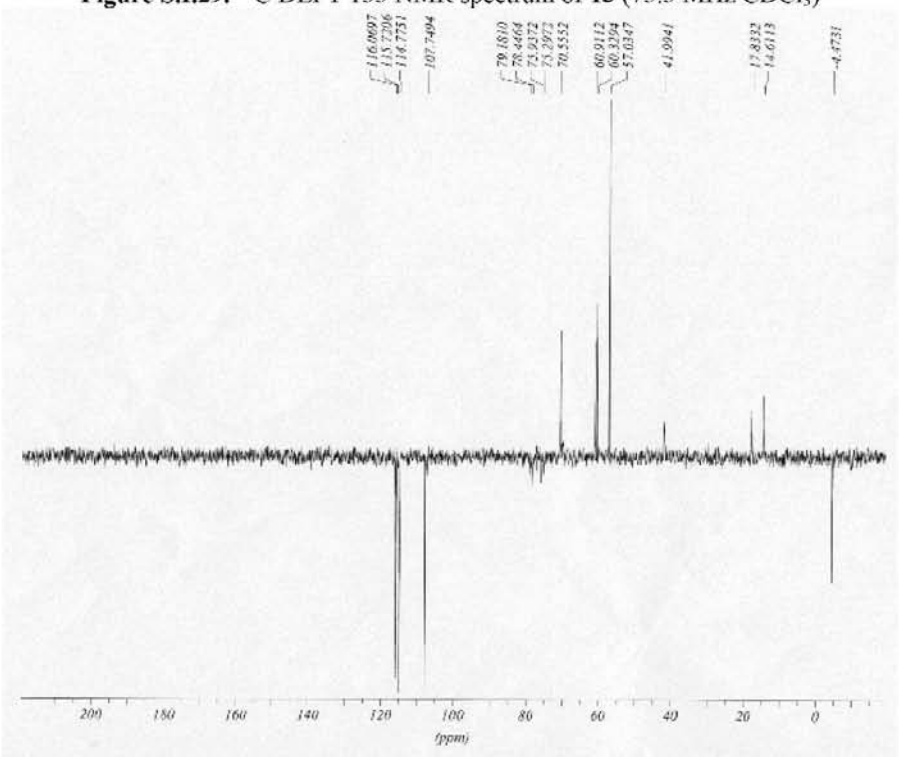


Figure S.I.29. ^{13}C DEPT 135 NMR spectrum of **13** (75.5 MHz $CDCl_3$)



SI24

Figure S.I.30. ^{29}Si NMR spectrum of **13** (59.6 MHz $CDCl_3$)

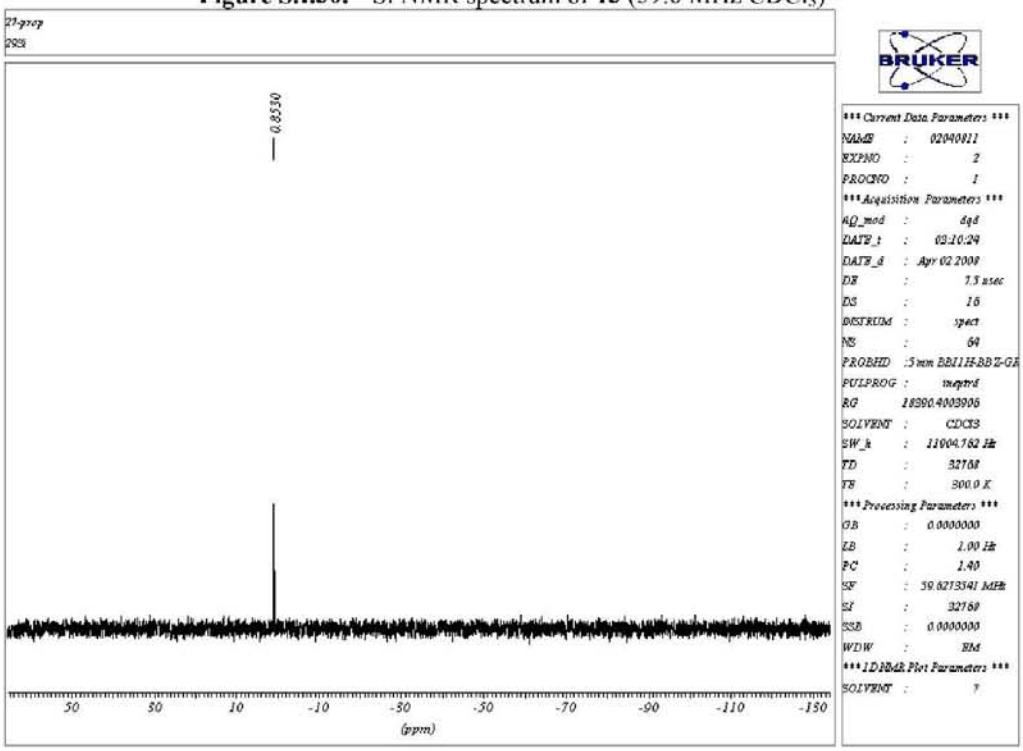


Figure S.I.31. IR spectrum of **13**

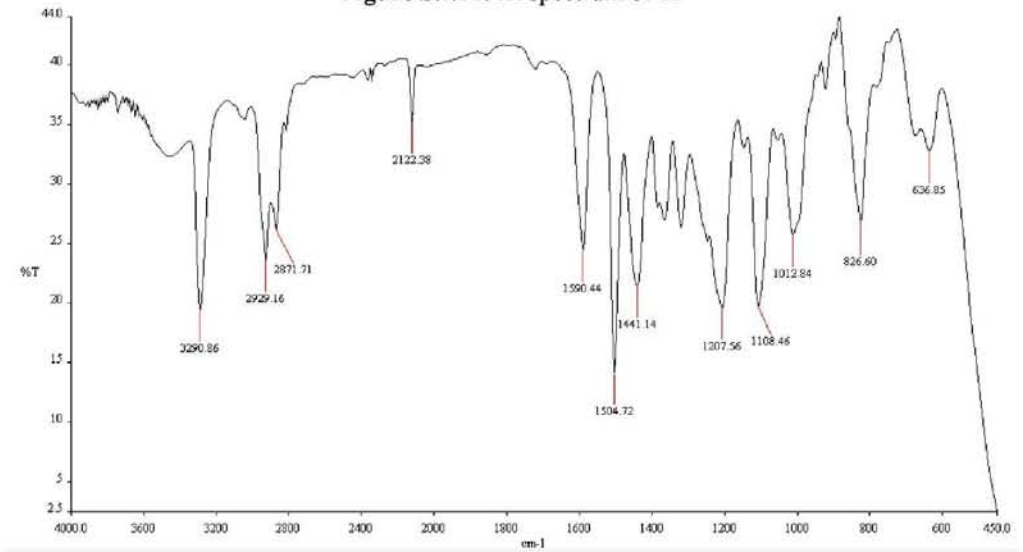


Figure S.I.32. MALDI-TOF mass spectrum of **13** (1/3)

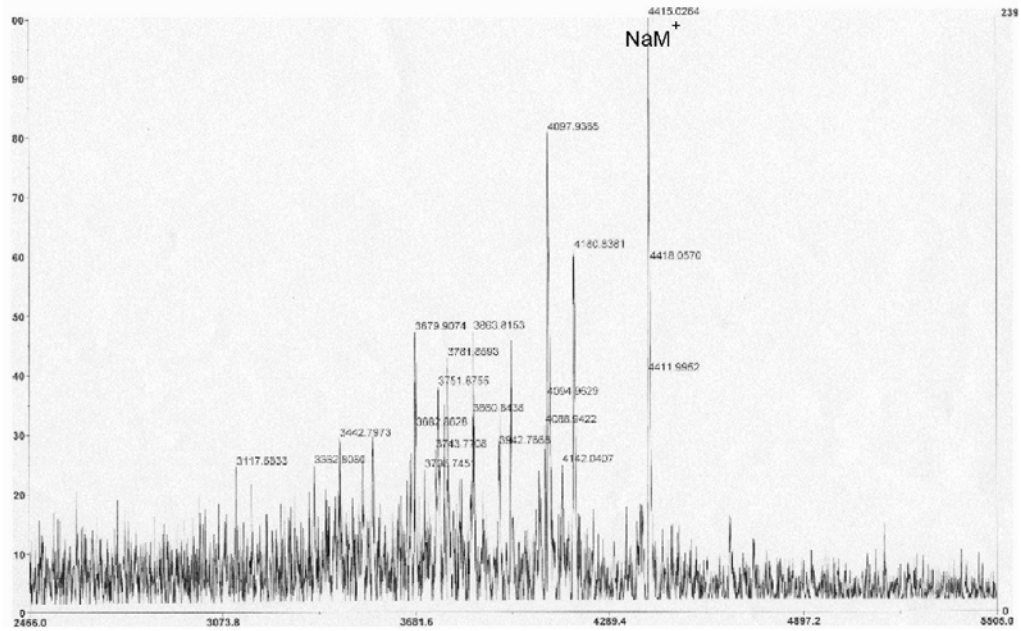


Figure S.I.33. MALDI-TOF mass spectrum of **13** (2/3)
Molecular peak observed and calculated

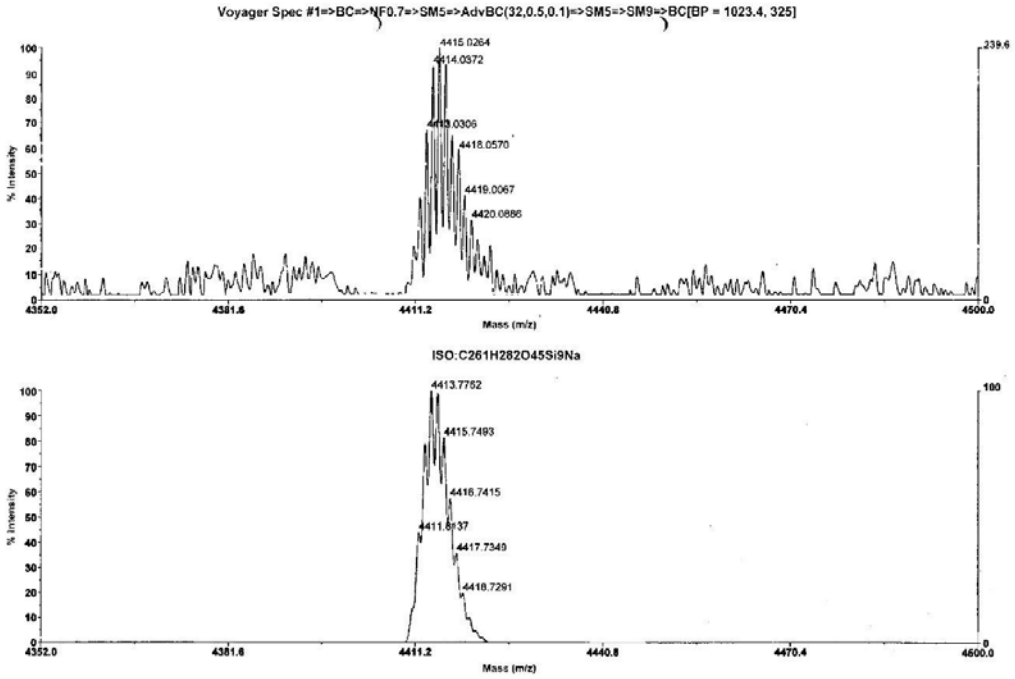


Figure S.I.34. MALDI-TOF mass spectrum of **13** (3/3)
Molecular peak observed

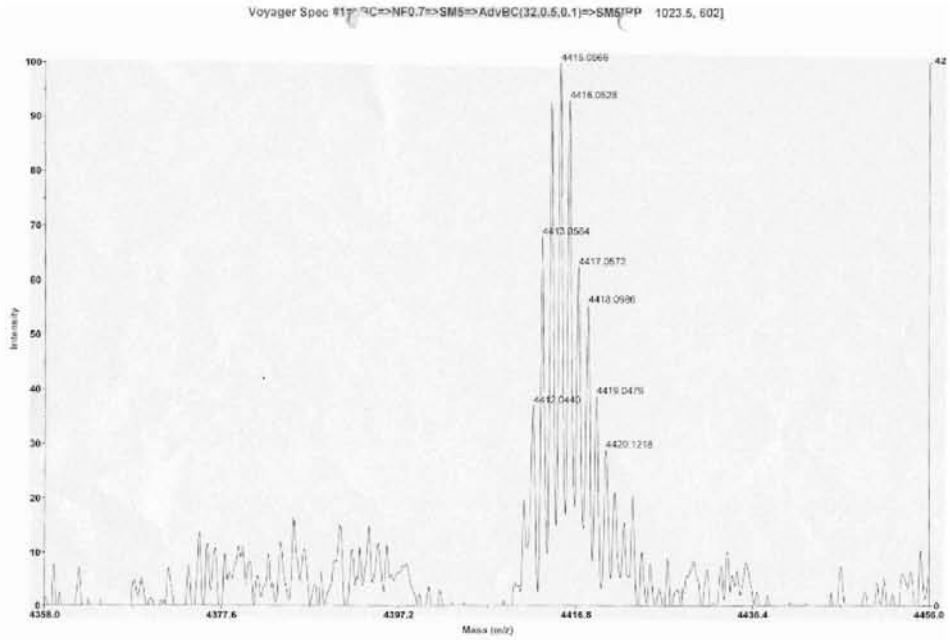
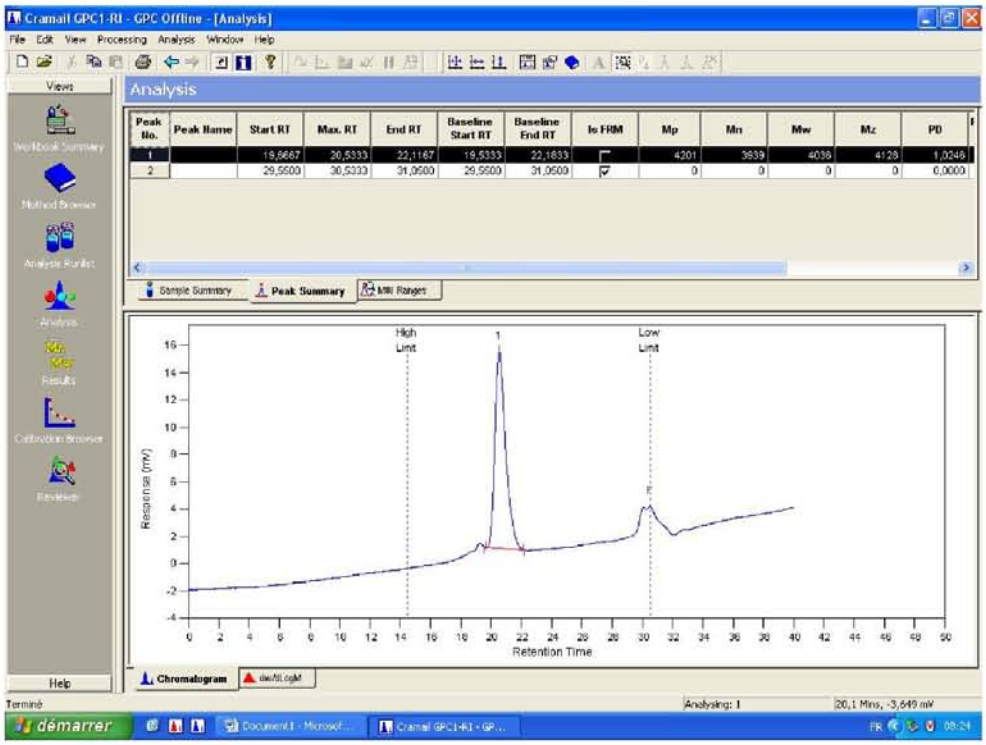
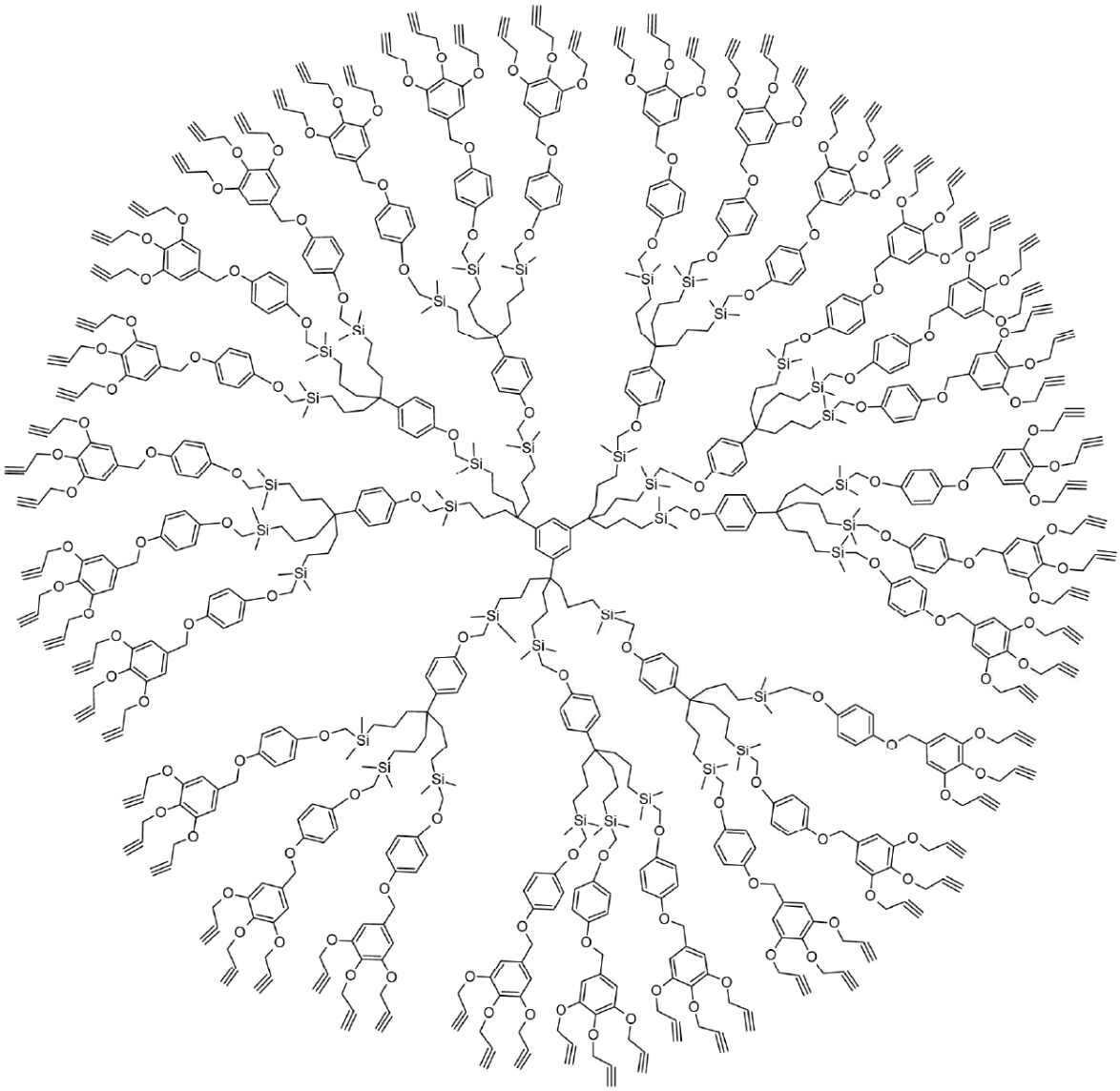


Figure S.I.35. SEC curve of **13**



SI27

Compound **14**: 81-alkynyl dendrimer



$C_{882}H_{1002}O_{144}Si_{36}$; MW 14918.46 g.mol^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=7.20 to 6.80 ppm (m, 201H, $\underline{H}_{Ar}$), 4.90 ppm (s, 54H, O-C$\underline{H}_2$-C_{Ar}), 4.74 ppm (s, 162H, O-C$\underline{H}_2$-C≡C), 3.57 ppm (s, 18H, inner Si-C$\underline{H}_2$-O), 3.48 ppm (s, 54H, outer Si-C$\underline{H}_2$-O), 2.50 ppm (s, 81H, C≡C-$\underline{H}$), 1.65 ppm (s, 72H, C$\underline{H}_2$-CH_2-CH_2-Si), 1.16 ppm (s, 72H, CH_2-C$\underline{H}_2$-CH_2-Si), 0.59 ppm (s, 72H, CH_2-CH_2-C$\underline{H}_2$-Si), 0.12 ppm (s, 54H, inner Si-C$\underline{H}_3$), 0.05 ppm (s, 162H, outer Si-C$\underline{H}_3$); ^{13}C NMR (75 MHz, $CDCl_3$, 25°C, TMS): δ=158.00, 155.04, 151.41, 150.60, 144.76, 138.26, 135.58 and 132.53 (C_{Ar}quat), 126.14, 117.01, 114.70, 113.76, 112.38 and 106.68 (C_{Ar}-H), 78.17, 77.44, 74.98 and 74.34 (*C*≡C-H and C≡*C*-H), 69.50 (C_{Ar}-*C*H_2-O), 59.89, 59.27, 59.07 and 55.98 (O-*C*H_2-C≡C-H and Si-*C*H_2-O), 42.00 (*Cquat.*), 40.98 (*C*H2-CH2-CH_2-Si), 16.61 (CH2-*C*H2-CH_2-Si), 13.53 (CH2-CH2-*C*H_2-Si), -5.44 and –5.60 (Si-*C*H_3); ^{29}Si NMR (60 MHz, $CDCl_3$, 25°C, TMS) shows only one peak at 0.793 ppm (all the branches have reacted); IR: ν=2122 cm^{-1} (C≡C) and 3292 cm^{-1} (C≡C-H); Elemental analysis calcd (%) for: $C_{882}H_{1002}O_{144}Si_{36}$: C 71.01, H 6.77; found: C 70.51, H 7.28; DOSY NMR gives D = 2.41 .10^{-10} m².s^{-1} in chloroform at 25°C which corresponds to a size of 4.8 nm; DLS gives only one population at a size of 6.2 nm ± 0.2nm; Size exclusion chromatography (SEC) shows the low polydispersity (1.02) and the size progression for the three alkynyl dendrimers.

Figure S.I.36. ^{1}H NMR spectrum of **14** (300 MHz $CDCl_3$)

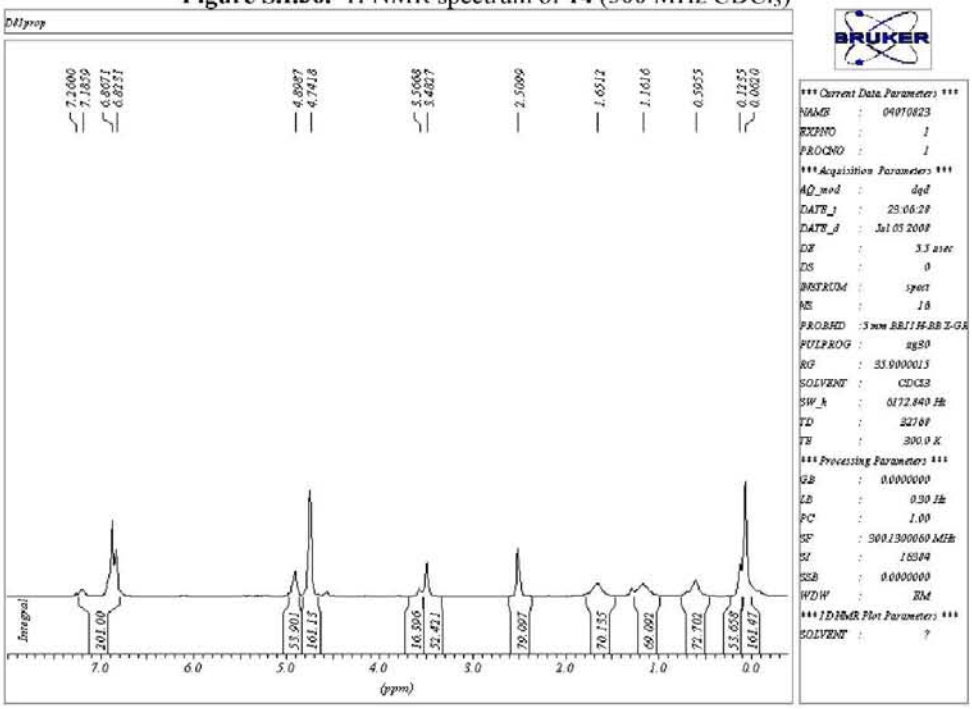
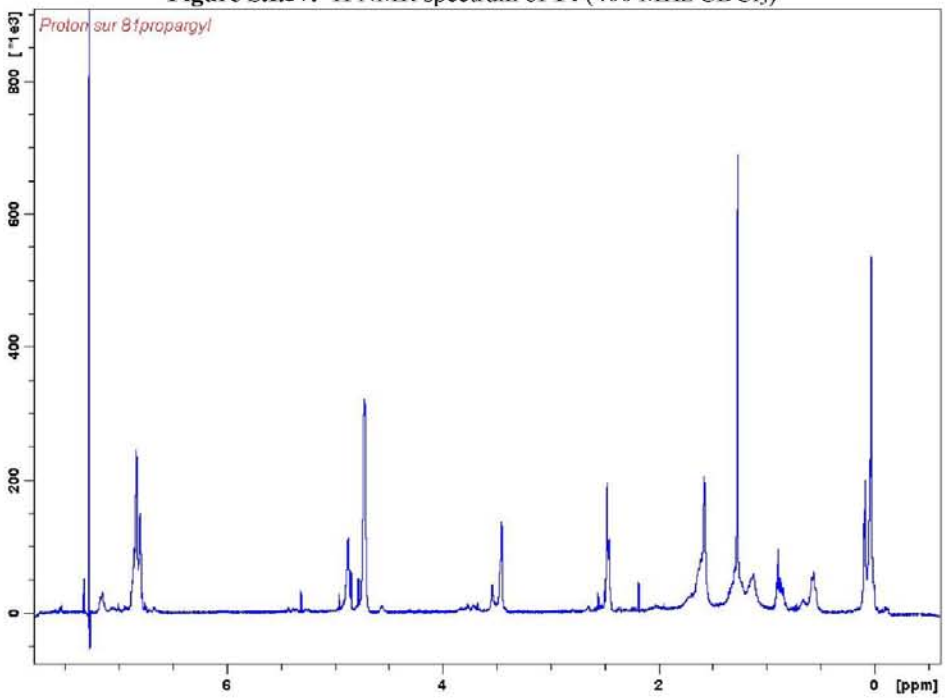


Figure S.I.37. ^{1}H NMR spectrum of **14** (400 MHz $CDCl_3$)



SI29

Figure S.I.38. ^{13}C NMR spectrum of **14** (62.9 MHz $CDCl_3$)

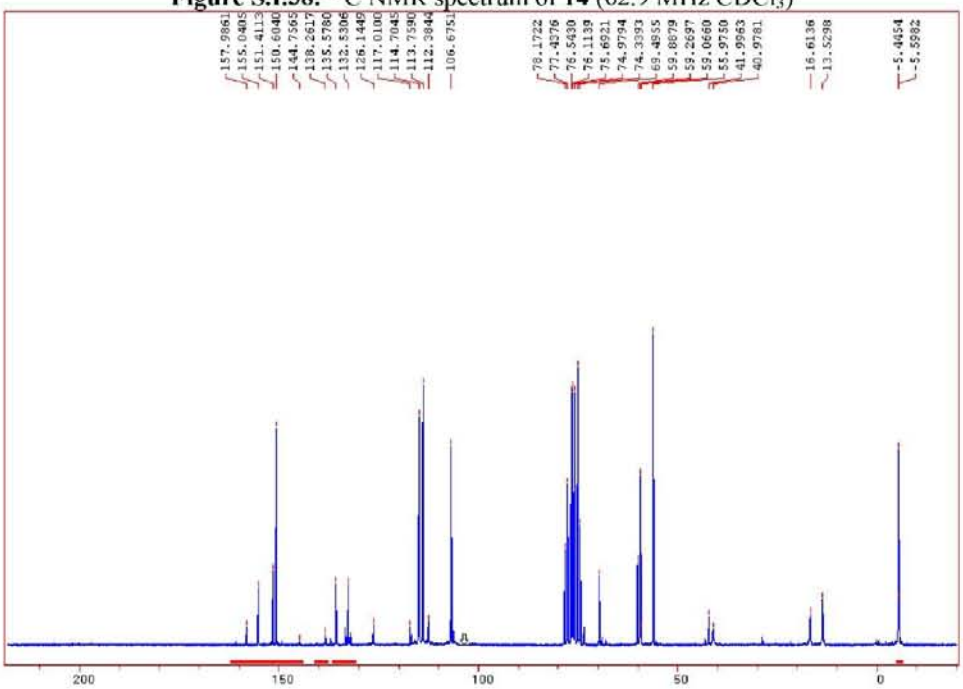
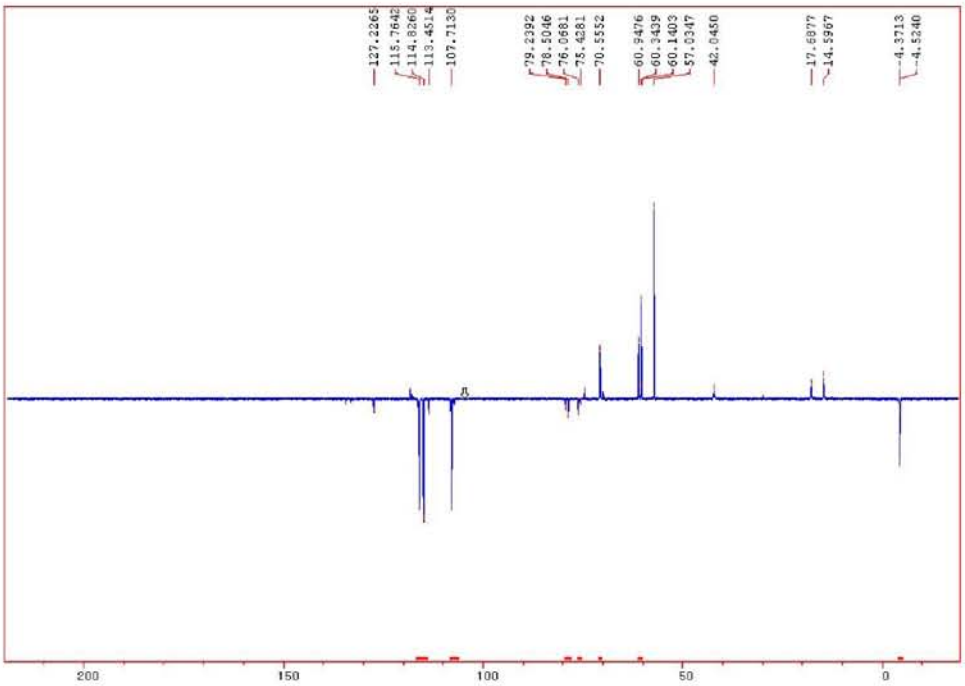


Figure S.I.39. ^{13}C DEPT 135 NMR spectrum of **14** (75.5 MHz $CDCl_3$)



SI30

Figure S.I.40. ^{29}Si NMR spectrum of **14** (59.6 MHz $CDCl_3$)

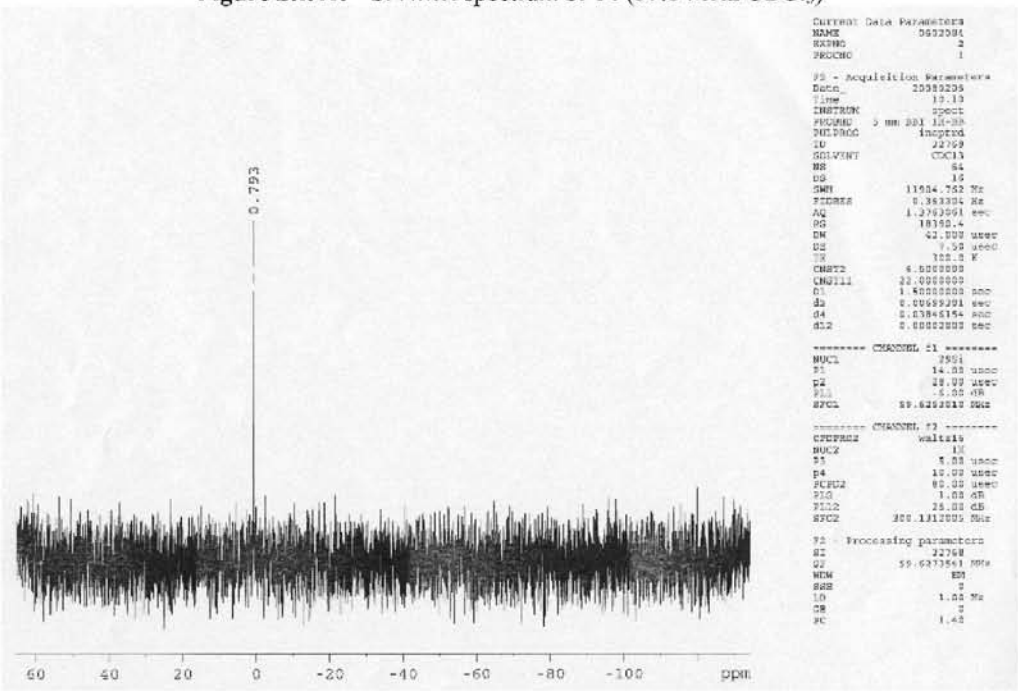


Figure S.I.41. IR spectrum of **14**

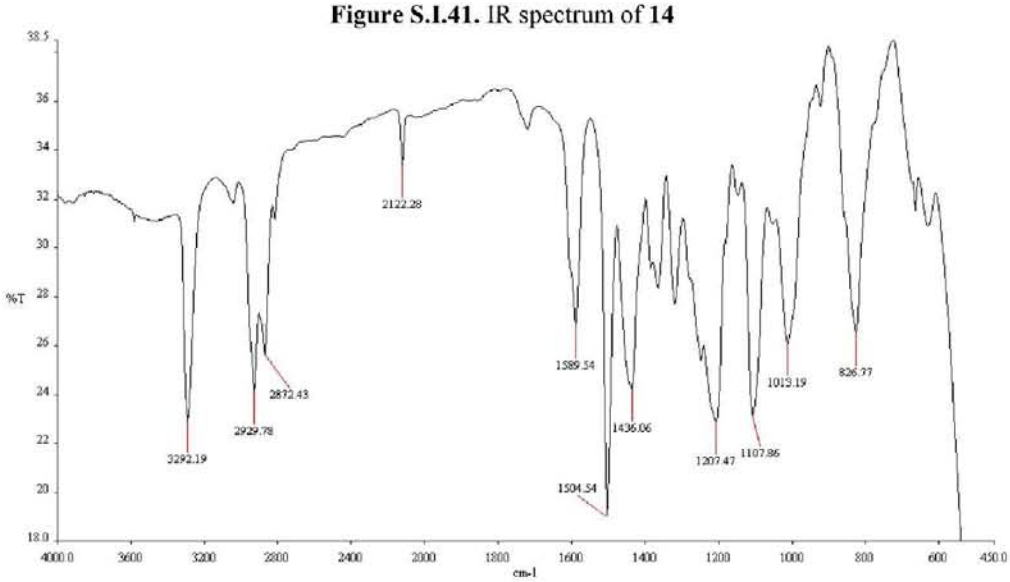
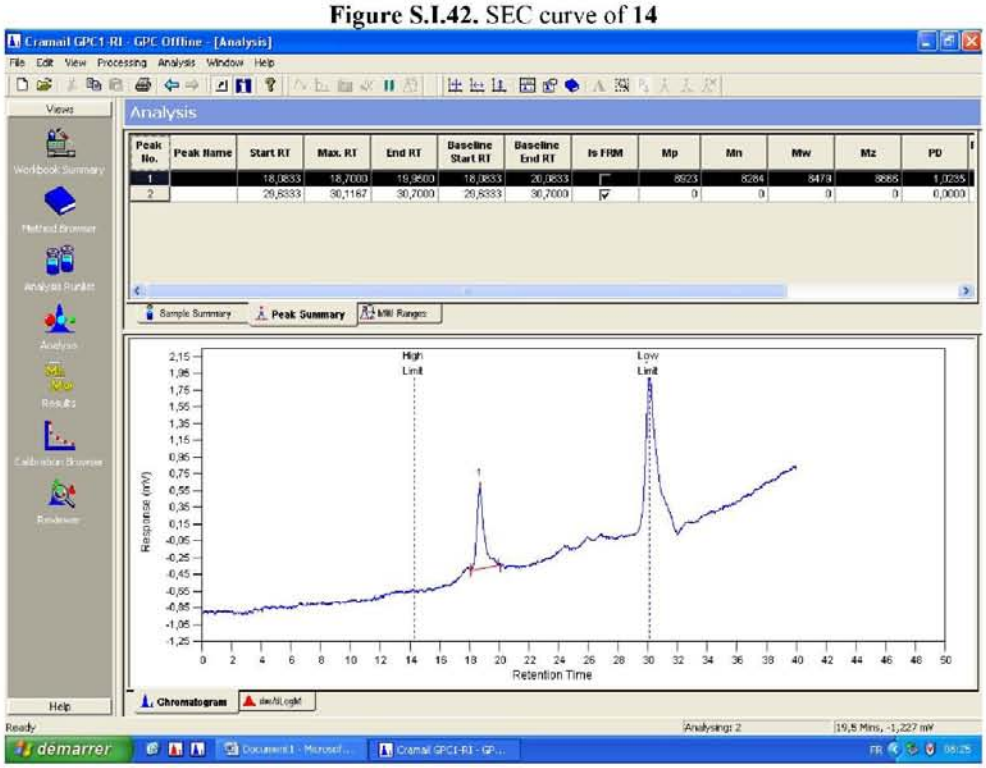
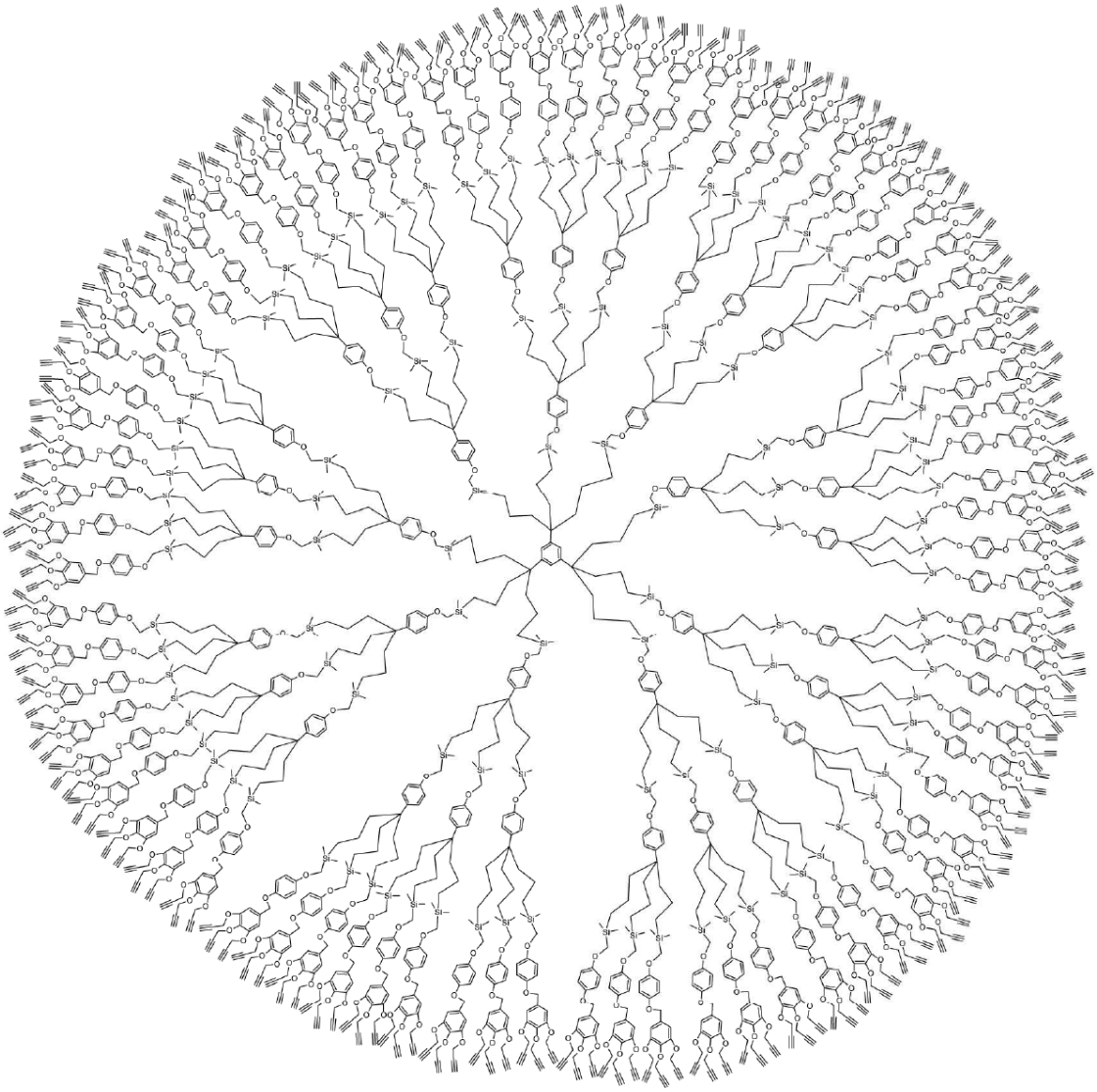


Figure S.I.42. SEC curve of **14**



SI32



Compound **15**: 243-alkynyl dendrimer

$C_{2745}H_{3162}O_{441}Si_{117}$; MW 46498.43 g.mol^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$, 25°C, TMS): δ=7.14 to 6.75 ppm (m, 633H, $\underline{H}_{Ar}$) 4.84 ppm (s, 162H, O-C$\underline{H}_2$-C_{Ar}), 4.69 ppm (s, 486H, O-C$\underline{H}_2$-C≡C), 3.50 ppm (s, 72H, inner Si-C$\underline{H}_2$-O), 3.42 ppm (s, 162H, outer Si-C$\underline{H}_2$-O), 2.47 to 2.43 ppm (m, 243H, C≡C-$\underline{H}$), 1.61 ppm (s, 234H, C$\underline{H}_2$-CH_2-CH_2-Si), 1.11 ppm (s, 234H, CH_2-C$\underline{H}_2$-CH_2-Si), 0.54 ppm (s, 234H, CH_2-CH_2-C$\underline{H}_2$-Si), 0.06 ppm (s, 216H, inner Si-C$\underline{H}_3$), 0.01 ppm (s, 486H, outer Si-C$\underline{H}_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25°C, TMS): δ=159.05, 156.10, 152.49, 151.69, 139.33, 136.69 and 133.58 ppm (quat. C_{Ar}), 127.21, 115.57, 114.83, 113.46 and 107.76 ppm (C_{Ar}-H), 79.24, 78.51, 76.04 and 75.37 ppm (*C*≡C-H and C≡*C*-H), 70.55 ppm (C_{Ar}-*C*H_2-O), 60.92, 60.35, 60.15 and 57.06 ppm (O-*C*H_2-C≡C-H and Si-*C*H_2-O), 43.06 ppm (quat. *C*.), 42.09 ppm (*C*H_2-CH_2-CH_2-Si), 17.71 ppm (CH_2-*C*H_2-CH_2-Si), 14.62 ppm (CH_2-CH_2-*C*H_2-Si), -4.51 ppm (Si-*C*H_3); ^{29}Si NMR (59.6 MHz, $CDCl_3$, 25°C, TMS) shows only one peak at 0.792 ppm (all the branches have reacted); IR: ν=2122 cm^{-1} (C≡C) and 3293 cm^{-1} (C≡C-H); DOSY NMR gives D = 2.35.10^{-10} m².s^{-1} in chloroform at 25°C which corresponds to a size of 4.9 nm; DLS gives only one population at a size of 6.6 nm ± 0.2nm; Size exclusion chromatography (SEC) shows the low polydispersity (1.02) and the size progression for the three alkynyl dendrimers.

SI34

Figure S.I.43. ^{1}H NMR spectrum of **15** (300 MHz $CDCl_3$)

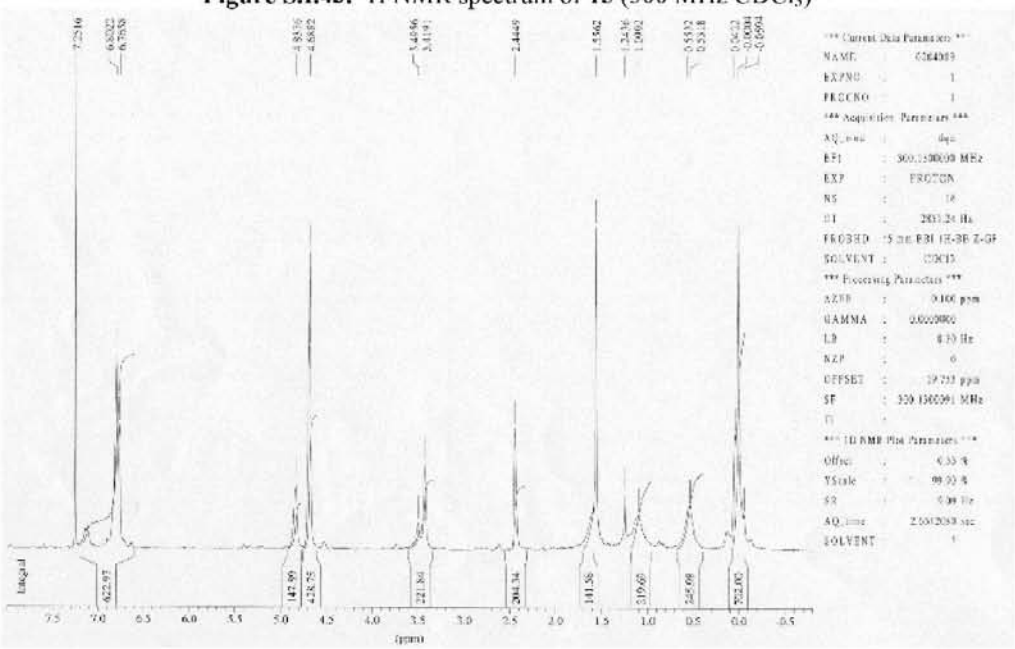
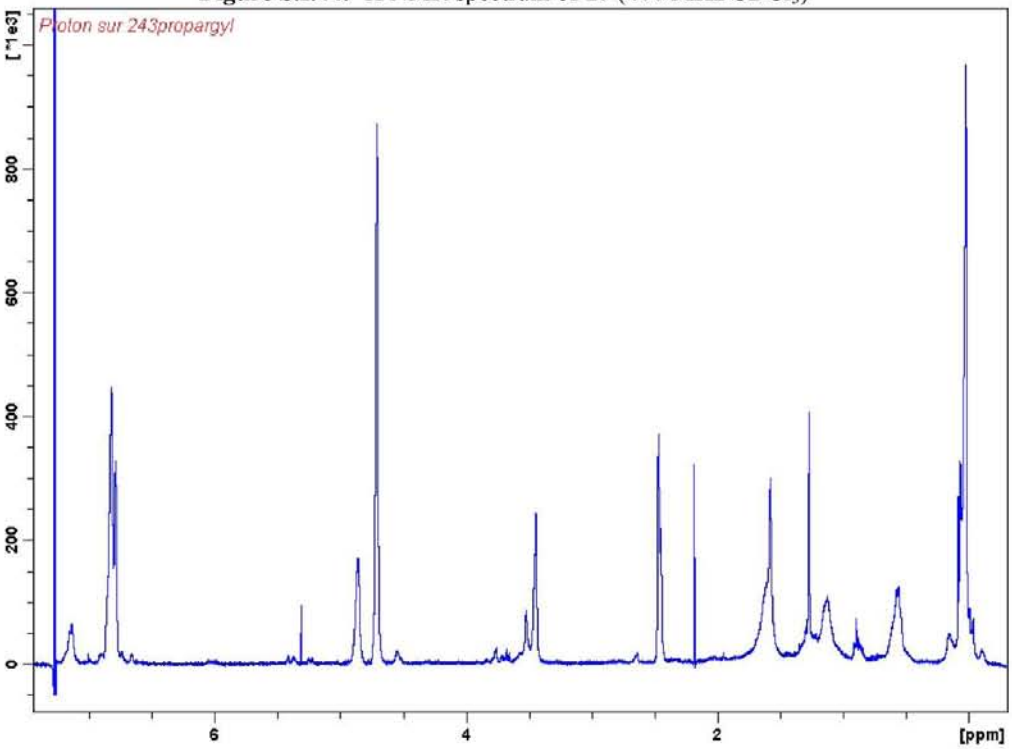


Figure S.I.44. ^{1}H NMR spectrum of **15** (400 MHz $CDCl_3$)



SI35

Figure S.I.45. ^{13}C NMR spectrum of **15** (62.9 MHz $CDCl_3$)

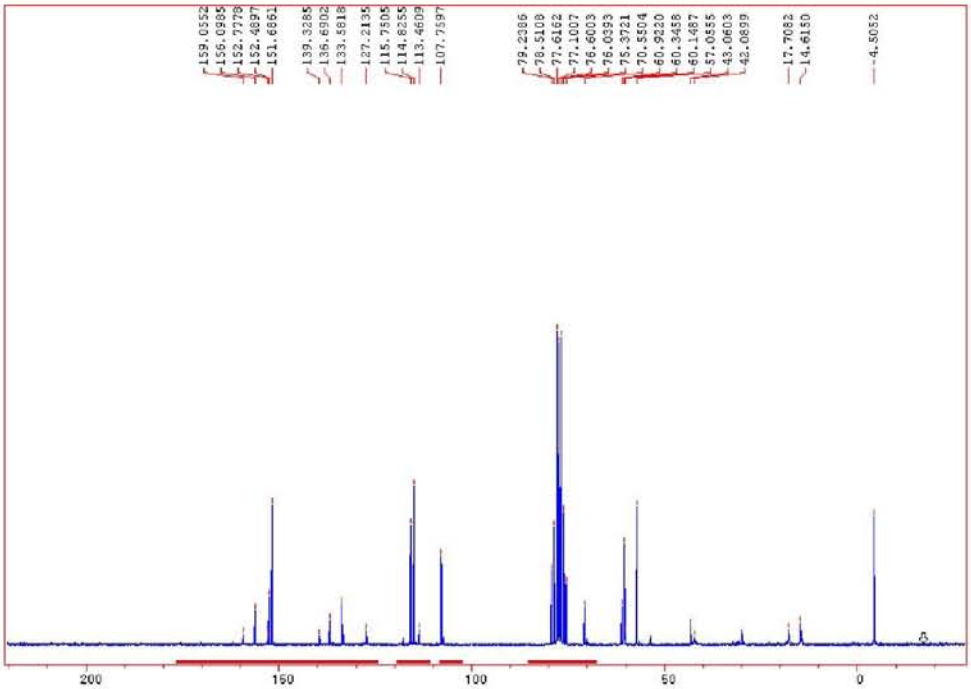
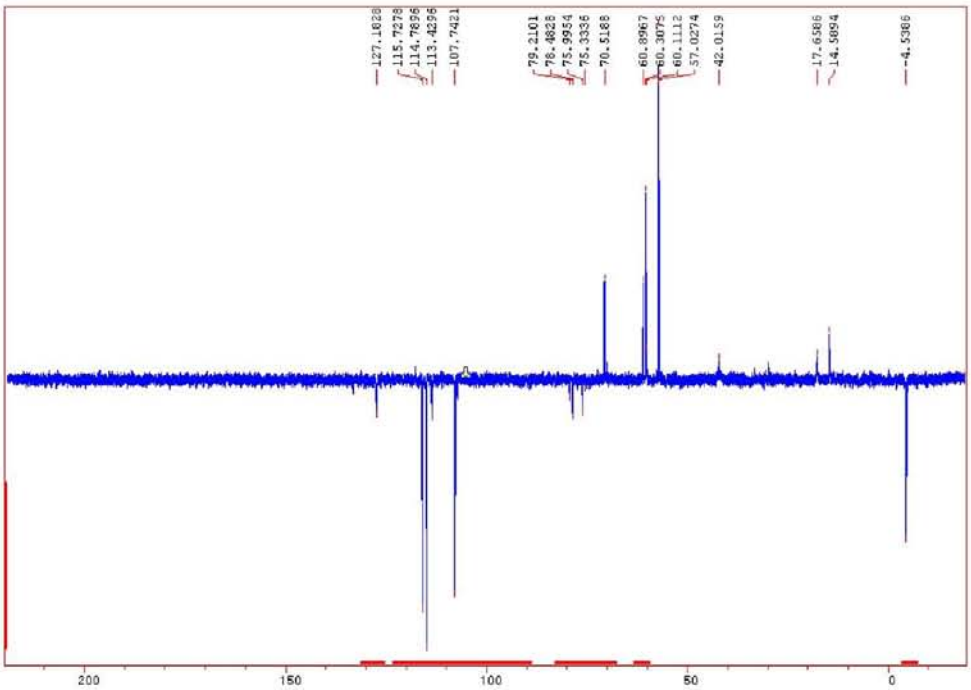


Figure S.I.46. ^{13}C DEPT 135 NMR spectrum of **15** (75.5 MHz $CDCl_3$)



SI36

Figure S.I.47. ^{29}Si NMR spectrum of **15** (59.6 MHz $CDCl_3$)

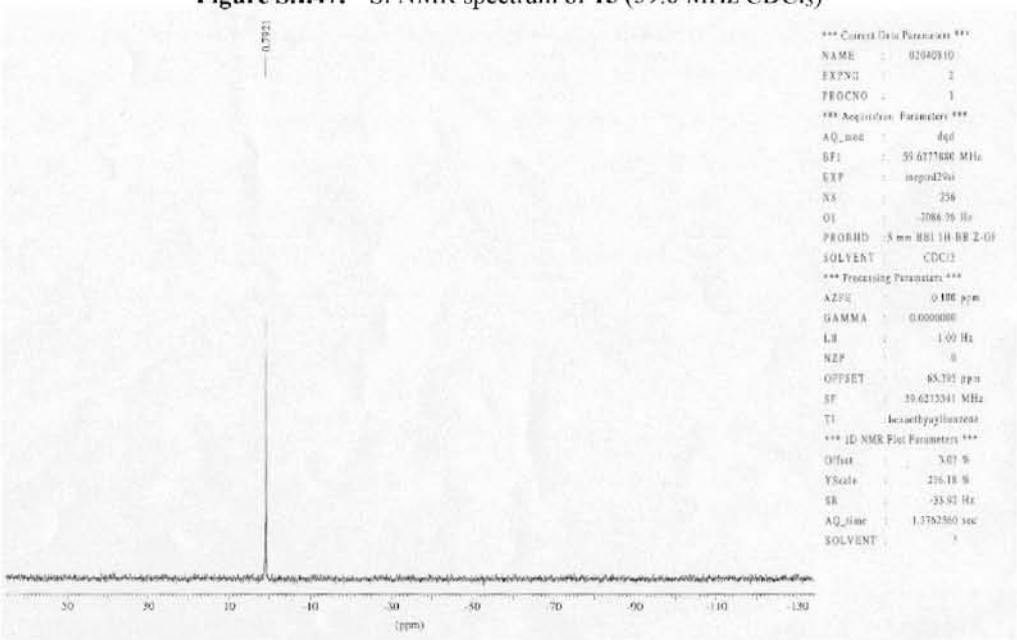
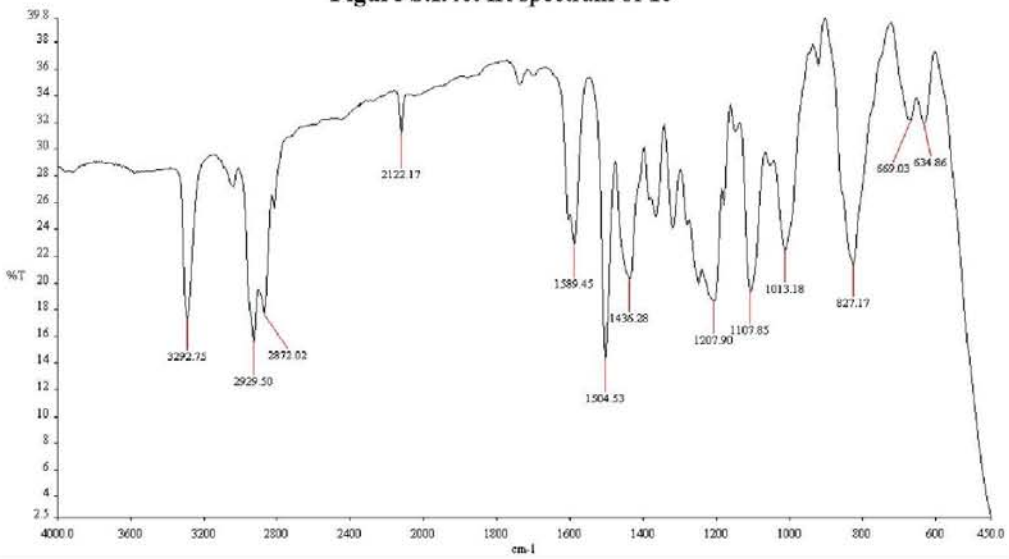


Figure S.I.48. IR spectrum of **15**



SI37

Figure S.I.49. SEC curve of **15**

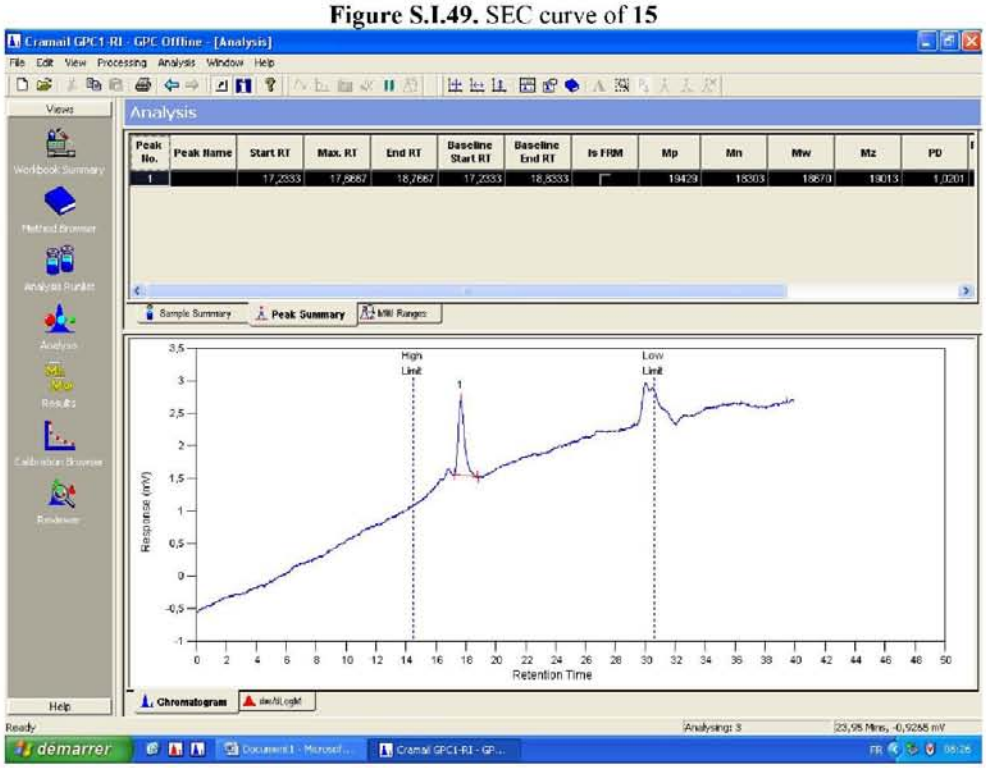
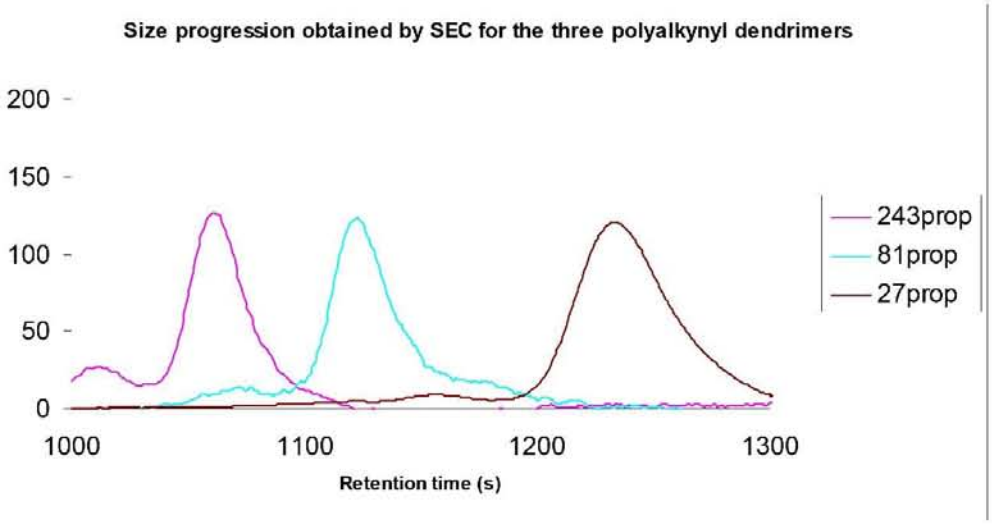
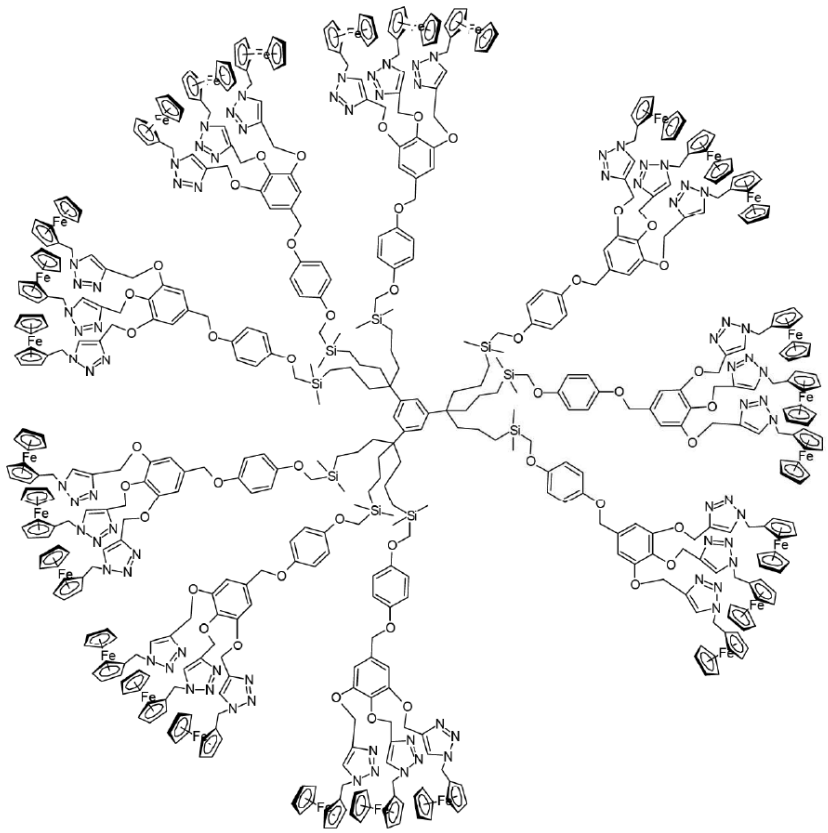


Figure S.I.50. Size progression obtained by SEC for the three polyalkynyl dendrimers **13, 14** and **15**





Compound **16**: 27-ferrocenyl dendrimer

$C_{558}Fe_{27}H_{579}N_{81}O_{45}Si_9$; MW 10900.88 g.mol^{-1}; ^{1}H NMR (300MHz, $CDCl_3$, 25°C, TMS): δ=7.62 and 7.60 ppm (s, 27H, $\underline{H}_{triazole}$), 7.12 to 6.66 ppm (m, 57H, $\underline{H}_{Ar}$), 5.24 to 5.05 ppm (m, 108H, $C_{triazole}$-C$\underline{H}_2$-$C_{ferrocene}$ and $C_{triazole}$-C$\underline{H}_2$-O), 4.72 ppm (s, 18H, C_{Ar}-C$\underline{H}_2$-O), 4.27 to 4.13 ppm (m, 243H, $C_{Ferrocene}$-$\underline{H}$), 3.48 ppm (s, 18H, Si-C$\underline{H}_2$-O), 1.68 ppm (s, 18H, C$\underline{H}_2$-CH_2-CH_2-Si), 1.15 ppm (s, 18H, CH_2-C$\underline{H}_2$-CH_2-Si), 0.60 ppm (s, 18H, CH_2-CH_2-C$\underline{H}_2$-Si), 0.05 ppm (s, 54H, Si-C$\underline{H}_3$); ^{13}C NMR (63 MHz, $CDCl_3$, 25°C, TMS): δ=156.44, 152.82 and 152.58 ppm (quat. C_{Ar}), 146.62 ppm (core quat. C_{Ar}), 144.72 and 143.98 ppm (quat. $C_{triazol}$), 137.10 and 133.84 ppm (quat. C_{Ar}), 123.77 and 123.28 ppm ($C_{triazol}$-H), 116.38 and 115.88 ppm (C_{Ar}-H), 115.19 (core C_{Ar}-H), 107.26 ppm (C_{Ar}-H), 81.80 and 81.48 ppm (quat. $C_{ferrocene}$), 72.58, 70.73, 69.30, 69.14, 66.67 and 66.01 ppm ($C_{ferrocene}$-H), 63.41 and 63.36 ppm ($C_{triazol}$-CH_2-O), 61.27 ppm (Si-CH_2-O), 50.40 and 50.24 ppm ($C_{ferrocene}$-CH_2-N), 44.31 ppm (*Cquat*), 42.35 ppm (CH_2-CH_2-CH_2-Si), 18.24 ppm (CH_2-CH_2-CH_2-Si), 14.95 ppm (CH_2-CH_2-CH_2-Si), -4.04 ppm (Si-CH_3); ^{29}Si NMR shows only one peak at -0.388 ppm ; No more azide or alkyne absorption in IR spectroscopy; MALDI-TOF mass spectrum: molecular peak obtained at m/z = 10927 (calc. for NaM^+ 10924) and side peaks m/z = 10686 [M – 1 ferrocenyl], 10444 [M – 2 ferrocenyl], 9866 [M – 1 dendron] and 9632 [M – 1 dendron – 1 ferrocenyl]; DOSY NMR gives D = $3.65.10^{-10}$ m².s^{-1} in chloroform which corresponds to a size of 3.2 nm; Size exclusion chromatography (SEC) shows the low polydispersity (1.03) and the size progression for the three ferrocenyl dendrimers. Some signals are doubled in NMR spectroscopy due to the difference between meta and para substituents (such as for the 81-ferrocenyl and the 243-ferrocenyl dendrimers).

Figure S.I.51. ^{1}H NMR spectrum of **16** (300 MHz $CDCl_3$)

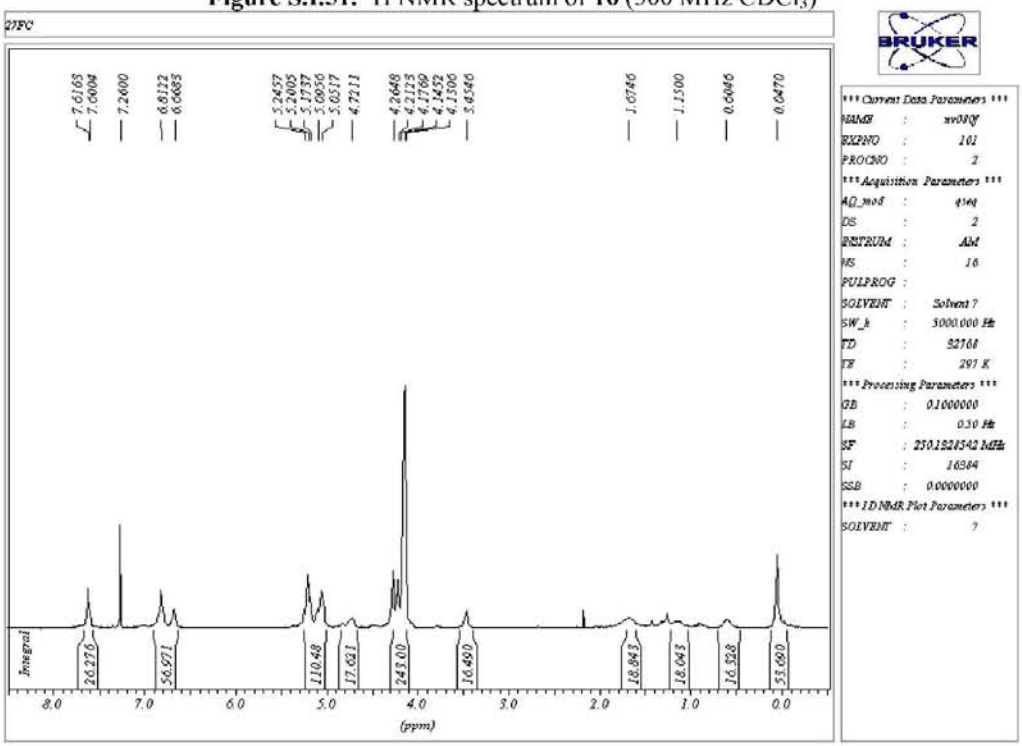
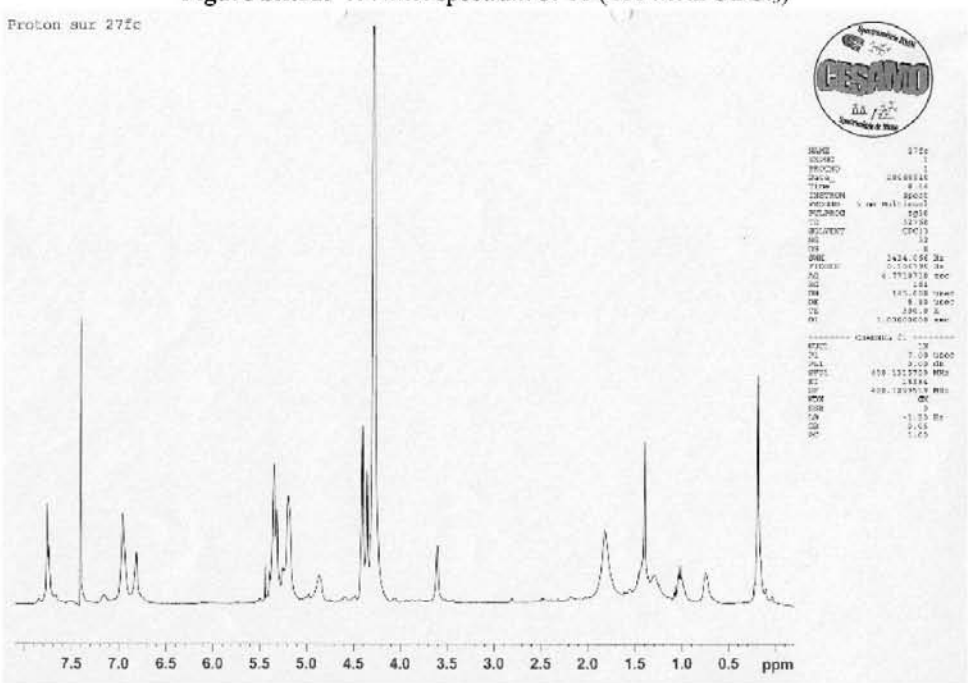


Figure S.I.52. ^{1}H NMR spectrum of **16** (400 MHz $CDCl_3$)



SI40

Figure S.I.53. ^{13}C NMR spectrum of **16** (75.5 MHz $CDCl_3$)

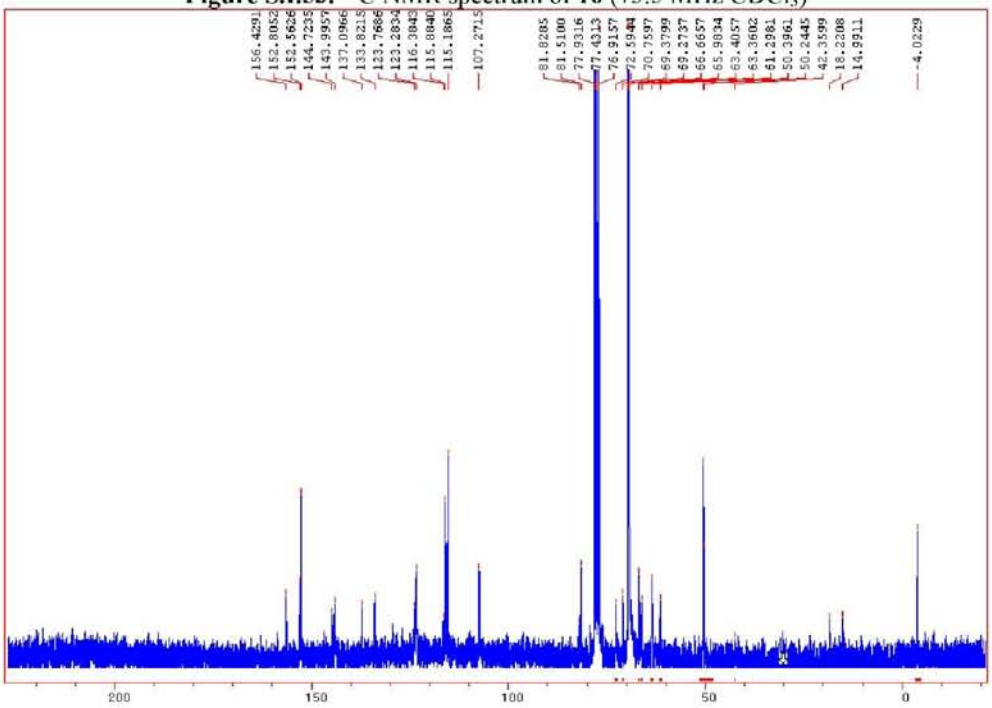
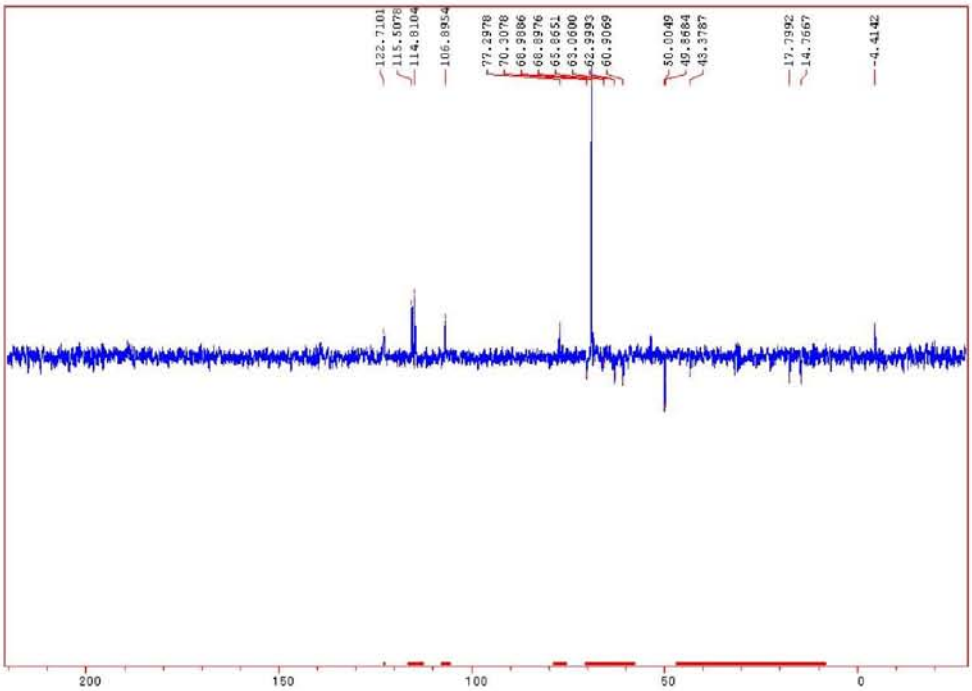


Figure S.I.54. ^{13}C DEPT 135 NMR spectrum of **16** (75.5 MHz $CDCl_3$)



SI41

Figure S.I.55. ^{29}Si NMR spectrum of **16** (59.6 MHz $CDCl_3$)

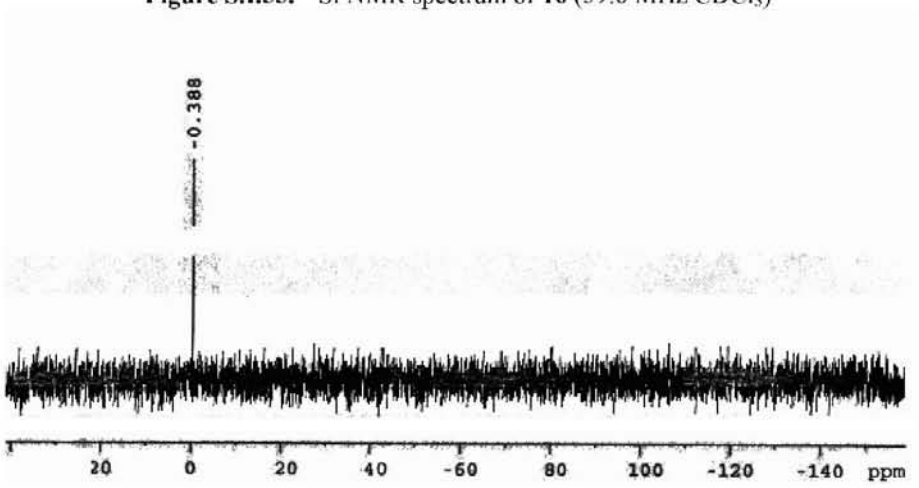
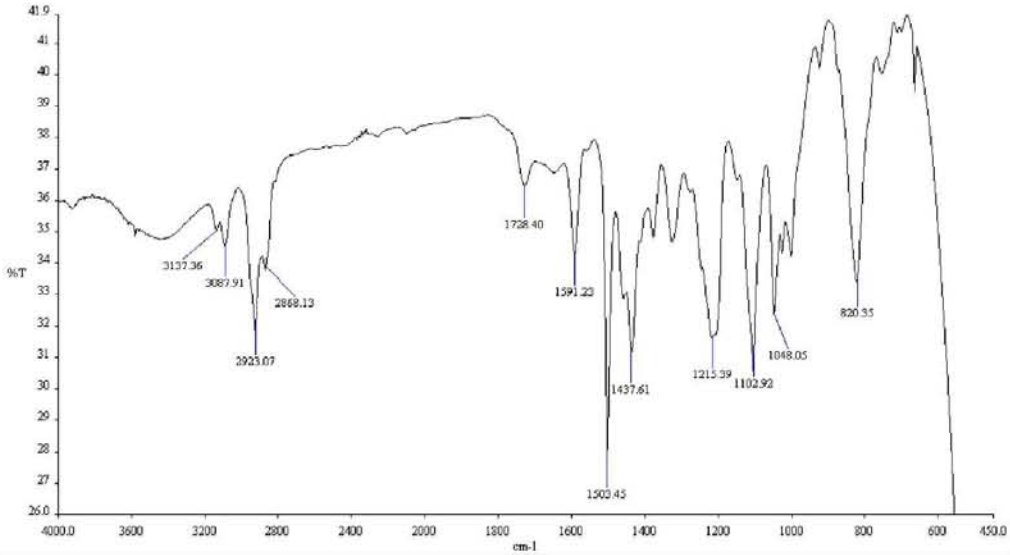


Figure S.I.56. IR spectrum of **16**



The two tiny peaks between 2000 and 2400 cm^{-1} appear for all the poly(ferrocenylmethyltriazolyl) dendrimers. They are located at 2258.7 and 2095.0 cm^{-1} for **16**, 2258 and 2094 cm^{-1} for the 81-ferrocenyl dendrimer **17** and 2254 and 2087 cm^{-1} for the 243-ferrocenyl dendrimer **18**, and do not correspond to residual alkynyl branches whose absorption is always found at 2122 cm^{-1} in the poly-alkynyl dendrimers.

Figure S.I.57. SEC curve of **16**

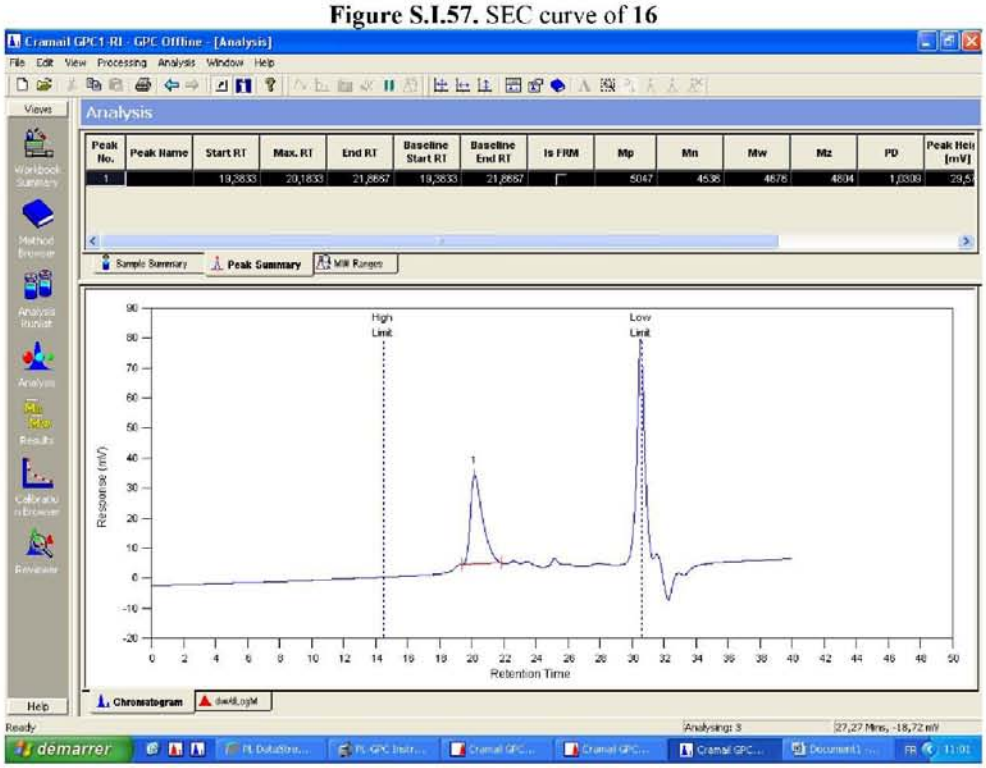


Figure S.I.58. MALDI-TOF mass spectrum of **16** (1/4)

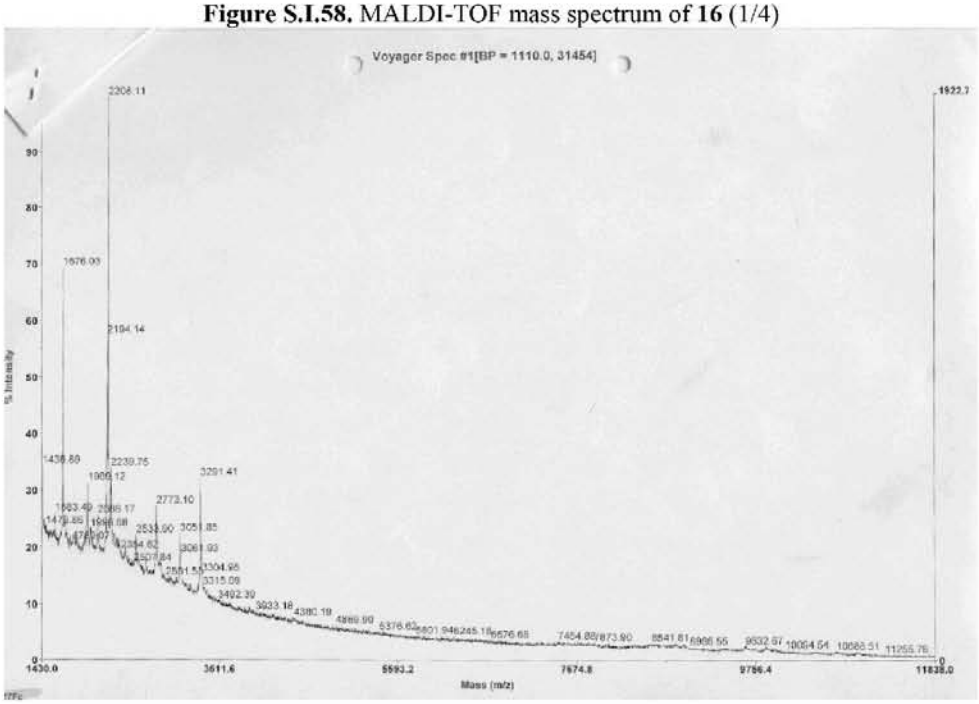


Figure S.I.59. MALDI-TOF mass spectrum of **16** (2/4)

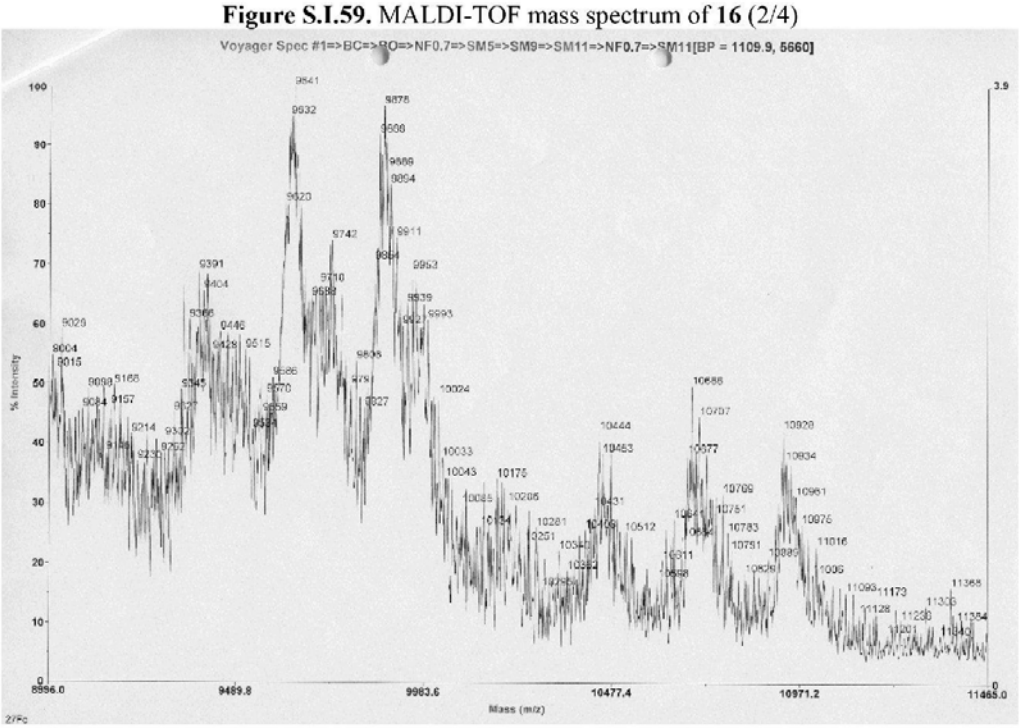
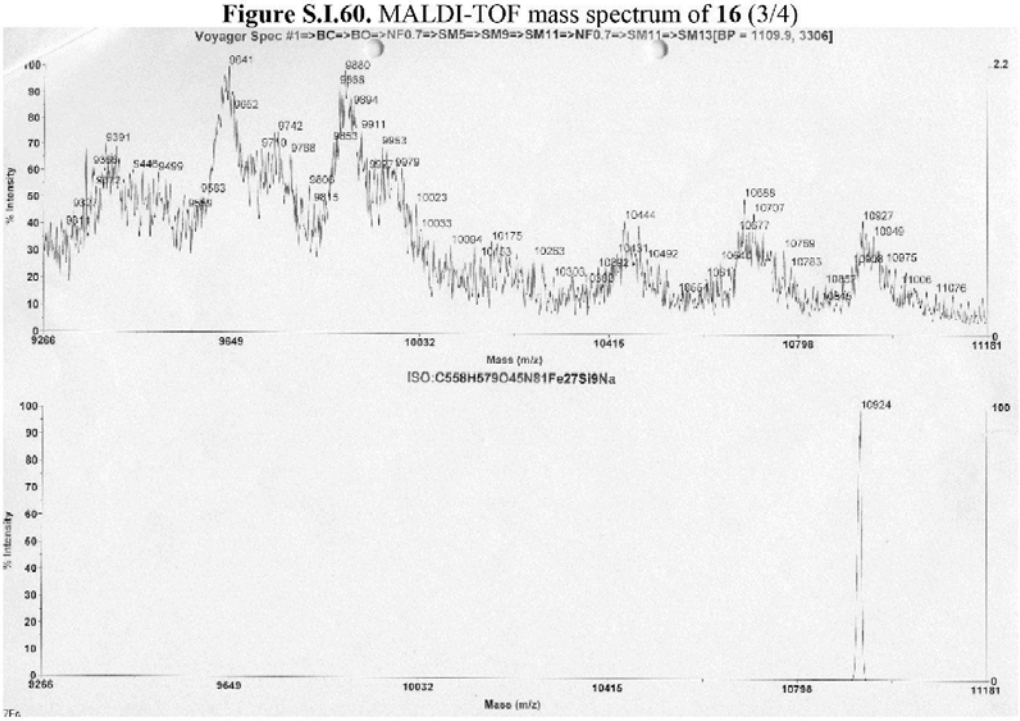
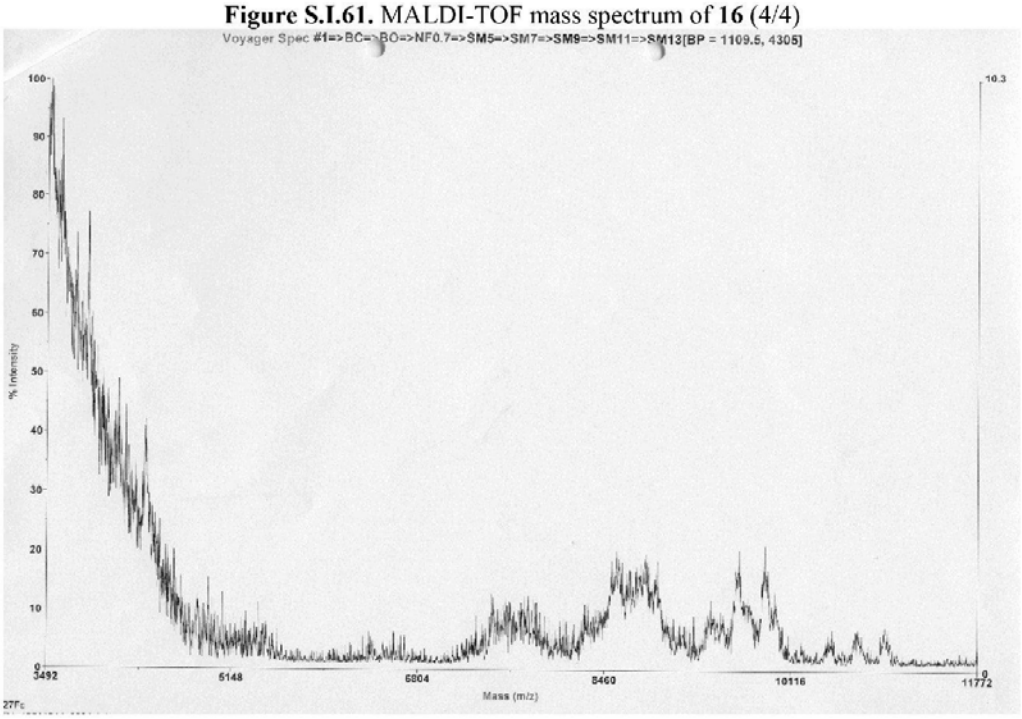


Figure S.I.60. MALDI-TOF mass spectrum of **16** (3/4)

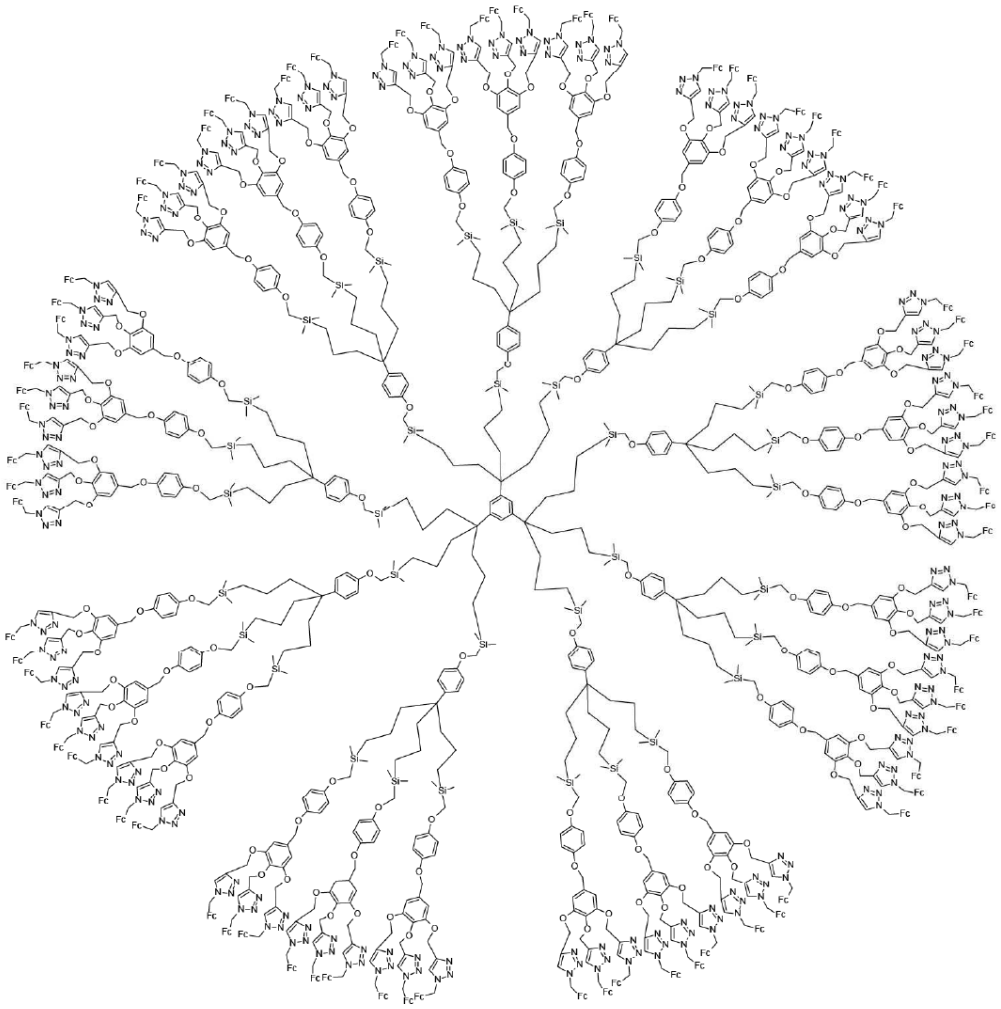


SI44

Figure S.I.61. MALDI-TOF mass spectrum of **16** (4/4)



SI45



Compound **17**: 81-ferrocenyl dendrimer

Fc = Ferrocenyl

81-ferrocenyl dendrimer, **17**: $C_{1773}Fe_{81}H_{1893}N_{243}O_{144}Si_{36}$; MW 34445.72 g.mol^{-1}; ^{1}H NMR (300MHz, $CDCl_3$, 25°C, TMS): δ=7.62 and 7.59 ppm (s, 81H, $\underline{H}_{triazole}$), 7.16 to 6.66 ppm (m, 201H, $\underline{H}_{Ar}$), 5.20 to 5.02 ppm (m, 324H, $C_{triazole}$-C$\underline{H}_2$-$C_{ferrocene}$ and $C_{triazole}$-C$\underline{H}_2$-O), 4.71 ppm (s, 54H, C_{Ar}-C$\underline{H}_2$-O), 4.25 to 4.11 ppm (m, 729H, $C_{Ferrocene}$-$\underline{H}$), 3.54 ppm (s, 18H, inner Si-C$\underline{H}_2$-O), 3.44 ppm (s, 54H, outer Si-C$\underline{H}_2$-O), 1.63 ppm (s, 72H, C$\underline{H}_2$-CH_2-CH_2-Si), 1.12 ppm (s, 72H, CH_2-C$\underline{H}_2$-CH_2-Si), 0.56 ppm (s, 72H, CH_2-CH_2-C$\underline{H}_2$-Si), 0.12 ppm (s, 54H, inner Si-C$\underline{H}_3$), 0.02 (s, 162H, outer Si-C$\underline{H}_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25°C, TMS): δ=159.07 ppm (inner quat. C_{Ar}), 156.10, 152.46 and 152.22 ppm (outer quat. C_{Ar}), 144.33 and 143.60 ppm (quat. $C_{triazol}$), 139.26 ppm (inner quat. C_{Ar}), 136.84 and 133.51 ppm (outer quat. C_{Ar}), 127.18 ppm (inner C_{Ar}-H), 123.48 and 123.00 ppm ($C_{triazol}$-H), 116.07 and 115.56 ppm (outer C_{Ar}-H), 114.87 ppm (inner C_{Ar}-H), 107.00 ppm (outer C_{Ar}-H), 81.49 and 81.21 ppm (quat. $C_{ferrocene}$), 72.02, 70.41, 68.93, 68.75, 66.30 and 65.94 ppm ($C_{ferrocene}$-H), 63.04 ppm ($C_{triazol}$-CH_2-O), 60.97 ppm (Si-CH_2-O), 50.02 and 49.88 ppm ($C_{ferrocene}$-CH_2-N), 43.06 ppm (*Cquat*), 42.00 ppm (CH_2-CH_2-CH_2-Si), 17.62 ppm (CH_2-CH_2-CH_2-Si), 14.57 ppm (CH_2-CH_2-CH_2-Si), -4.49 ppm (Si-CH_3); ^{29}Si NMR shows only one peak at –0.412 ppm ; No more azide or alkyne absorption in IR spectroscopy; DOSY NMR gives D = 3.02.10^{-10} m².s^{-1} in chloroform which corresponds to a size of 3.8 nm; Size exclusion chromatography (SEC) shows the low polydispersity (1.01) and the size progression for the three ferrocenyl dendrimers.

Figure S.I.62. ^{1}H NMR spectrum of **17** (300 MHz $CDCl_3$)

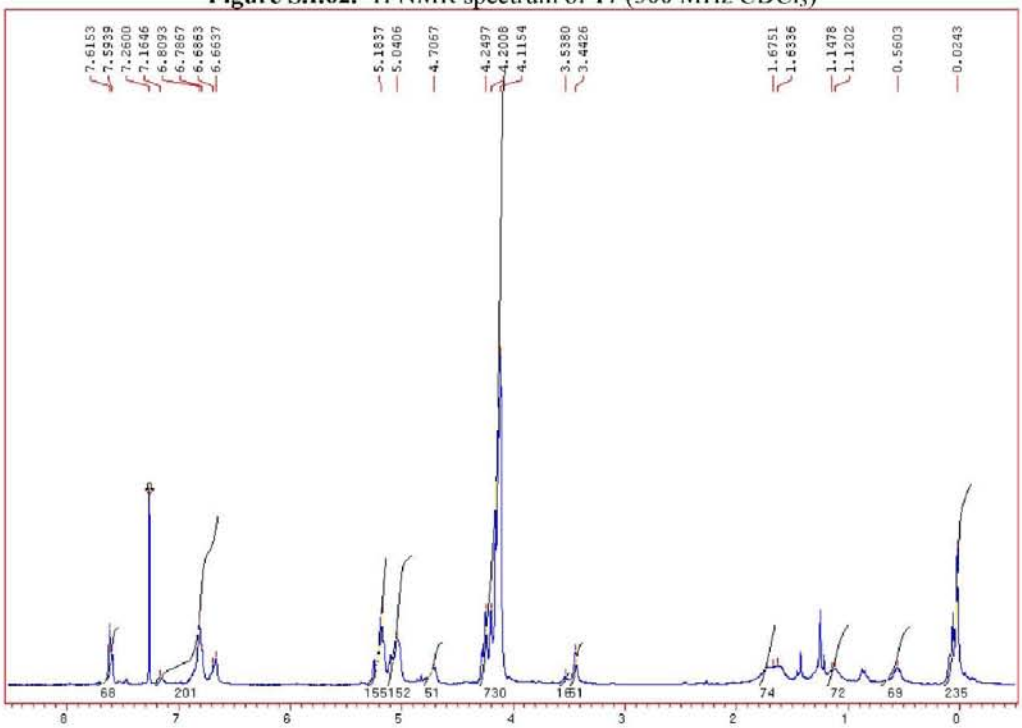
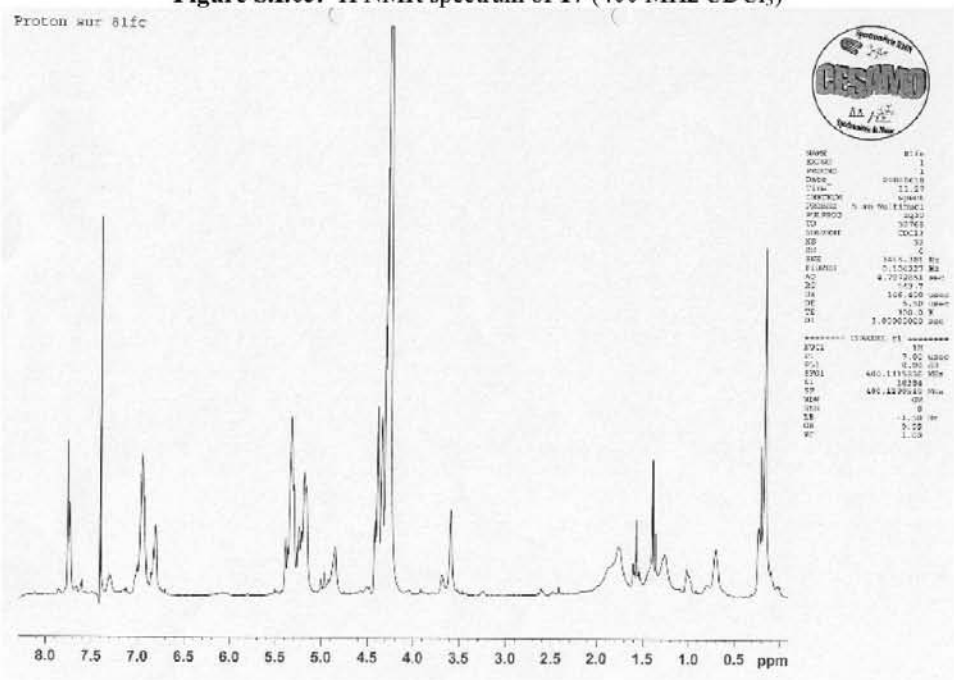


Figure S.I.63. ^{1}H NMR spectrum of **17** (400 MHz $CDCl_3$)



SI47

Figure S.I.64. ^{13}C NMR spectrum of **17** (75.5 MHz $CDCl_3$)

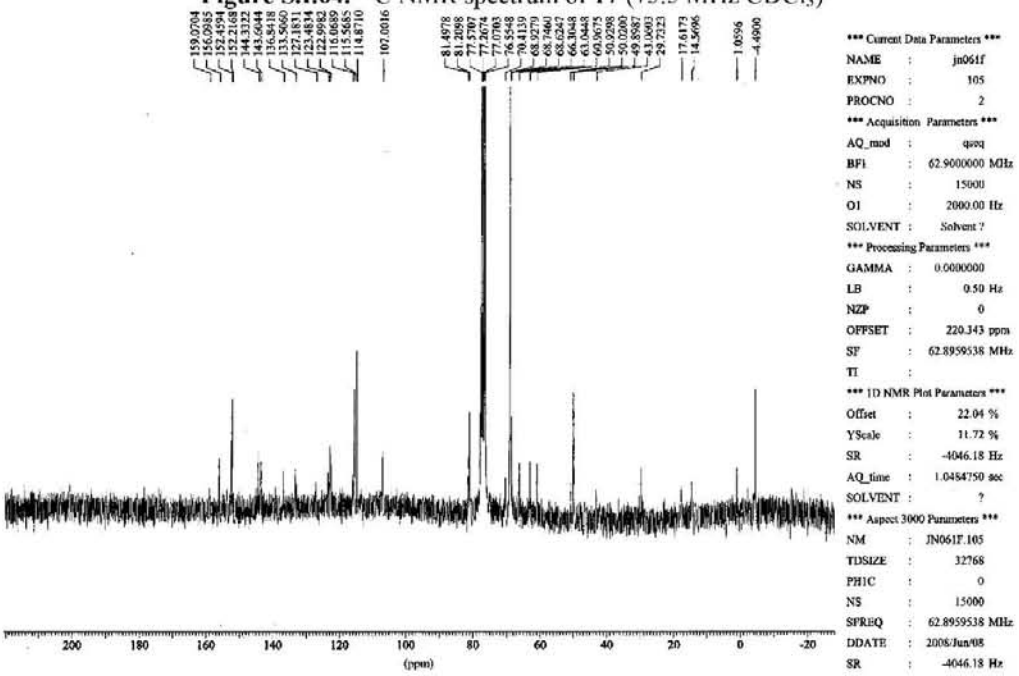


Figure S.I.65. ^{13}C DEPT 135 NMR spectrum of **17** (75.5 MHz $CDCl_3$)

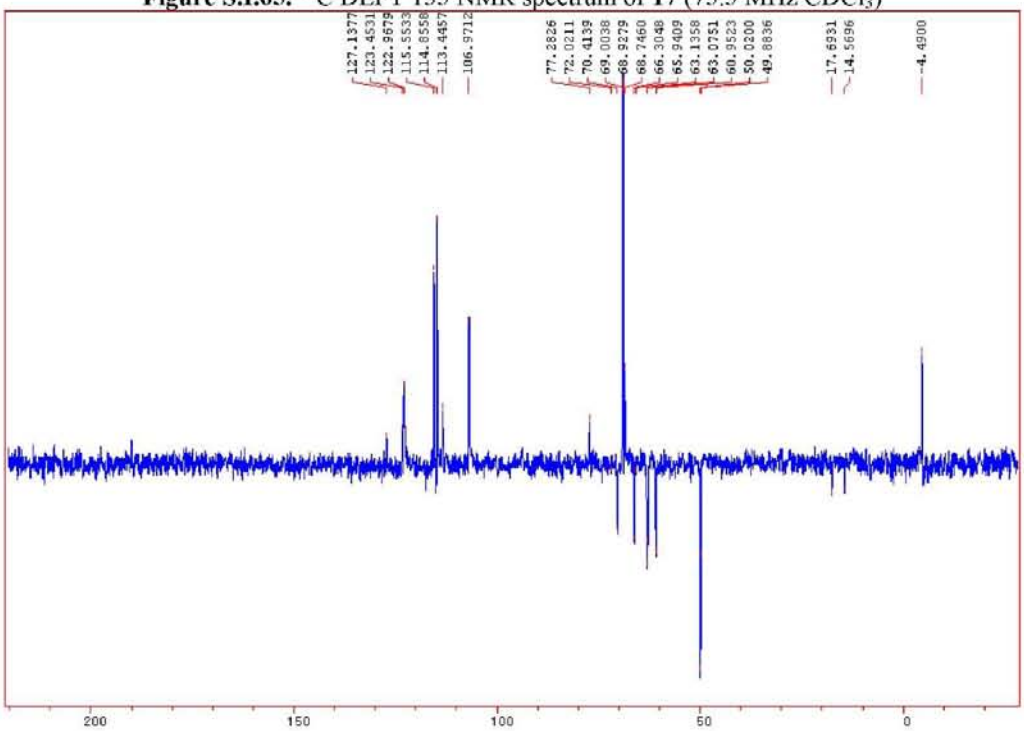
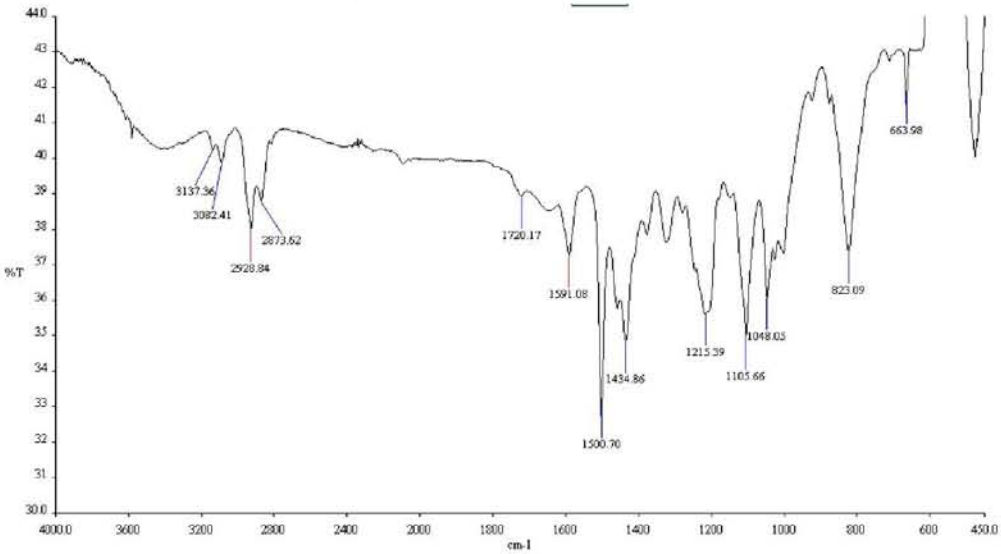
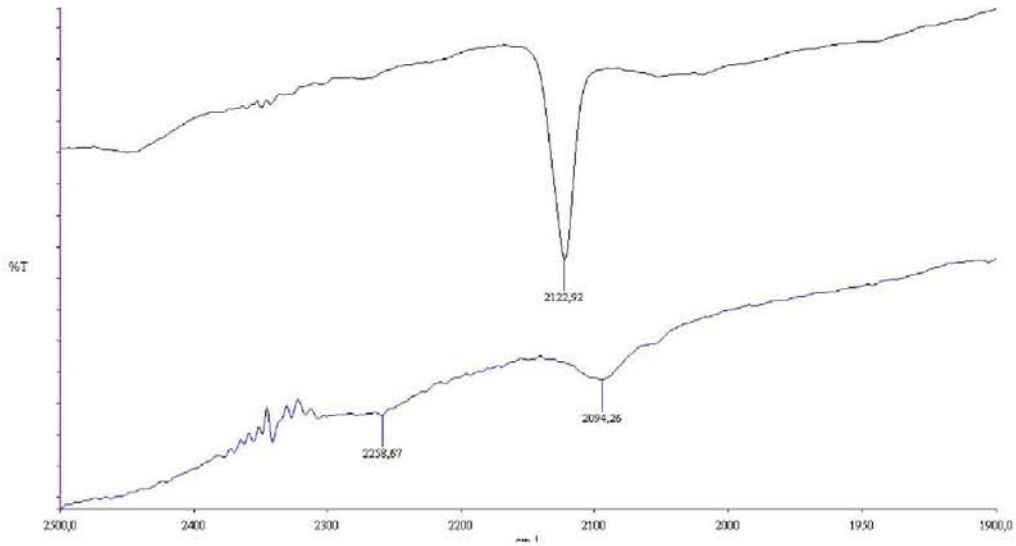


Figure S.I.66. IR spectrum of **17**



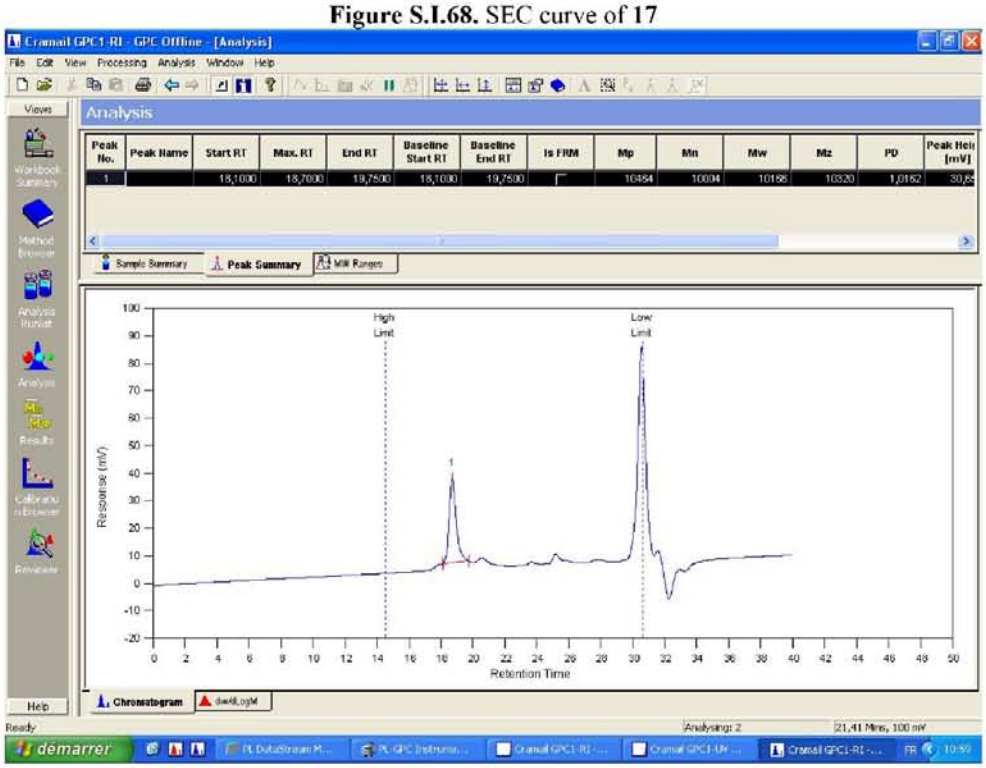
The two tiny peaks between 2000 and 2400 cm^{-1} appear for all the poly(ferrocenylmethyltriazolyl) dendrimers. They are located at 2258.7 and 2094.3 cm^{-1} for **17,** 2258 and 2095 cm^{-1} for the 27-ferrocenyl dendrimer **16** and 2254 and 2087 cm^{-1} for the 243-ferrocenyl dendrimer **18**, and do not correspond to residual alkynyl branches whose absorption is always found at 2122 cm^{-1} in the poly-alkynyl dendrimers.

Figure S.I.67. Enlarged region around 2000-2300 cm^{-1} of the IR spectrum of **17** (bottom) vs. that of the corresponding polyalkynyl dendrimer **14** (top).



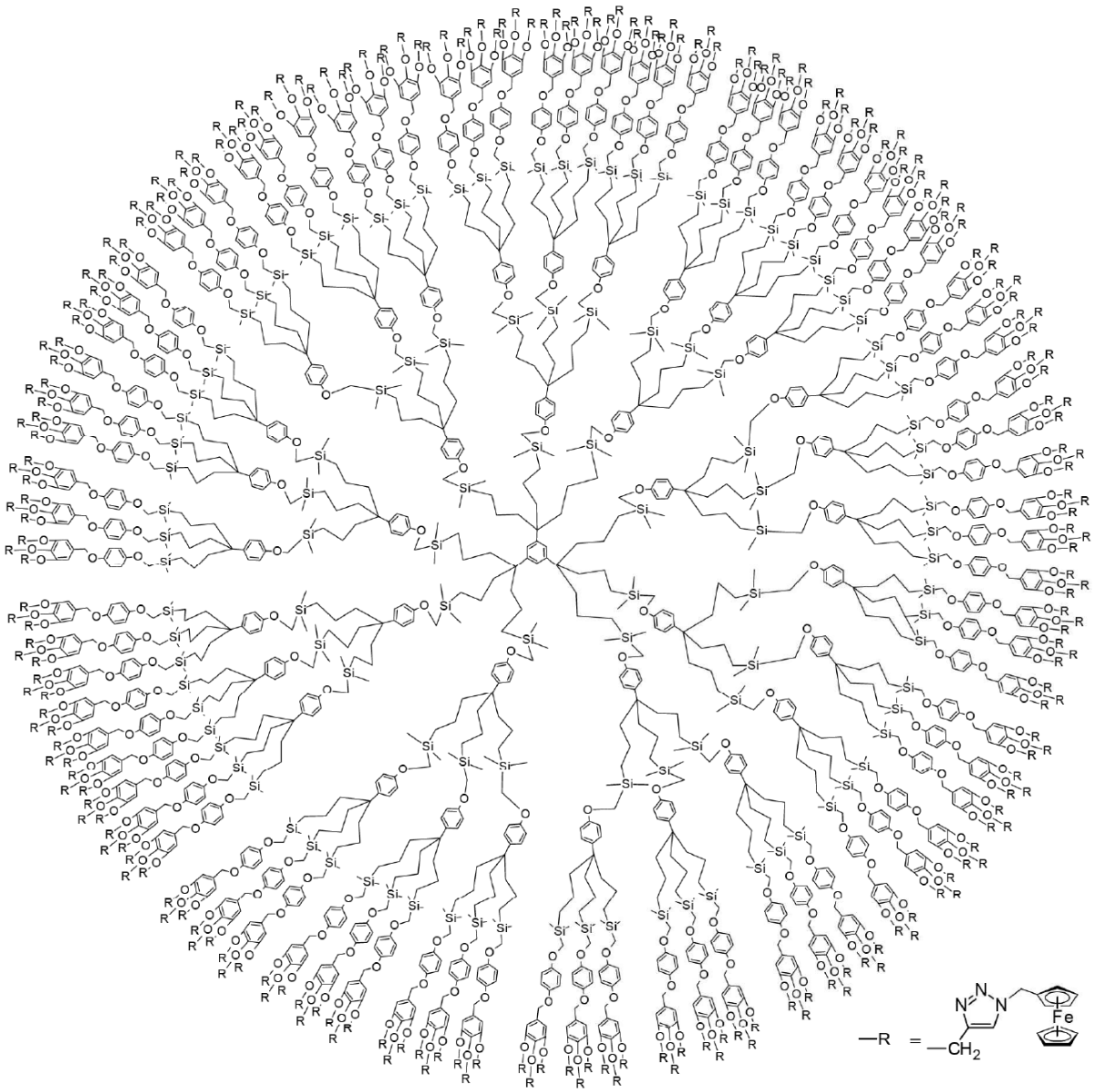
SI49

Figure S.I.68. SEC curve of **17**



SI50

Compound **18**: 243-ferrocenyl dendrimer



$C_{5418}Fe_{243}H_{5835}N_{729}O_{441}Si_{117}$; MW 105080.24 g.mol^{-1}; ^{1}H NMR (300MHz, $CDCl_3$, 25°C, TMS): δ=7.61 and 7.59 ppm (s, 243H, $\underline{H}_{triazole}$), 7.16 to 6.64 ppm (m, 633H, $\underline{H}_{Ar}$), 5.15 to 5.01 ppm (m, 972H, $C_{triazole}$-C$\underline{H}_2$-$C_{ferrocene}$ and $C_{triazole}$-C$\underline{H}_2$-O), 4.70 ppm (s, 162H, C_{Ar}-C$\underline{H}_2$-O), 4.22 to 4.08 ppm (m, 2187H, $C_{Ferrocene}$-$\underline{H}$), 3.51 ppm (s, 72H, inner Si-C$\underline{H}_2$-O), 3.43 ppm (s, 162H, outer Si-C$\underline{H}_2$-O), 1.60 ppm (s, 234H, C$\underline{H}_2$-CH_2-CH_2-Si), 1.10 ppm (s, 234H, CH_2-C$\underline{H}_2$-CH_2-Si), 0.55 ppm (s, 234H, CH_2-CH_2-C$\underline{H}_2$-Si), 0.07 ppm (s, 216H, inner Si-C$\underline{H}_3$), 0.02 ppm (s, 486H, outer Si-C$\underline{H}_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25°C, TMS): δ=159.09 ppm (inner quat. C_{Ar}), 156.08, 152.46 and 152.22 ppm (outer quat. C_{Ar}), 144.33 and 143.60 ppm (quat. $C_{triazol}$), 138.92 ppm (inner quat. C_{Ar}), 136.81 and 133.48 ppm (outer quat. C_{Ar}), 128.85 and 127.17 ppm (inner C_{Ar}-H), 123.42 and 122.97 ppm ($C_{triazol}$-H), 115.82 and 115.55 ppm (outer C_{Ar}-H), 114.87 ppm (inner C_{Ar}-H), 106.99 ppm (outer C_{Ar}-H), 81.56 and 81.24 ppm (quat. $C_{ferrocene}$), 72.07, 70.41, 68.93, 68.61, 66.34 and 65.94 ppm ($C_{ferrocene}$-H), 63.08 ppm ($C_{triazol}$-CH_2-O), 60.95 ppm (Si-CH_2-O), 50.02 and 49.87 ppm ($C_{ferrocene}$-CH_2-N), 43.06 ppm (*Cquat*), 42.54 ppm (CH_2-CH_2-CH_2-Si), 17.62 ppm (CH_2-CH_2-CH_2-Si), 14.66 ppm (CH_2-CH_2-CH_2-

Si), -4.44 ppm (Si-CH_3); ^{29}Si NMR shows only one peak at -0.425 ppm; No more azide or alkynyl absorption in IR spectroscopy. DOSY NMR gives D = $2.74.10^{-10}$ $m^2.s^{-1}$ in chloroform which corresponds to a size of 4.2 nm. DLS gives only one population at a size of 5.3 ± 1.0 nm. Size exclusion chromatography (SEC) shows the low polydispersity (1.1) and the size progression for the three ferrocenyl dendrimers.

Figure S.I.69. ^{1}H NMR spectrum of **18** (300 MHz $CDCl_3$)

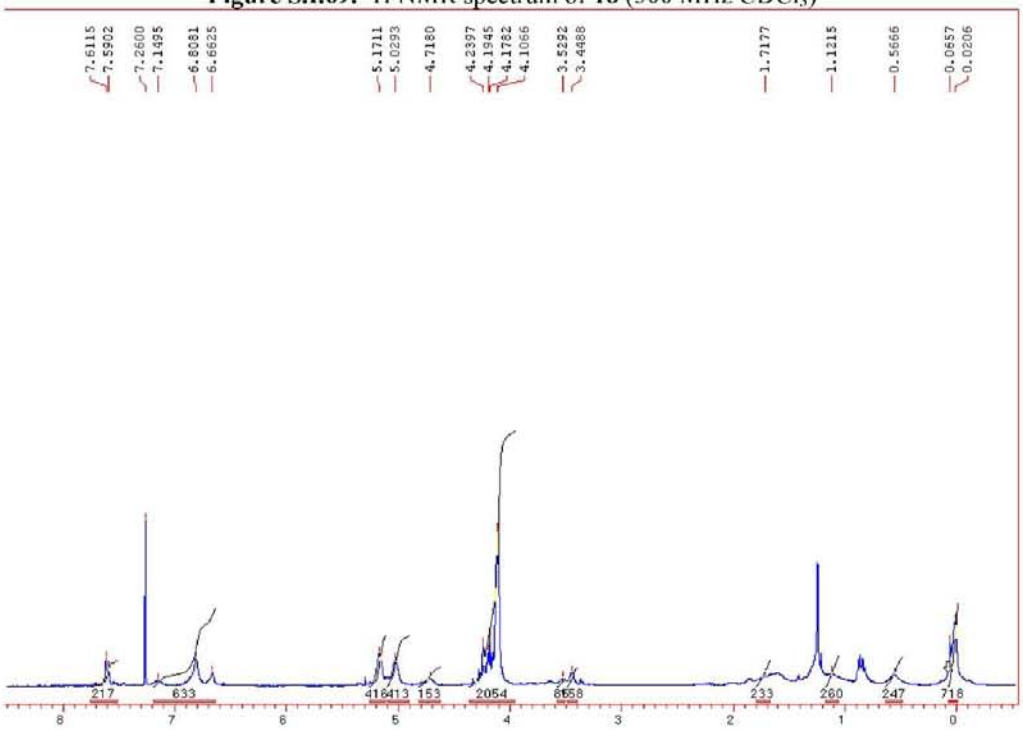
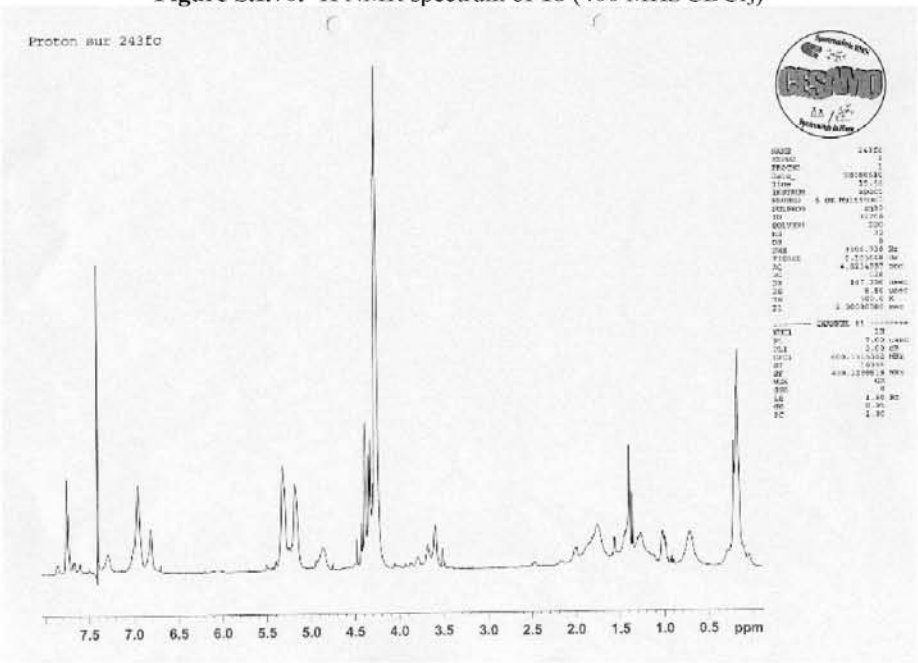


Figure S.I.70. ^{1}H NMR spectrum of **18** (400 MHz $CDCl_3$)



SI53

Figure S.I.71. ^{13}C NMR spectrum of **18** (75.5 MHz $CDCl_3$)

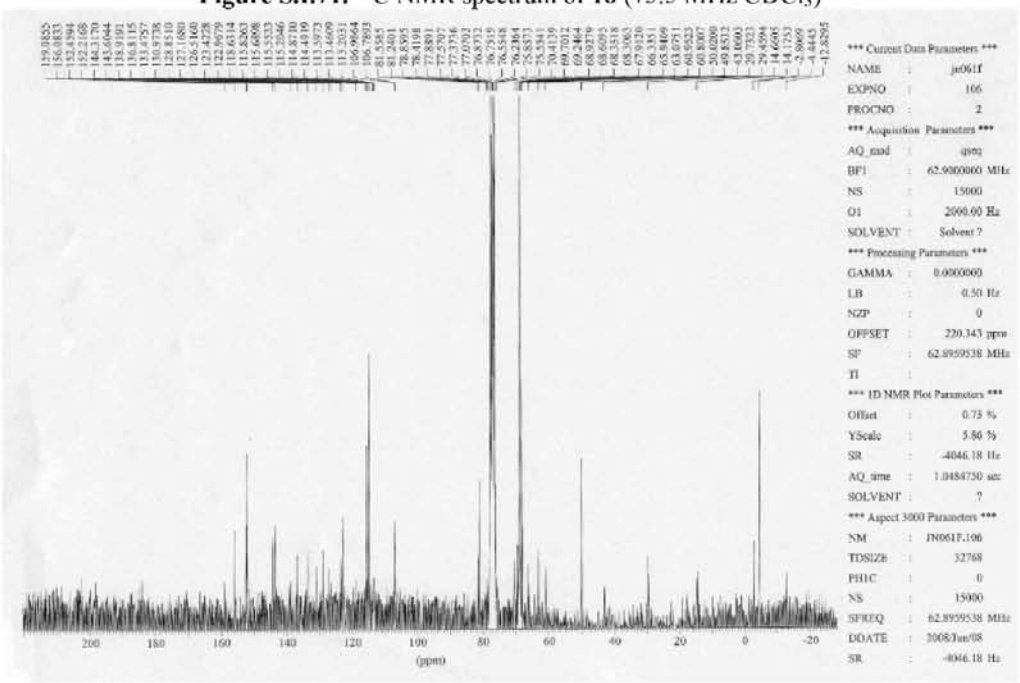
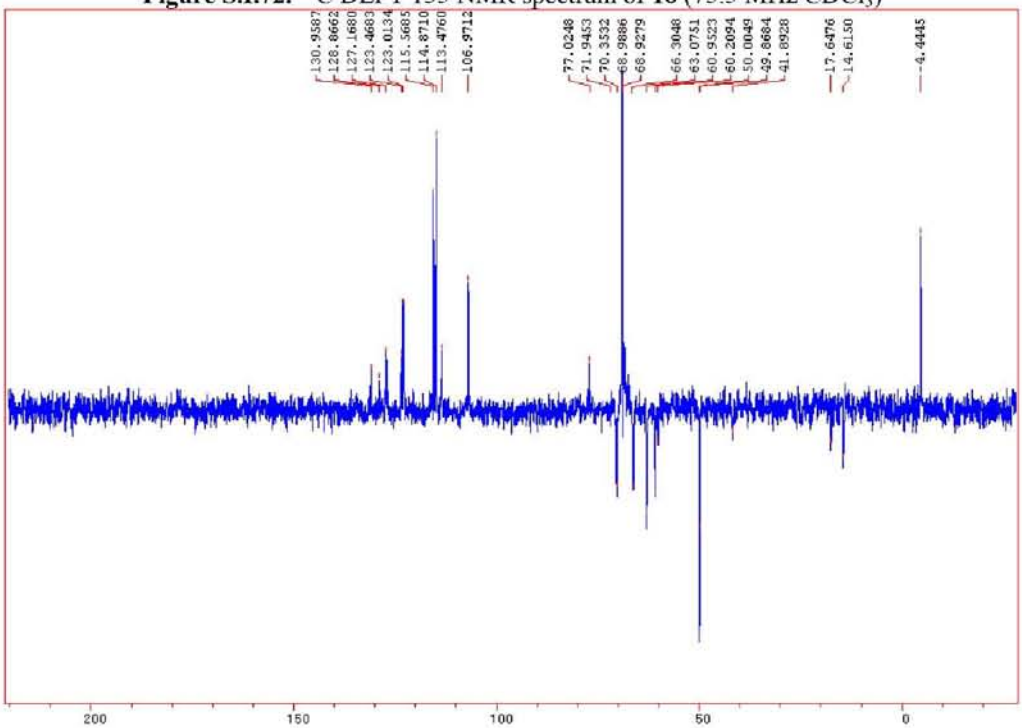
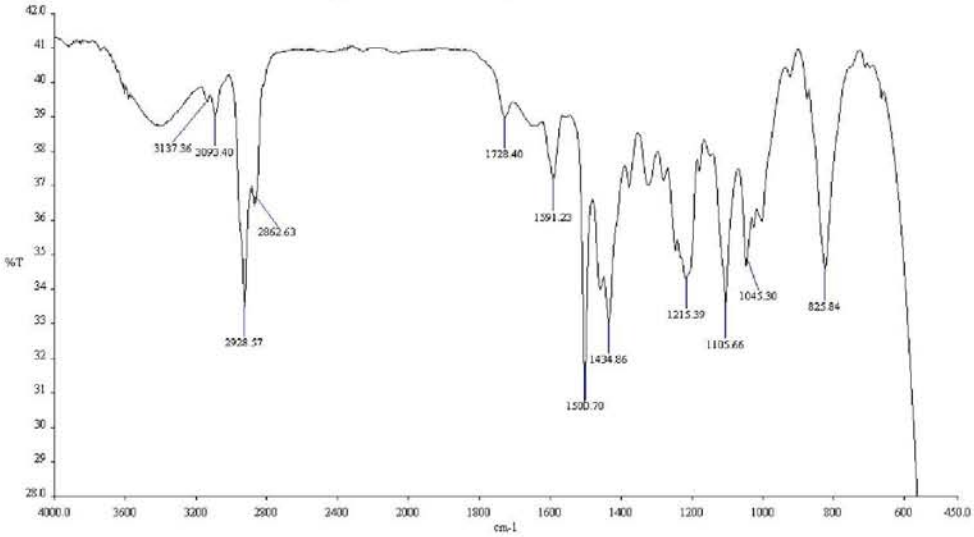


Figure S.I.72. ^{13}C DEPT 135 NMR spectrum of **18** (75.5 MHz $CDCl_3$)



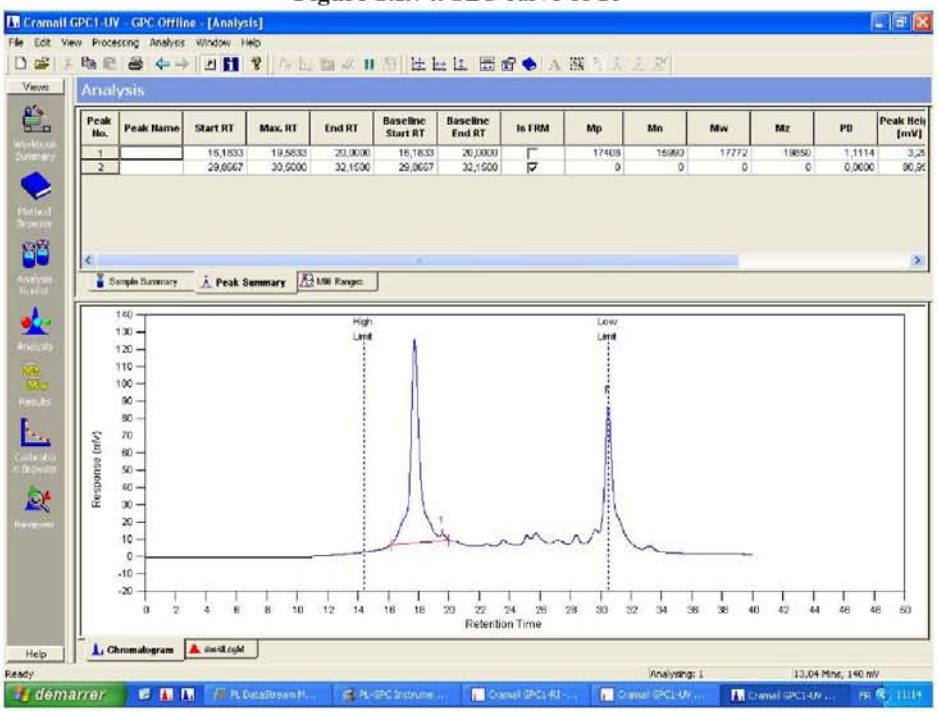
SI54

Figure S.I.73. IR spectrum of **18**



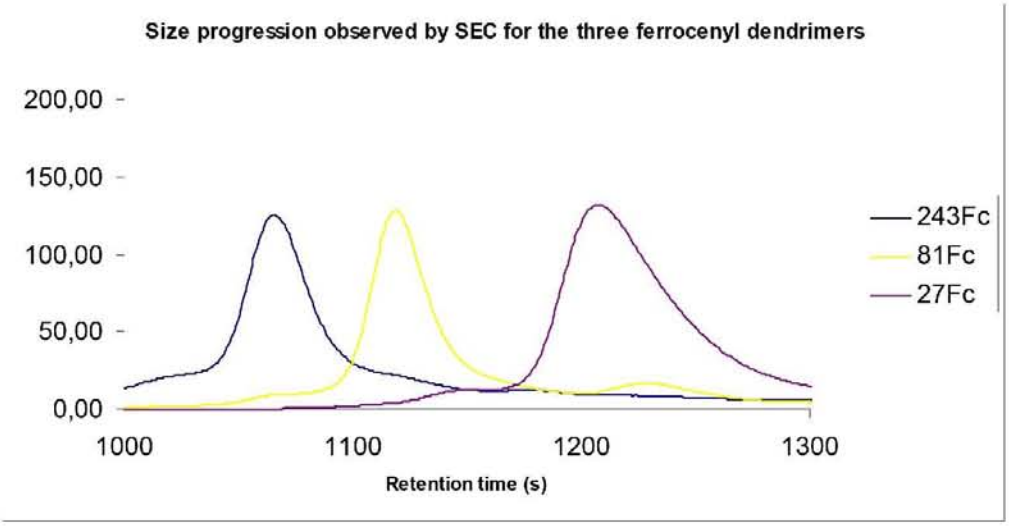
The two tiny peaks between 2000 and 2400 cm^{-1} appear for all the poly(ferrocenylmethyltriazolyl) dendrimers. They are located at 2254.9 and 2087.5 cm^{-1} for **18,** 2258 and 2095 cm^{-1} for the 27-ferrocenyl dendrimer **16** and 2258 and 2094 cm^{-1} for the 81-ferrocenyl dendrimer **17**, and do not correspond to residual alkynyl branches whose absorption is always found at 2122 cm^{-1} in the poly-alkynyl dendrimers.

Figure S.I.74. SEC curve of **18**



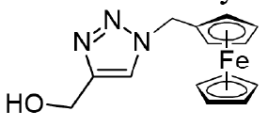
SI56

Figure S.I.75. Size progression observed by SEC for the three ferrocenyl dendrimers



SI57

Compound **19**: ferrocenyl monomer



m.p. 161.2°C; ^{1}H NMR (300MHz, $CDCl_3$, 25°C, TMS): δ=7.42 ppm (s, 1H, $\underline{H}_{Triazole}$), 5.29 ppm (s, 2H, N-C$\underline{H}_2$-$C_{Ferrocene}$), 4.74 ppm (d, ^{3}J(H,H) = 6.1 Hz, 2H, $C_{Triazole}$-C$\underline{H}_2$-OH), 4.29 to 4.19 ppm (m, 9H, $C_{Ferrocene}$-$\underline{H}$), 2.31 ppm (t, ^{3}J(H,H) = 6.1 Hz, 1H, O-$\underline{H}$); ^{13}C NMR (75.5 MHz, $CDCl_3$, 25°C, TMS): δ=147.43 ppm (quat. $C_{triazole}$), 120.91 ppm ($C_{triazole}$-H), 80.65 ppm (quat. $C_{ferrocene}$), 69.12, 68.95 and 68.91 ppm ($C_{ferrocene}$-H), 56.70 ppm ($C_{ferrocene}$-CH_2-N), 50.09 ppm (CH_2-OH); IR: No more alkyne or azide absorption; MS: *m/z*: 617 [NaM_2^+], 320.05 [NaM^+], 298 [HM^+]; Elemental analysis calcd (%) for $C_{14}H_{15}ON_3Fe$: C 56.59, H 5.09; found: C 56.82, H 5.34.

Figure S.I.76. ^{1}H NMR spectrum of **19** (250 MHz $CDCl_3$)

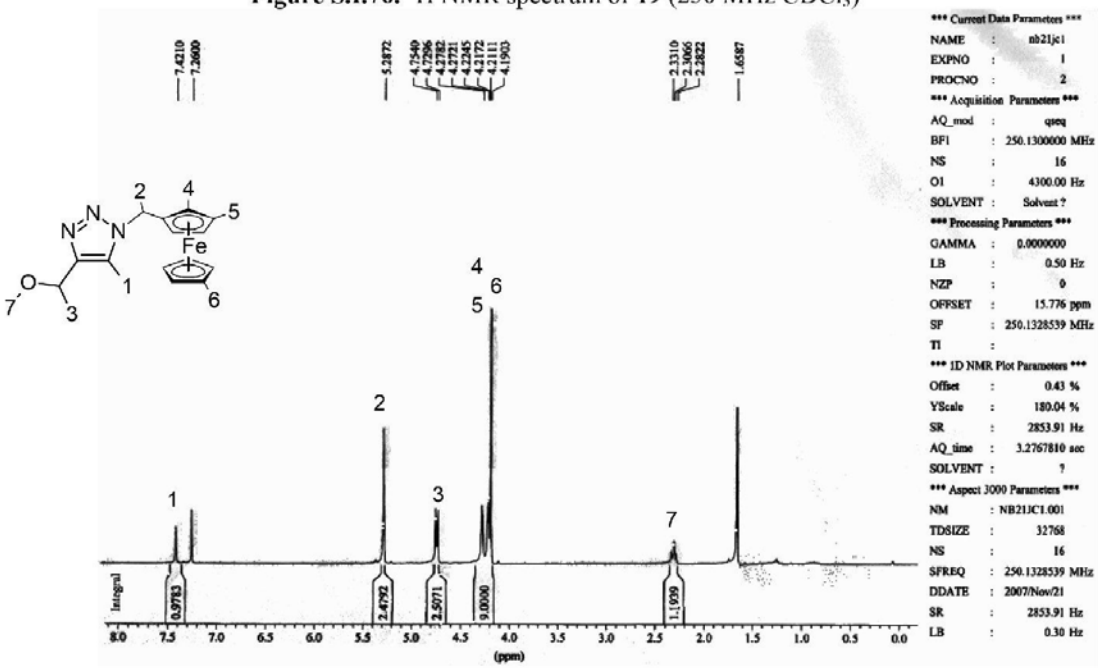
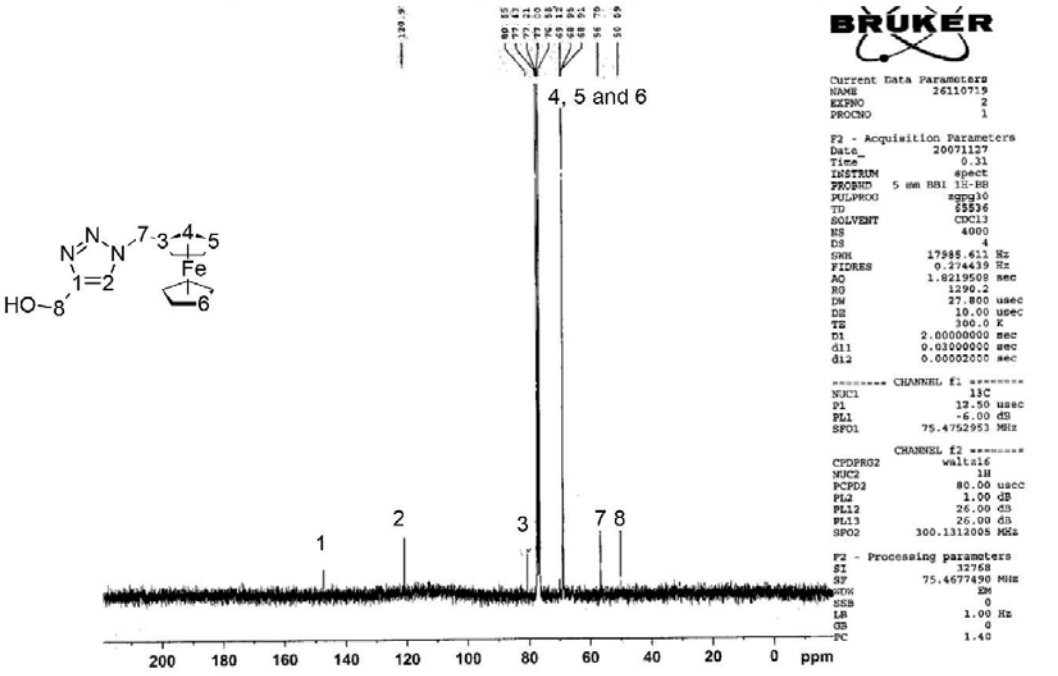


Figure S.I.77. ^{13}C NMR spectrum of **19** (75.5 MHz $CDCl_3$)



SI59

Figure S.I.78. ^{13}C DEPT 135 NMR spectrum of **19** (75.5 MHz $CDCl_3$)

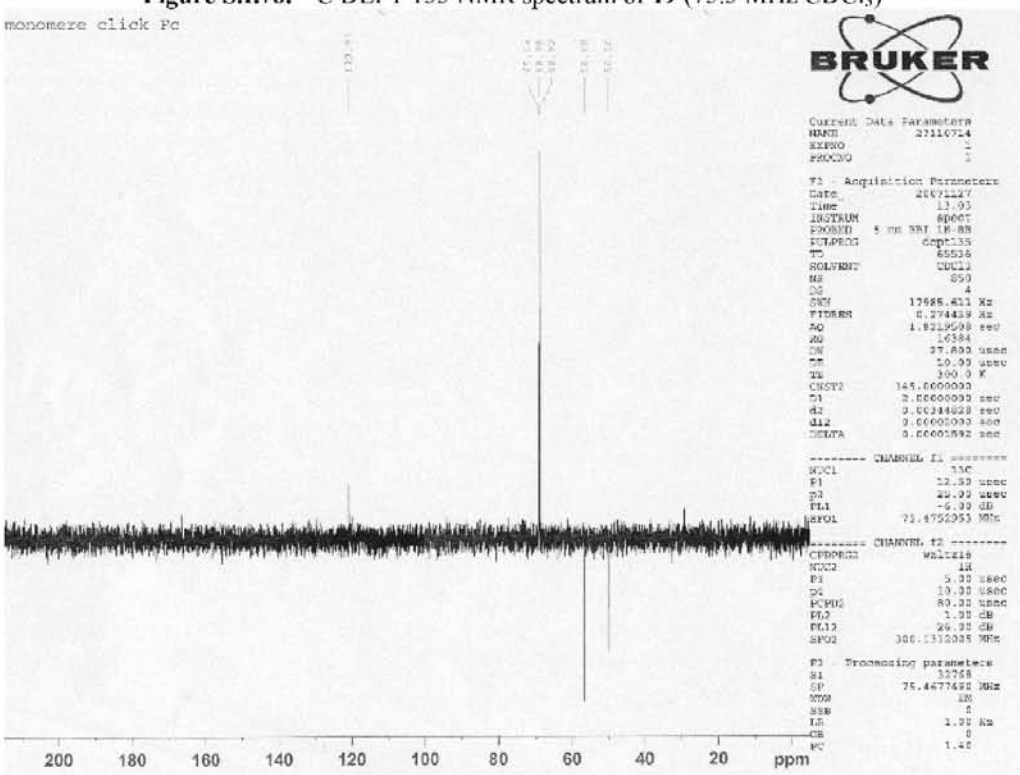


Figure S.I.79. IR spectrum of **19**

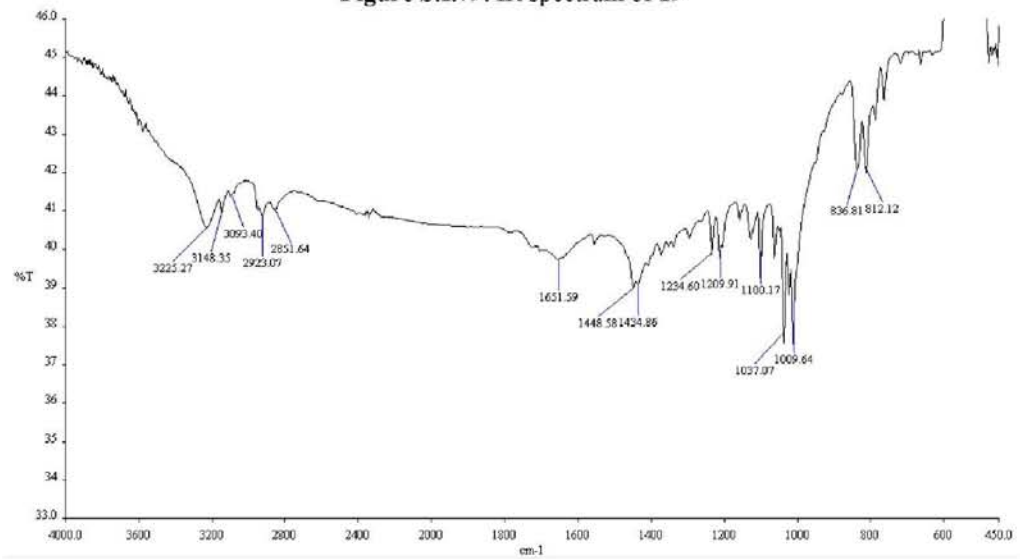


Figure S.I.80. mass spectrum of **19** (1/3)

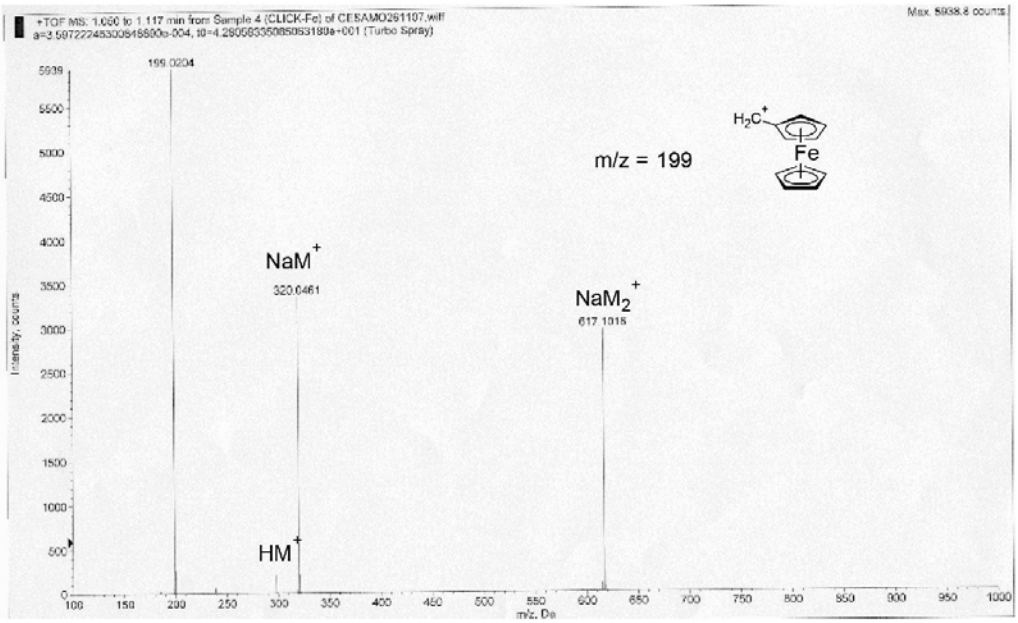


Figure S.I.81. mass spectrum of **19** (2/3)

Elemental composition calculator

Target m/z: +320.0461 Da
Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: -0.5000 Max DBE: +50.0000
Electron state: OddAndEven
Num of charges: 0
Add water: N/A
Add proton: N/A
File Name: CESAMO261107.wiff

	Elements	Min Number	Max Number
1	C	0	500
2	Cl	0	0
3	Fe	1	1
4	H	0	1000
5	K	0	0
6	N	0	3
7	Na	0	1
8	O	0	1
9	P	0	0
10	S	0	0
11	Si	0	0

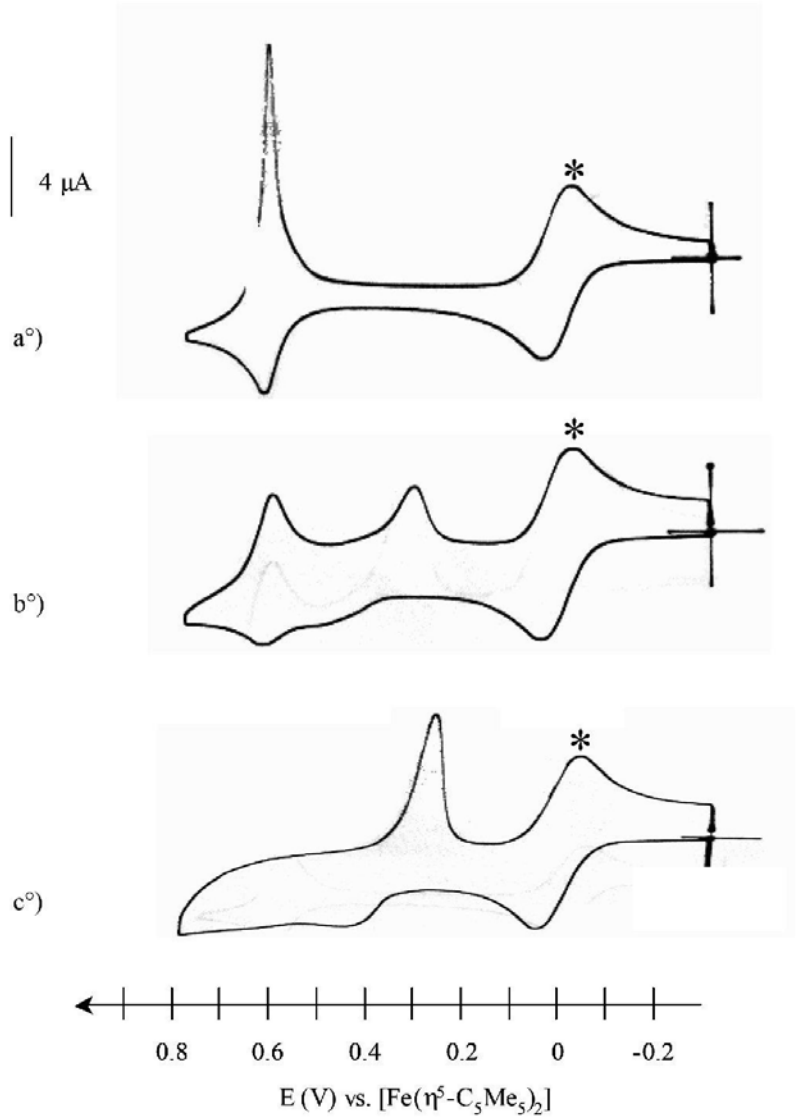
Figure S.I.82. mass spectrum of **19** (3/3)

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C14 H15 N3 O Na Fe	320.0462	-0.1212	-0.3788	8.5

SI62

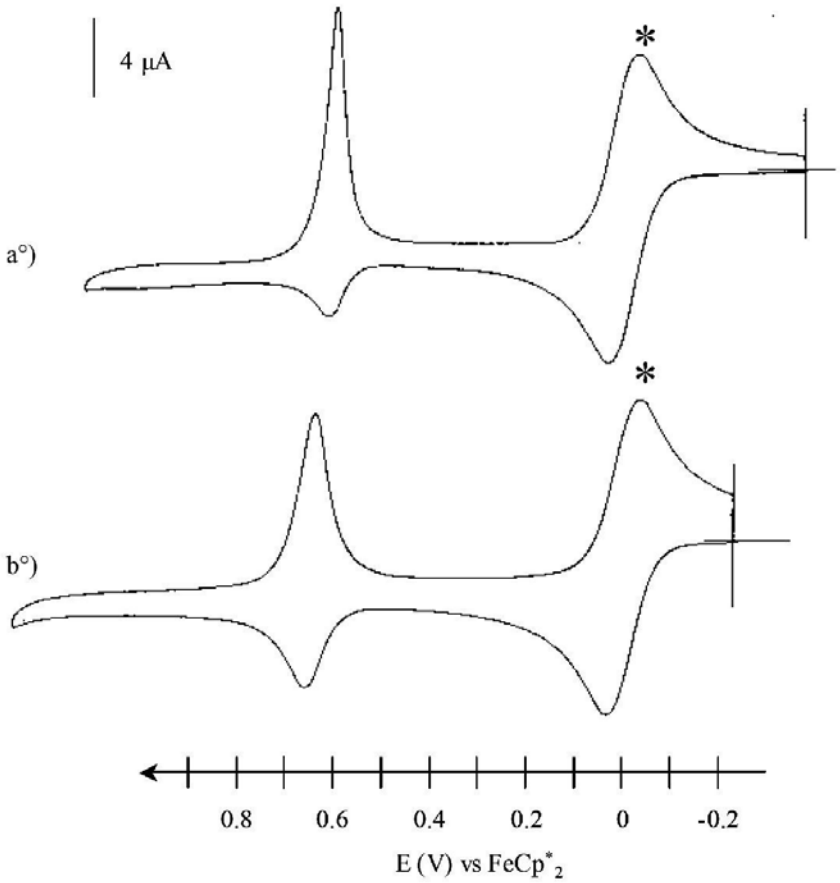
Electrochemistry Data

Figure S.I.83. Titration of $H_2PO_4^-$ with the 27-ferrocenyl dendrimer **16 b**y cyclic voltammetry



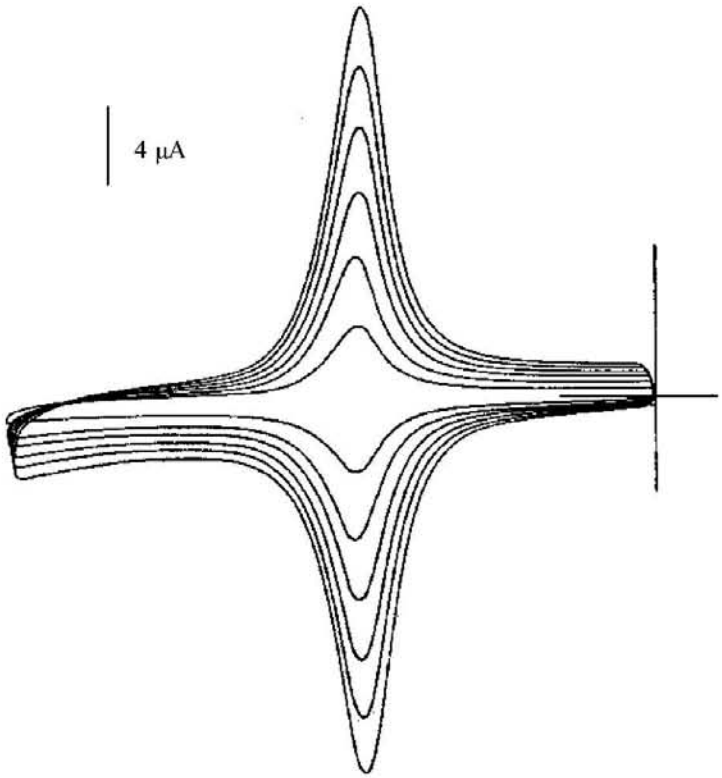
Cyclic voltammograms of the titration of $H_2PO_4^-$ with the 27-ferrocenyl dendrimer, **16**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of [*n*-Bu_4N][H_2PO_4], b) during titration of [*n*-Bu_4N][H_2PO_4] and c) after addition of excess [*n*-Bu_4N][H_2PO_4], * internal reference: [Fe(η^5-C_5Me_5)$_2$].

Figure S.I.84. Titration of $[Pd(MeCN)_4](BF_4)_2$ with the 27-ferrocenyl dendrimer **16** by cyclic voltammetry



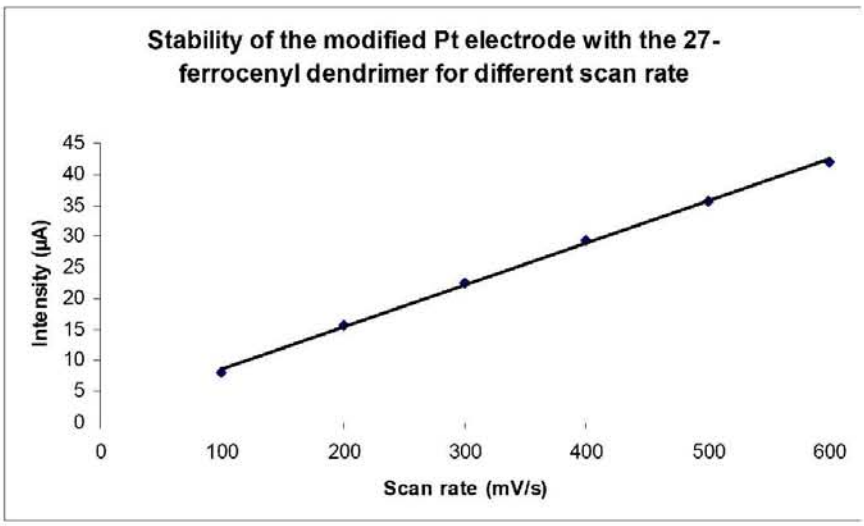
Cyclic voltammograms of the titration of Pd^{2+} with the 27-ferrocenyl dendrimer, **16**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of $[Pd(MeCN)_4](BF_4)_2$, b) after addition of excess $[Pd(MeCN)_4](BF_4)_2$, * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

Figure S.I.85. Stability of the Pt electrode with adsorbed 27-ferrocenyl dendrimer **16** for various scan rates



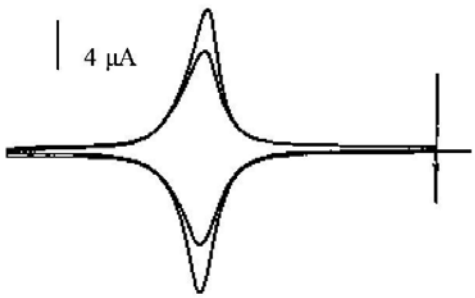
From smaller to larger at 100 mV/s, 200 mV/s, 300 mV/s, 400 mV/s, 500 mV/s and 600 mV/s

Figure S.I.86. Stability of the Pt electrode with adsorbed 27-ferrocenyl dendrimer **16** observed by cyclic voltammetry in CH_2Cl_2



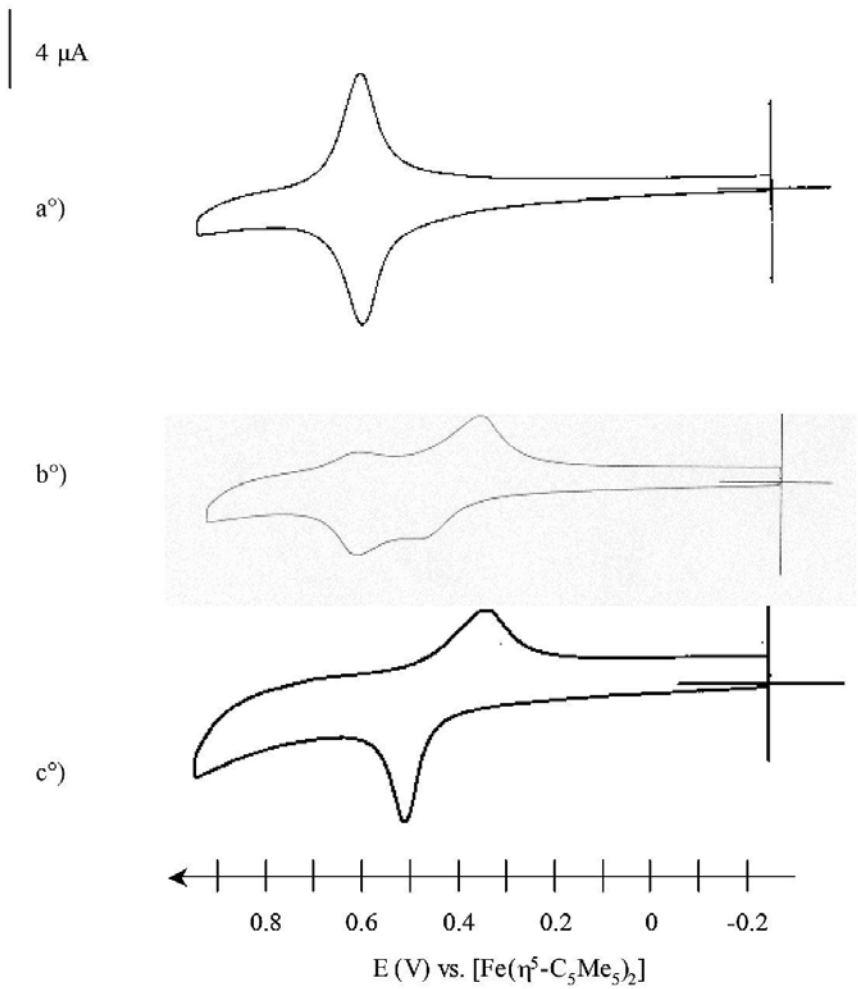
SI65

Figure S.I.87. Robustness of the Pt electrode with adsorbed 27-ferrocenyl dendrimer **16** observed by cyclic voltammetry in CH_2Cl_2



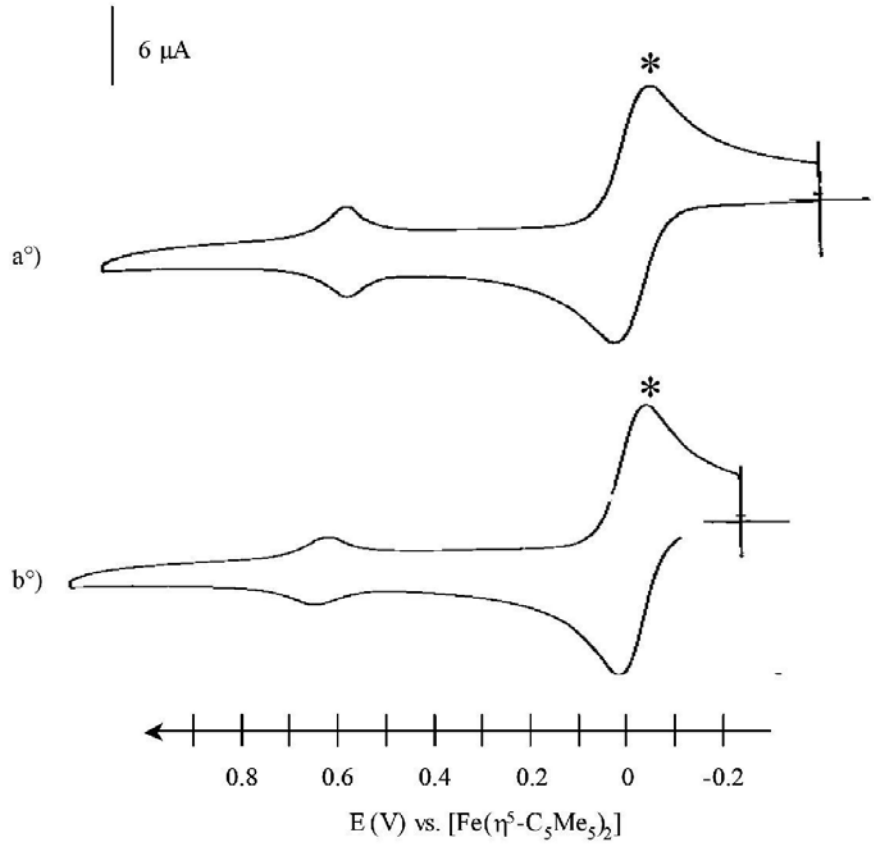
Modified Pt electrode obtained by 200 cycles adsorption in a dendrimer solution before (large one) and after (small one) 30 minutes working (about 200 cycles) in a fresh solution of [*n*-Bu_4N][PF_6] in CH_2Cl_2

Figure S.I.88. Recognition of ATP^{2-} with the modified Pt electrode with adsorbed 27-ferrocenyl dendrimer **16** by cyclic voltammetry



Cyclic voltammograms of the recognition of ATP^{2-} by the modified Pt electrode with adsorbed 27-ferrocenyl dendrimer, **16**, in CH_2Cl_2 at 20°C: a) before addition of [*n*-$Bu_4N]_2$[ATP], b) during the recognition of [*n*-$Bu_4N]_2$[ATP], c) after addition of excess [*n*-$Bu_4N]_2$[ATP].

Figure S.I.89. Recognition of $[Pd(MeCN)_4](BF_4)_2$ with the modified Pt electrode with adsorbed 27-ferrocenyl dendrimer **16** by cyclic voltammetry



Cyclic voltammograms of the recognition of Pd^{2+} by the modified Pt electrode with adsorbed 27-ferrocenyl dendrimer, **16**, in CH_2Cl_2 at 20°C: a) before addition of $[Pd(MeCN)_4](BF_4)_2$, b) after addition of excess $[Pd(MeCN)_4](BF_4)_2$, * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

Figure S.I.90. Titration of [*n*-Bu_4N][H_2PO_4] with the 27-ferrocenyl dendrimer **16** by cyclic voltammetry

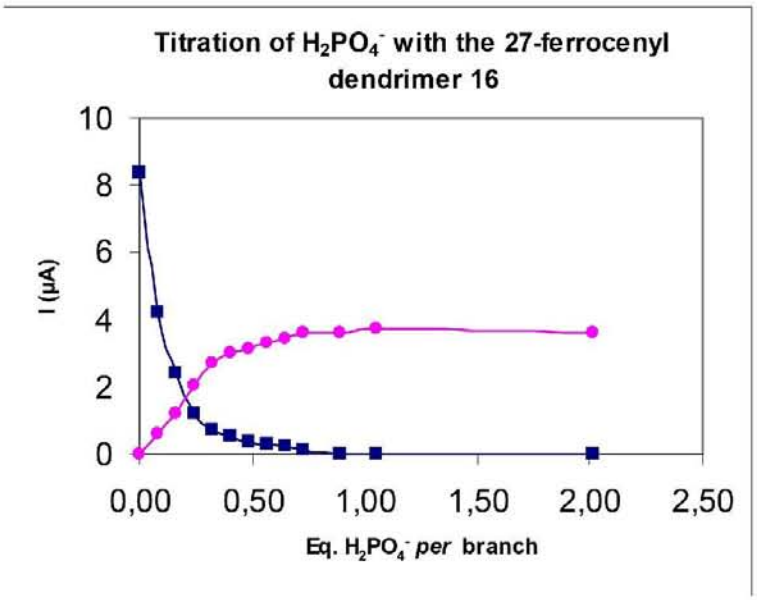
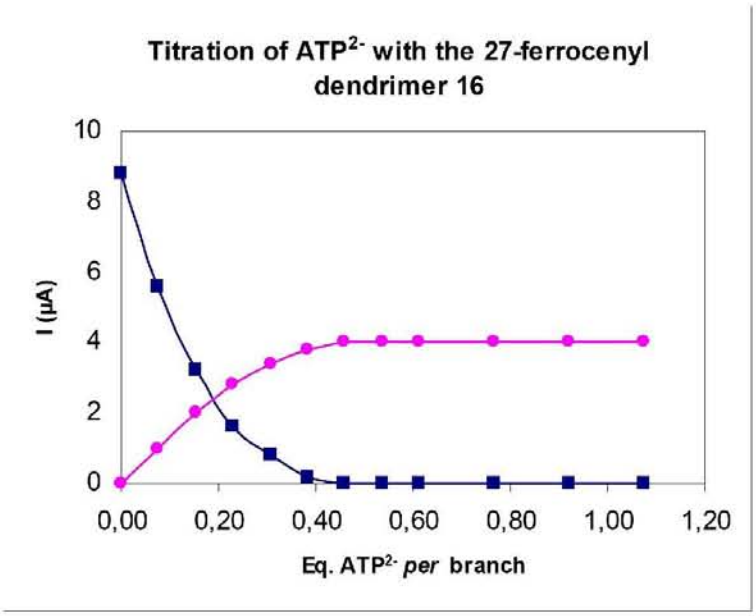
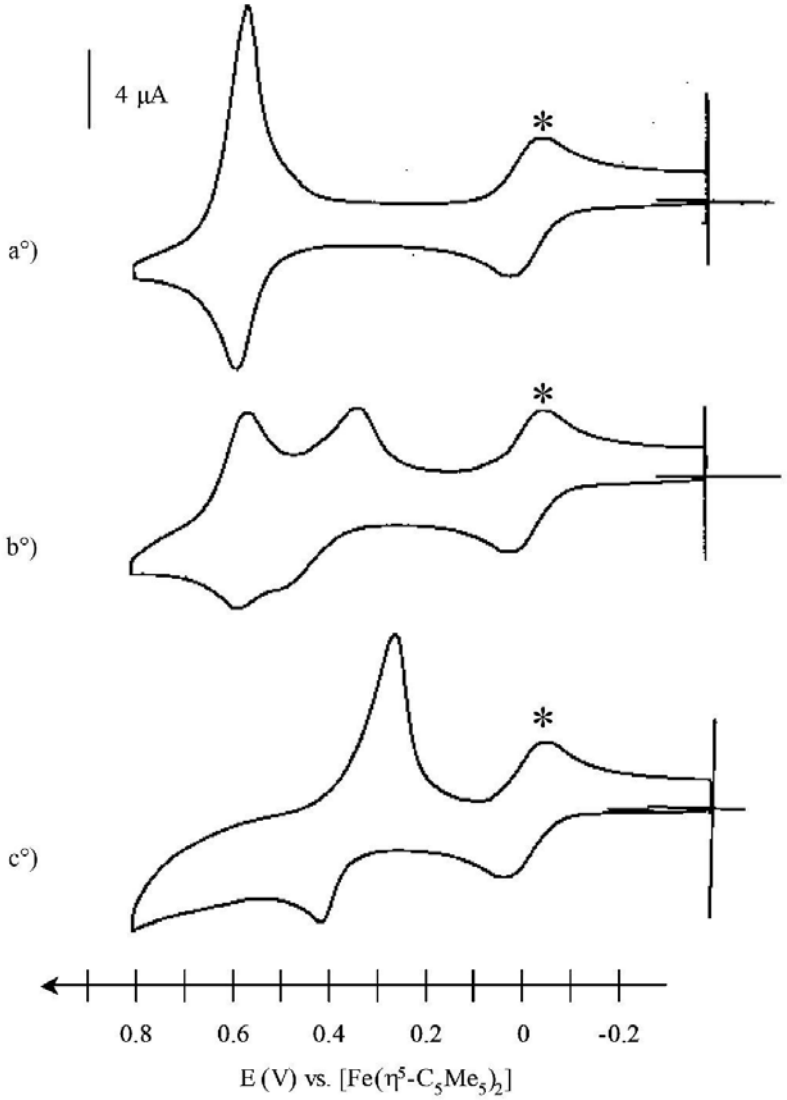


Figure S.I.91 Titration of [*n*-Bu_4N]$_2$[ATP] with the 27-ferrocenyl dendrimer **16** by cyclic voltammetry



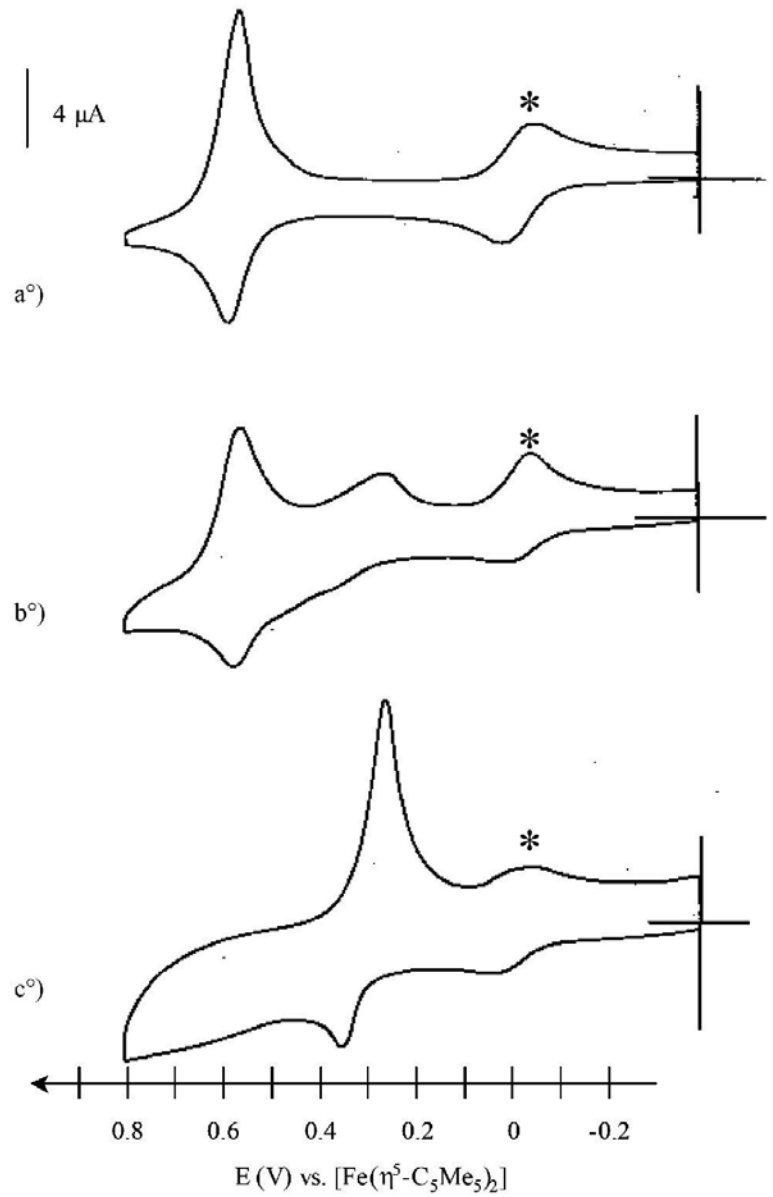
SI69

Figure S.I.92. Titration of ATP^{2-} with the 81-ferrocenyl dendrimer **17** by cyclic voltammetry



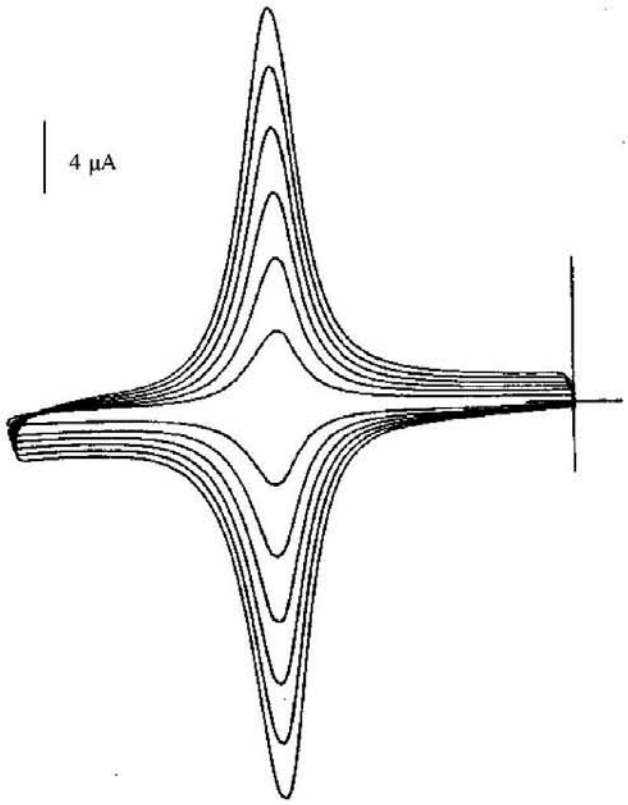
Cyclic voltammograms of the titration of ATP^{2-} with the 81-ferrocenyl dendrimer, **17**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of [*n*-$Bu_4N]_2$[ATP], b) during titration of [*n*-$Bu_4N]_2$[ATP] and c) after addition of excess [*n*-$Bu_4N]_2$[ATP], * internal reference: [Fe(η^5-$C_5Me_5)_2$].

Figure S.I.93. Titration of $H_2PO_4^-$ with the 81-ferrocenyl dendrimer **17** by cyclic voltammetry



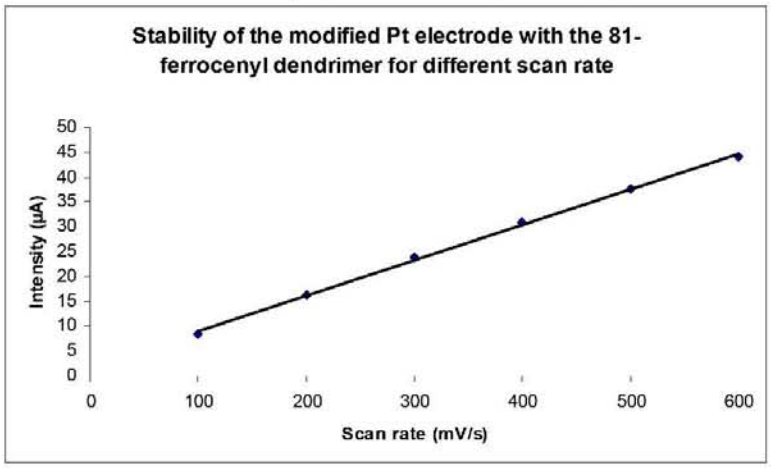
Cyclic voltammograms of the titration of $H_2PO_4^-$ with the 81-ferrocenyl dendrimer, **17**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of [*n*-Bu_4N][H_2PO_4], b) during titration of [*n*-Bu_4N][H_2PO_4] and c) after addition of excess [*n*-Bu_4N][H_2PO_4], * internal reference: [Fe(η^5-C_5Me_5)$_2$].

Figure S.I.94. Stability of the Pt electrode with adsorbed 81-ferrocenyl dendrimer **17** for various scan rates



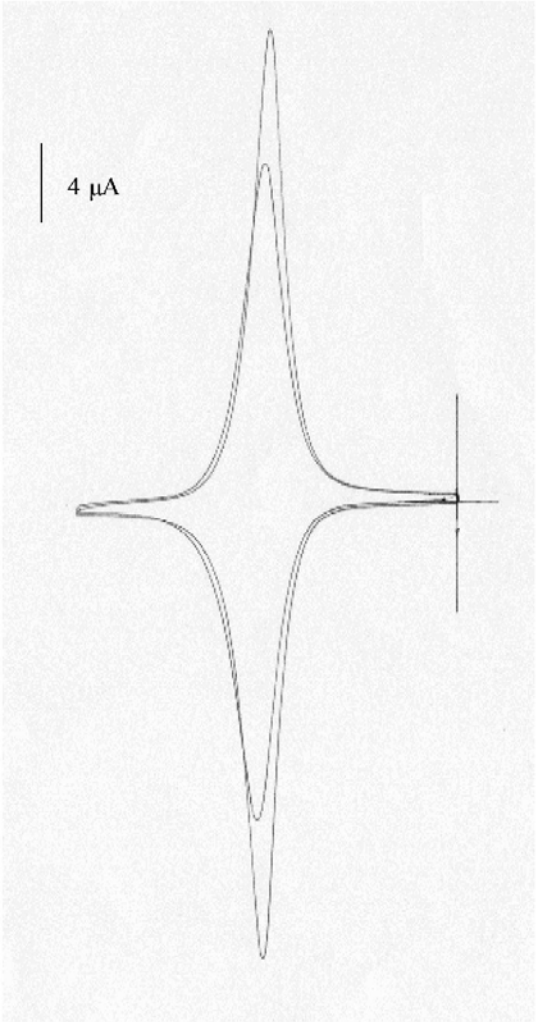
From smaller to larger at 100 mV/s, 200 mV/s, 300 mV/s, 400 mV/s, 500 mV/s and 600 mV/s

Figure S.I.95. Stability of the Pt electrode with adsorbed 81-ferrocenyl dendrimer **17** observed by cyclic voltammetry in CH_2Cl_2



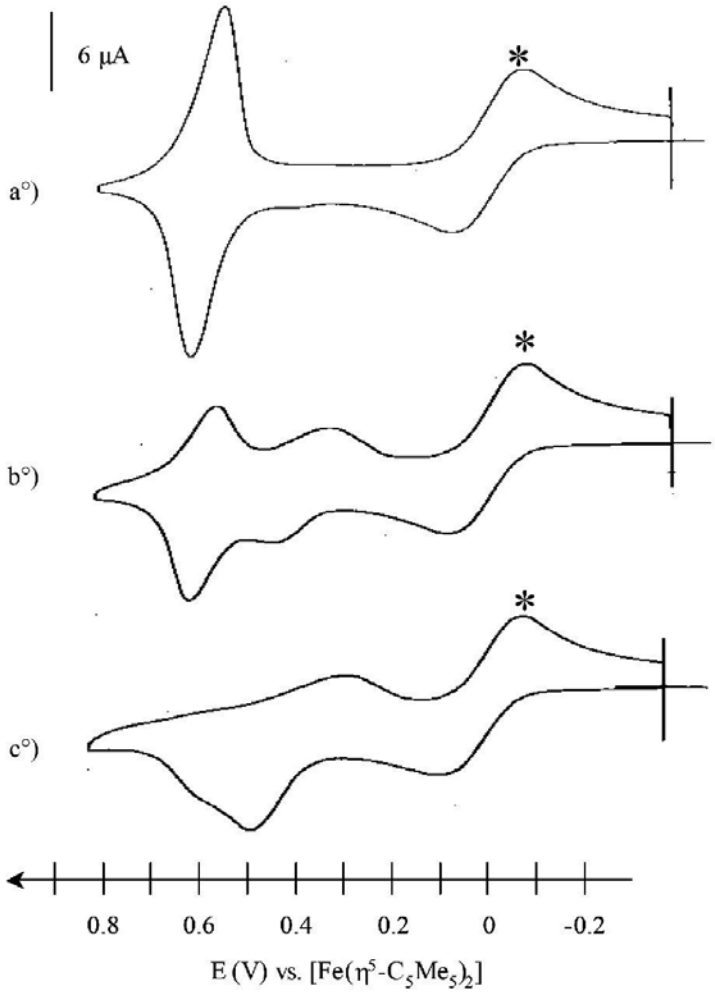
SI72

Figure S.I.96. Robustness of the Pt electrode with adsorbed 81-ferrocenyl dendrimer **17** observed by cyclic voltammetry in CH_2Cl_2



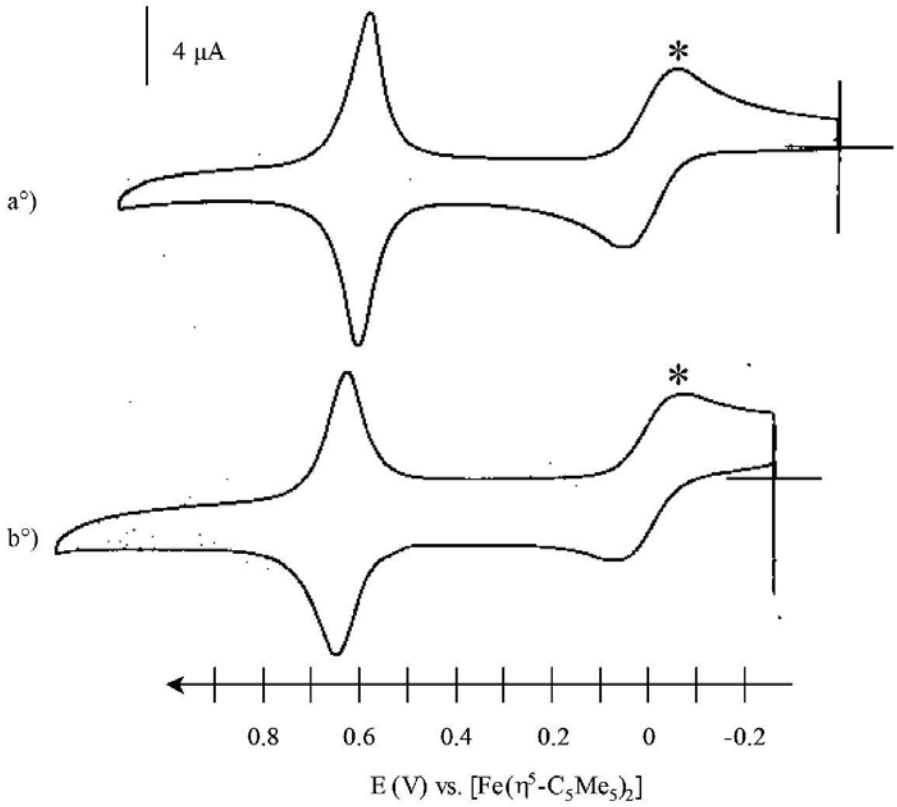
Modified Pt electrode obtained by 200 cycles adsorption in a dendrimer solution before (large one) and after (small one) 30 minutes working in a fresh solution of [*n*-Bu_4N][PF_6] in CH_2Cl_2

Figure S.I.97. Recognition of ATP^{2-} with the modified Pt electrode with adsorbed 81-ferrocenyl dendrimer **17** by cyclic voltammetry



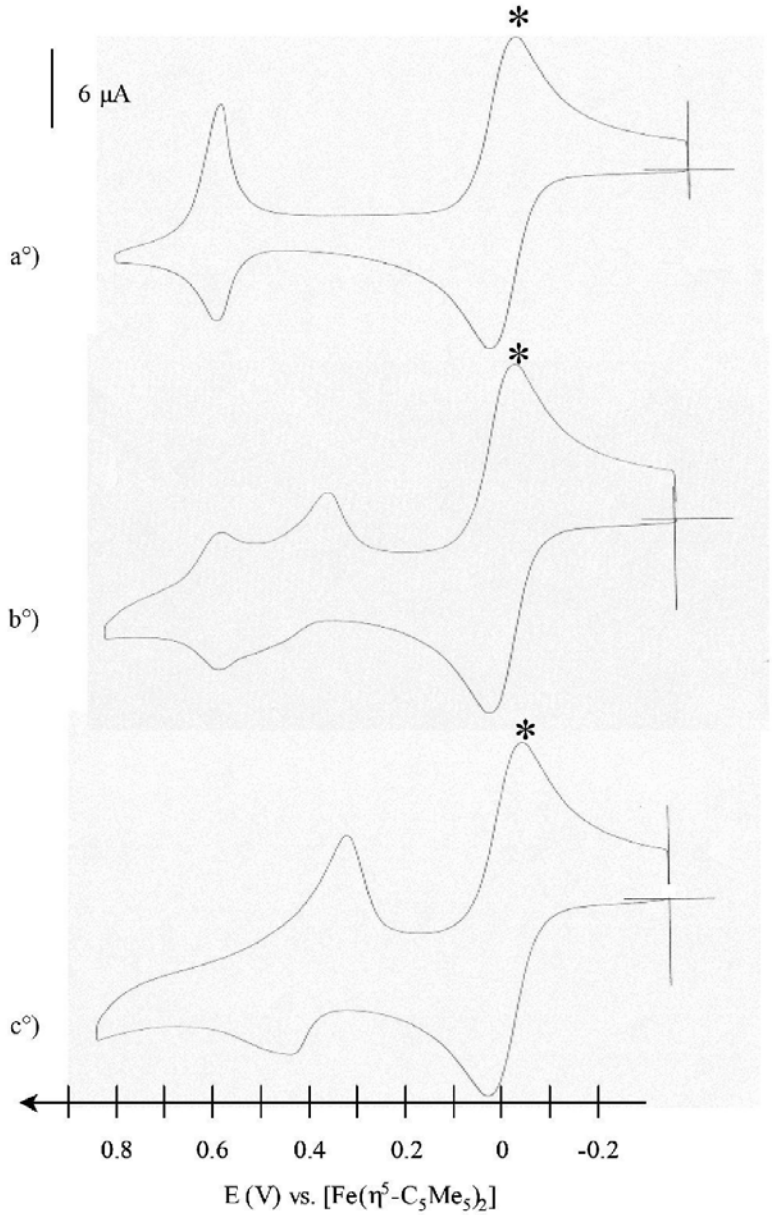
Cyclic voltammograms of the recognition of ATP^{2-} by the modified Pt electrode with adsorbed 81-ferrocenyl dendrimer, **17**, in CH_2Cl_2 at 20°C: a) before addition of [*n*-$Bu_4N]_2$[ATP], b) during the recognition of [*n*-$Bu_4N]_2$[ATP], c) after addition of excess [*n*-$Bu_4N]_2$[ATP], * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

Figure S.I.98. Recognition of $[Pd(MeCN)_4](BF_4)_2$ with the modified Pt electrode with adsorbed 81-ferrocenyl dendrimer **17** by cyclic voltammetry



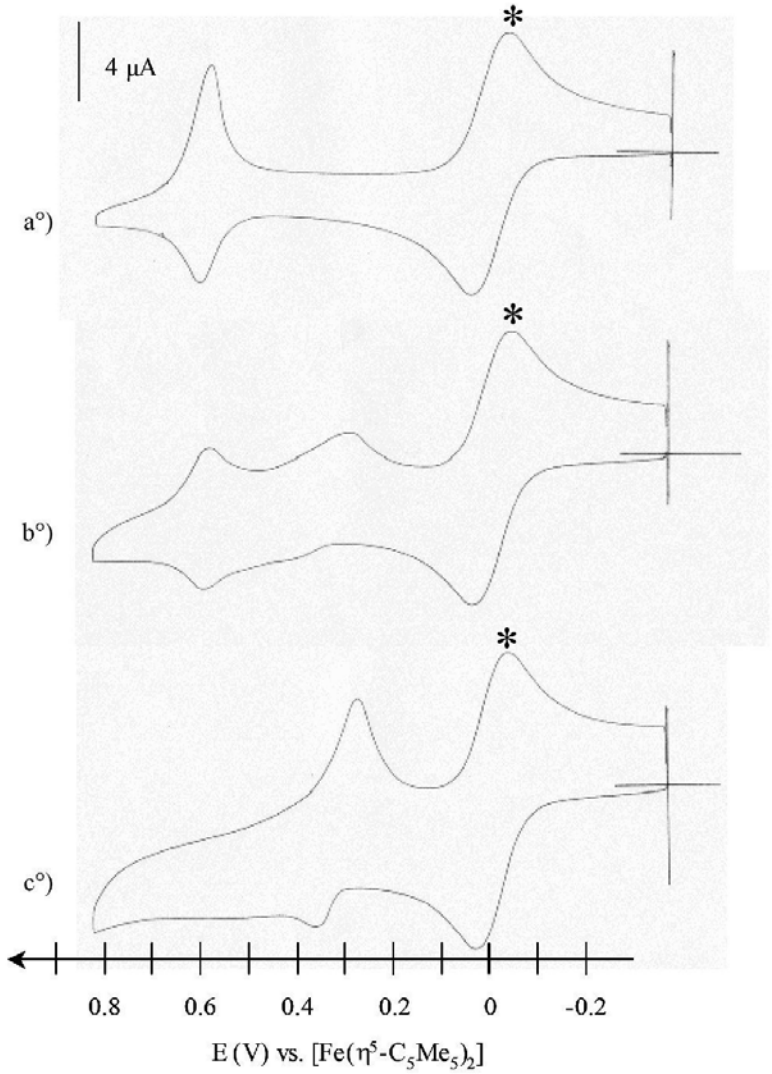
Cyclic voltammograms of the recognition of Pd^{2+} by the modified Pt electrode with adsorbed 81-ferrocenyl dendrimer, **17**, in CH_2Cl_2 at 20°C: a) before addition of $[Pd(MeCN)_4](BF_4)_2$, b) after addition of excess $[Pd(MeCN)_4](BF_4)_2$, * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

Figure S.I.99. Titration of ATP^{2-} with the 243-ferrocenyl dendrimer **18** by cyclic voltammetry



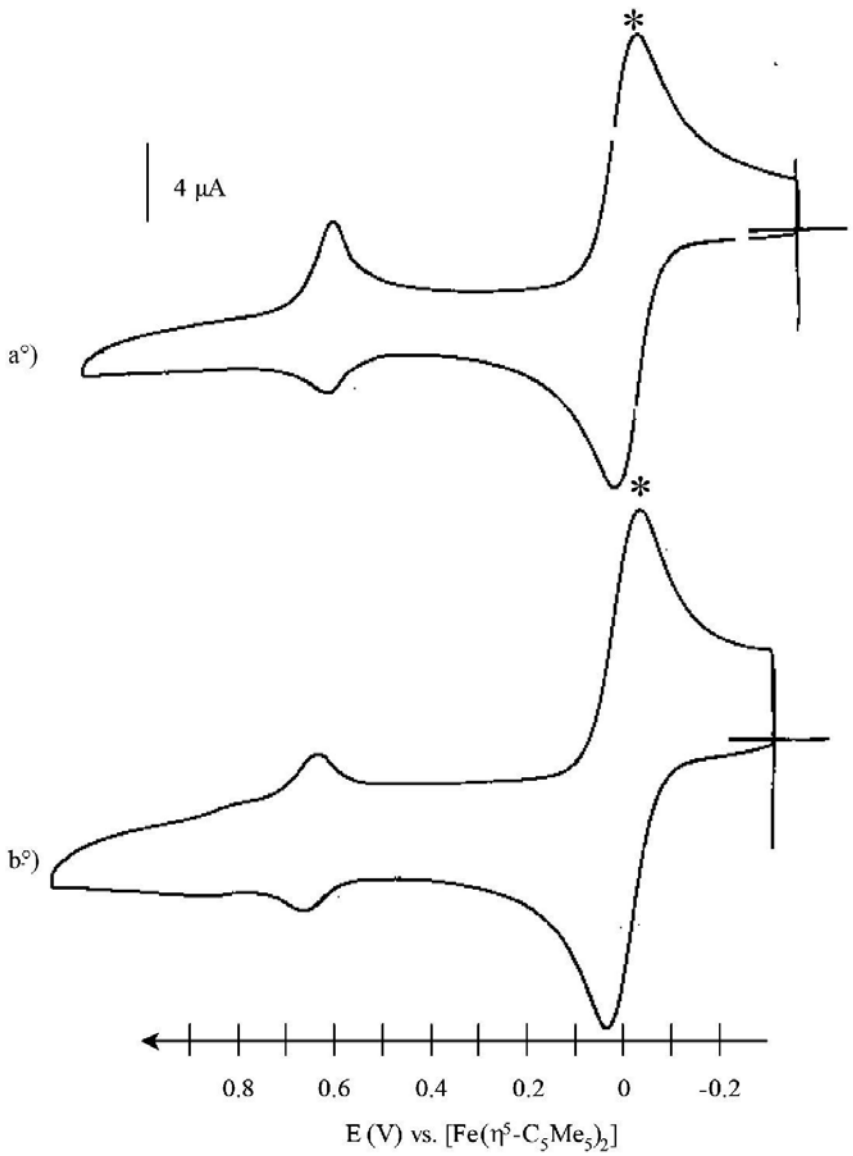
Cyclic voltammograms of the titration of ATP^{2-} with the 243-ferrocenyl dendrimer, **18**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of $[n\text{-}Bu_4N]_2[ATP]$, b) during titration of $[n\text{-}Bu_4N]_2[ATP]$ and c) after addition of excess $[n\text{-}Bu_4N]_2[ATP]$, * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

Figure S.I.100. Titration of $H_2PO_4^-$ with the 243-ferrocenyl dendrimer **18** by cyclic voltammetry



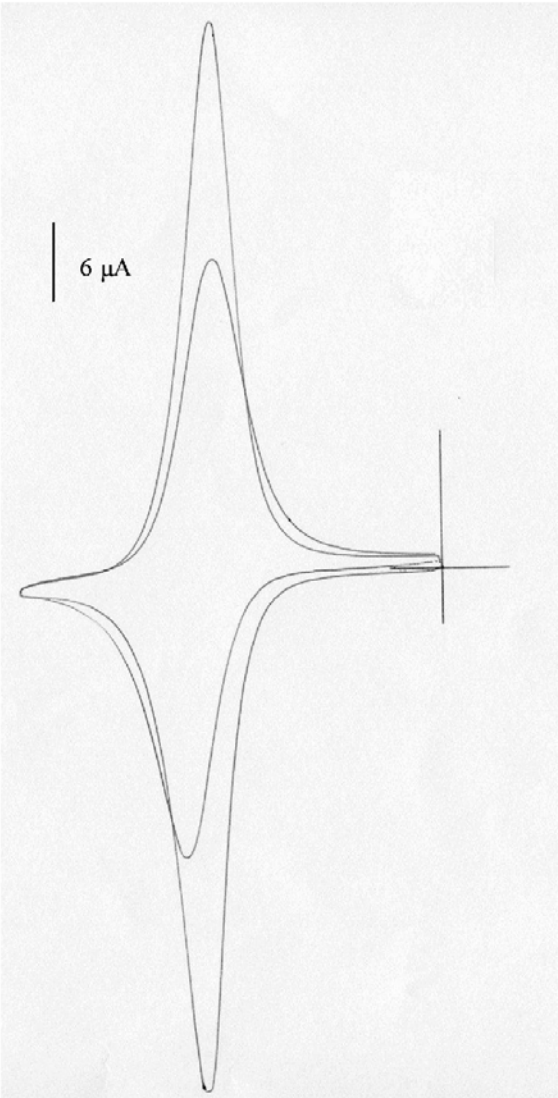
Cyclic voltammograms of the titration of $H_2PO_4^-$ with the 243-ferrocenyl dendrimer, **18**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of [*n*-Bu_4N][H_2PO_4], b) during titration of [*n*-Bu_4N][H_2PO_4] and c) after addition of excess [*n*-Bu_4N][H_2PO_4], * internal reference: [Fe(η^5-C_5Me_5)$_2$].

Figure S.I.101. Titration of $[Pd(MeCN)_4](BF_4)_2$ with the 243-ferrocenyl dendrimer **18** by cyclic voltammetry



Cyclic voltammograms of the titration of Pd^{2+} with the 243-ferrocenyl dendrimer, **18**, in CH_2Cl_2 at 20°C by adding the salt of the ion into the dendrimer solution: a) before addition of $[Pd(MeCN)_4](BF_4)_2$, b) after addition of excess $[Pd(MeCN)_4](BF_4)_2$, * internal reference: $[Fe(\eta^5\text{-}C_5Me_5)_2]$.

Figure S.I.102. Robustness of the Pt electrode with adsorbed 243-ferrocenyl dendrimer **18** observed by cyclic voltammetry in CH_2Cl_2



Modified Pt electrode obtained by 200 cycles adsorption in a dendrimer solution before (large one) and after (small one) 30 minutes working (about 200 cycles) in a fresh solution of [*n*-Bu_4N][PF_6] in CH_2Cl_2

Figure S.I.103. Titration of [*n*-Bu_4N][H_2PO_4] with the 243-ferrocenyl dendrimer **18** by cyclic voltammetry

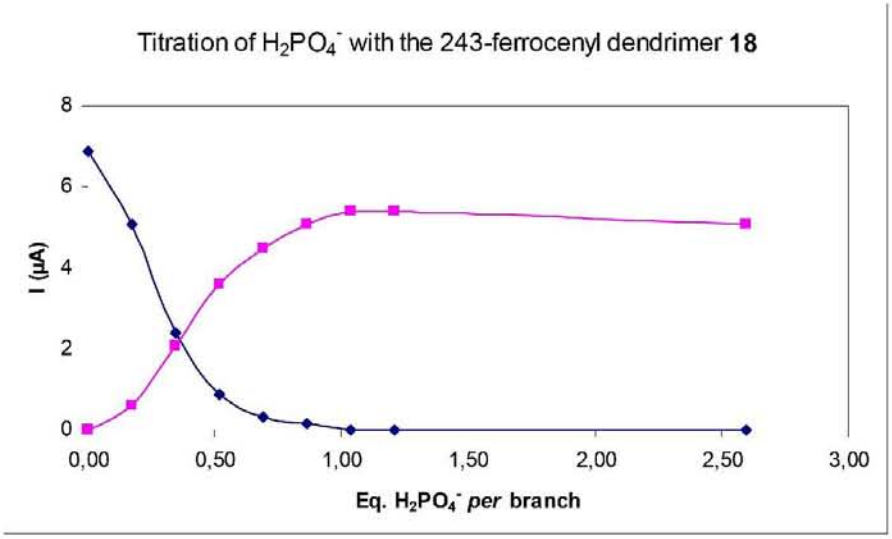
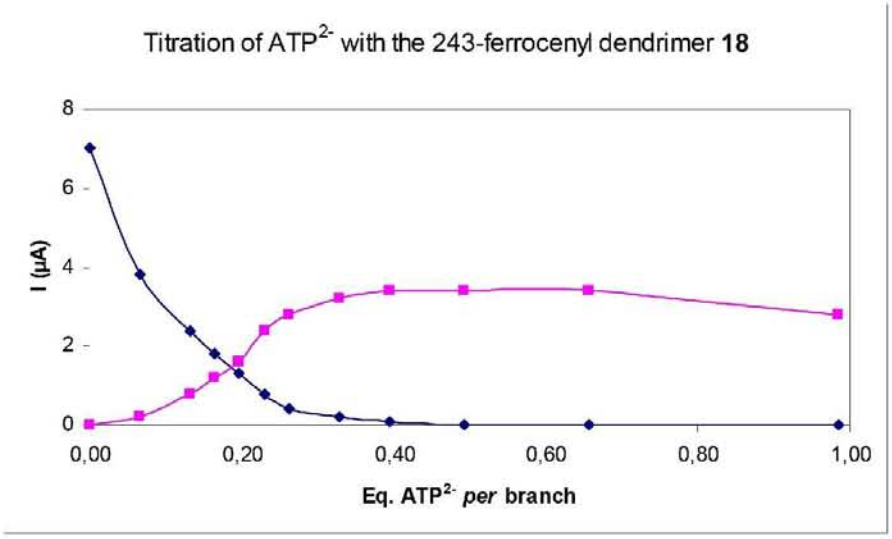


Figure S.I.104. Titration of [*n*-Bu_4N]$_2$[ATP] with the 243-ferrocenyl dendrimer **18** by cyclic voltammetry



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Chapitre 2

Synthèse de Glycodendrimères à 27, 81 et 243 branches comportant le motif 1,2,3-triazole, valorisation d'agroressources régionales

Chapitre 2 : Synthèse de Glycodendrimères à 27, 81 et 243 branches comportant le motif 1,2,3-triazole, valorisation d'agroressources régionales

Le xylose est le constituant principal des hémicelluloses, présente dans la paille de blé par exemple. Son utilisation permettrait de valoriser cette ressource agricole jusqu'alors considérée comme un déchet. Ici, seul le xylose a été modifié et utilisé pour synthétiser les glycodendrimères, mais l'arabinose, un autre pentose présent en grande quantité dans ces matières premières, pourra lui aussi servir pour ce projet. Il a les mêmes propriétés que le xylose et l'ajout d'une fonction azoture peut se faire avec la même séquence réactionnelle.

Ce sont des sucres naturels, pour lesquels les modifications chimiques nécessaires au projet, étaient déjà connues. De plus, ils constituent une réserve peu coûteuse de matière chirale. L'utilisation des glycodendrimères ainsi formés pour réaliser de la catalyse asymétrique est donc envisageable.

Nous avons ici fonctionnalisé les cœurs dendritiques poylalcyne développés précédemment, par chimie « click ». Les conditions de synthèse mais surtout les étapes de purification ont été mises au point pour toute la série dendritique.

La problématique de la caractérisation de ces macromolécules a bien été approfondie, tout en se confrontant aux limites des différentes techniques. En effet, en fonction de la génération dendritique, les molécules peuvent être trop petites pour les mesures de taille par Dynamic Light Scattering, ou trop grosses pour les mesures en RMN DOSY. Pour cette dernière, il n'existe pas de limite franche de taille à partir de laquelle la technique ne fonctionne plus. Au fur et à mesure de la série dendritique, la modélisation corrèle de moins en moins bien avec les points expérimentaux, donnant des résultats avec peu de poids.

Il convient également de mettre en relation les analyses réalisées en chromatographie d'exclusion stérique (SEC) avec les spectres de masse MALDI-TOF obtenus. En effet, les spectres de masse présentés comportent tous le pic de l'ion moléculaire, mais également toute une série de pics correspondant à différents défauts dans la structure. Il faut bien garder en mémoire d'une part, que l'intensité relative de ces pics ne reflète en rien la proportion réelle au sein de l'échantillon et d'autre part, que dans ce cas précis, le signal n'a pu être obtenu qu'au maximum d'intensité du laser, donc avec la probabilité de fragmentation la plus grande bien que cette technique soit relativement douce.

Les analyses SEC réalisées sur toute la série montrent bien que la polymolécularité est bonne, c'est-à-dire que s'il y a un défaut dans la structure, celui-ci est reproductible et affecte l'ensemble des molécules de l'échantillon. Ceci permet donc de nuancer les résultats obtenus en MALDI-TOF. Cependant, dans le cas des dendrimères, nous ne pouvons pas obtenir de valeur cohérente pour la masse molaire moyenne par SEC car la référence utilisée pour calibrer l'appareil dans ce protocole est un polystyrène linéaire. Nous pouvons donc affirmer que le dendrimère complet est présent dans l'échantillon, que les molécules présentant un défaut sont assez proches de la structure parfaite, mais on ne peut pas conclure concernant la molécule majoritaire de l'échantillon.

Les défauts de la structure, qu'ils soient créés lors de l'analyse MALDI-TOF ou présents dans l'échantillon de départ, viennent du manque de robustesse des cœurs dendritiques. En effet, pour les deux séries dendritiques, on peut noter l'apparition de signaux parasites en RMN du silicium lors de tout stockage prolongé à température ambiante, dans les cas d'une montée en température trop importante ou encore de conditions réactionnelles trop dures. Ceci traduit des coupures au sein de la structure. Parfois, quelques précipitations suffisent à éliminer les molécules de plus faible poids moléculaires, mais ceci est insuffisant dans le cas de la réaction de déprotection. Ainsi, même avec le dendrimère le plus petit ne comportant que 27 branches, nous ne pouvons obtenir de déprotection totale sans induire des cassures inacceptables dans l'échantillon.

Nous avons donc envisagé une stratégie inverse en utilisant des cœurs dendritiques polyazotures plus robustes et un xylopyranose comportant une fonction alcyne. Le glycodendrimère à 9 branches a ainsi été synthétisé, grâce aux protocoles de synthèse et de purification mis au point pour l'autre série dendritique. De plus, la déprotection a été menée à bien (Schéma 1). Des études d'interaction du groupement 1,2,3-triazole avec le cisplatine notamment sont en cours par RMN. La série devra également être élargie par la synthèse des glycodendrimères de générations supérieures.

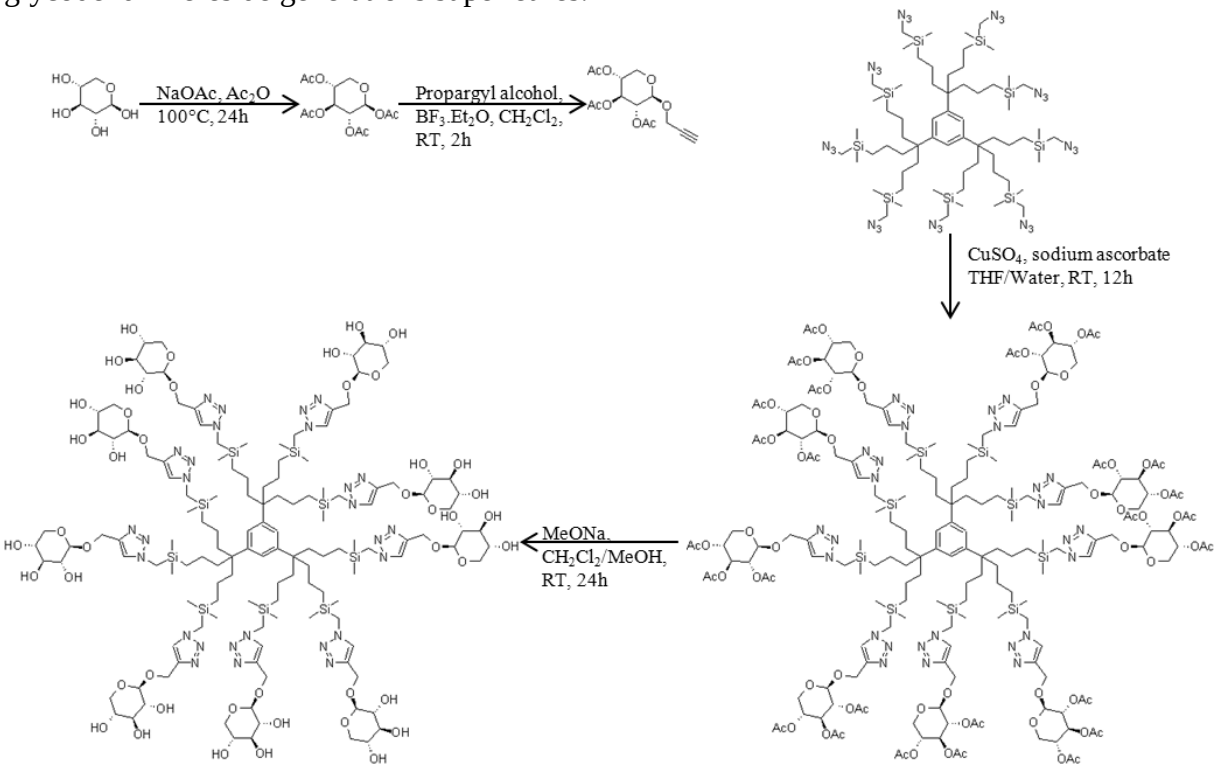

Schéma 1. Synthèse d'un glycodendrimère robuste à 9 branches

JOC*Note*

"Click" Glycodendrimers Containing 27, 81, and 243 Modified Xylopyranoside Termini

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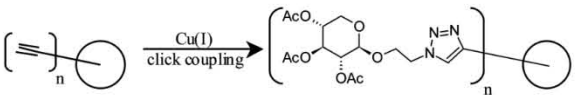

G_1-27, G_2-81 and G_3-243 polyalkynyl dendrimers

G_1-27, G_2-81 and G_3-243 polyxylopyranoside dendrimers

A series of large glycodendrimers containing 27, 81, and 243 terminal modified xylose branches from the first (G_1-27) to the third generation (G_3-243) were synthesized from 2′-azidoethyl 2,3,4-tri-*O*-acetyl-*β*-D-xylopyranoside and alkynyl-terminated dendrimers by "click" chemistry that is confirmed to be an excellent method to obtain large glycodendrimers exemplified by the use of modified xylose. The dendrimers were first characterized by ^{1}H NMR, ^{13}C{^{1}H} NMR, elemental analysis, and IR spectroscopy. The size progression in the series was also demonstrated using both DOSY NMR and size exclusion chromatography (SEC), the latter technique showing the good polydispersity of all the dendrimers. The size measured by dynamic light scattering (DLS) for the dendrimer G_3-243 is close to that obtained by the DOSY NMR method.

Agriculture leads to the production of many byproducts. Hemicelluloses obtained from the straw of cereals enable one to get low-cost molecules such as D-xylose and L-arabinose, which can be valorized. After studies leading to the transformation of the above pentoses into products possessing surfactant properties,[1] we are now using them in dendrimer chemistry.[2] Dendrimers are well-defined macromolecules[3] that can be used in various fields of nanosciences such as nanoreactors,[4] molecular micelles,[5] drug vectors,[6] sensors,[7] green catalysts,[8] supramolecular electronics,[9] and light-harvesting devices.[10]

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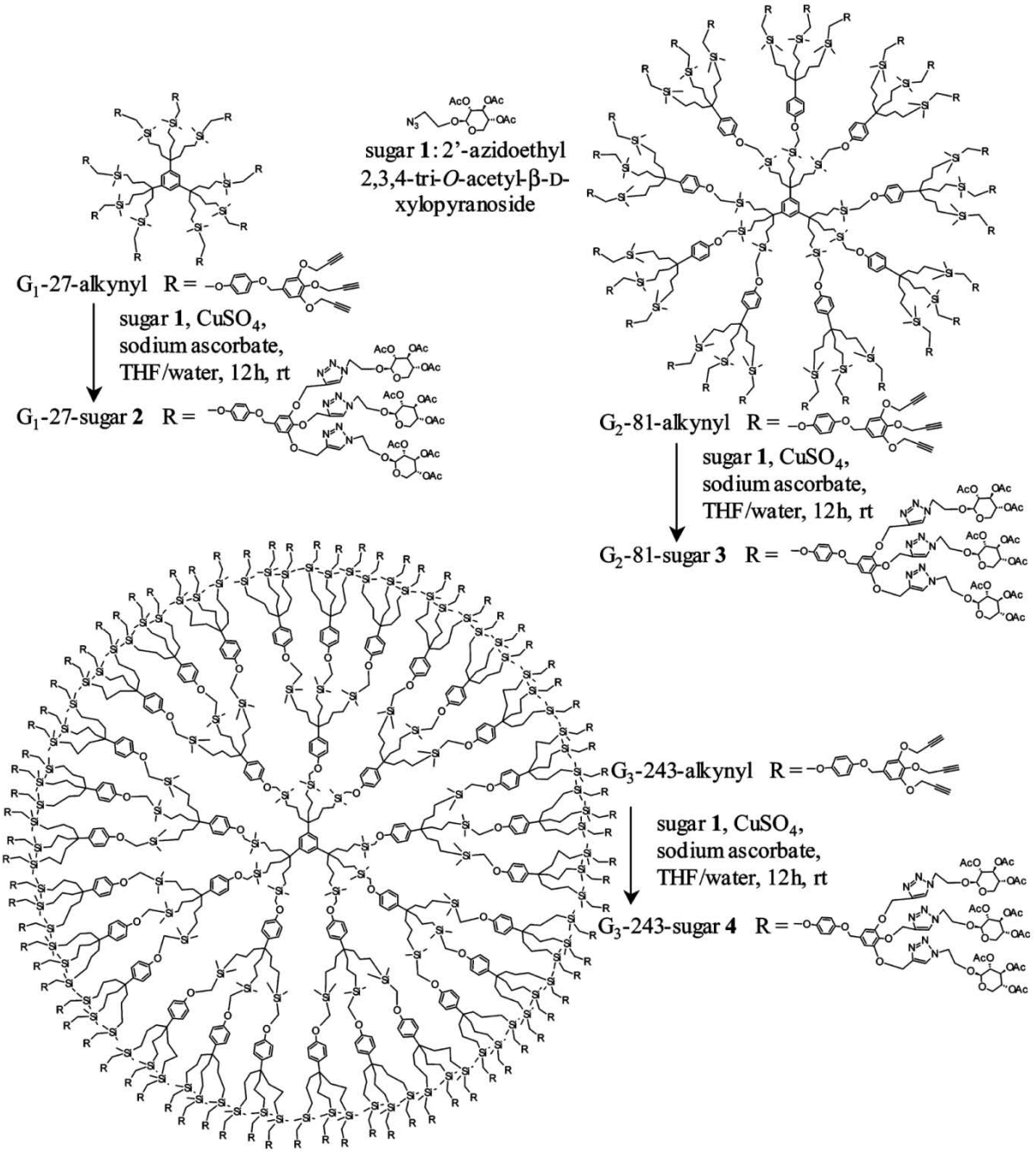
SCHEME 1. Synthesis of the Polyxylopyranoside Dendrimer Series



Glycodendrimers are already a rich family, with large possibilities of potential applications. The chirality of sugar allows for their use in enantioselective catalysis,[11] and the supramolecular interaction between sugars and proteins such as lectins,[12] for example, provides potential applications in nanomedicine.[13] With these perspectives, we report here the synthesis of a series of large glycodendrimers containing from 27 (G_1) to 243 (G_3) modified xylopyranoside termini by Cu(I)-catalyzed Huisgen cycloaddition.[14] The D-xylose was functionalized[15] to introduce the azido group, and the "click" cycloaddition was carried out using the corresponding

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alkynyl-terminated dendritic core[16] to yield the glycodendrimers with 27, 81, and 243 terminal branches.

We recently published the polyalkynyl-terminated dendrimers shown in Scheme 1, and we now report "click" reactions between these dendrimer cores[16] and the known 2′-azidoethyl 2,3,4-tri-*O*-acetyl-*β*-D-xylopyranoside,[15] including the syntheses and characterizations of large sugar-terminated dendrimers containing 3^n sugar termini ($n = 3-5$) shown in Scheme 1.

Cu^I-"catalyzed" Huisgen 1,3-dipolar cycloaddition reaction of the polyalkynyl dendritic cores with the modified azido sugar, **1**, was carried out in the presence of a stoichiometric amount of Cu^I [14] in a homogeneous THF/water mixture yielding the glycodendrimers G_1-27-xylopyranoside, **2**, G_2-81-xylopyranoside, **3**, and G_3-243-xylopyranoside, **4**, under the same reaction conditions (Scheme 1).[17]

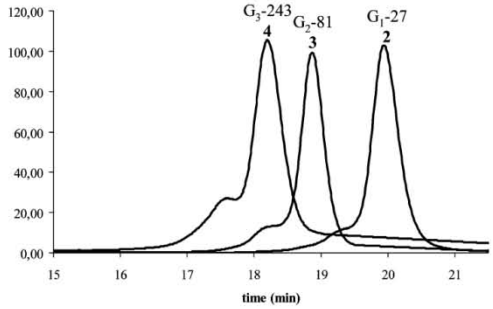
This set of dendrimers was purified by flash column chromatography followed by precipitations (see the Experimental Section). All these functionalized dendrimers were characterized by SEC, ^{1}H, ^{13}C{^{1}H}, and DOSY NMR, IR, elemental analysis, plus DLS for the largest dendrimer G_3-243-xylopyranoside, **4** (hydrodynamic diameter in CH_2Cl_2 at 25 °C of 7.1 ± 0.9 nm (Table 1)), and MALDI TOF mass spectrometry for the smallest dendrimer G_1-27-xylopyranoside, **2**.

TABLE 1. Sizes of the Dendrimers by DOSY NMR and DLS

	G_1-27	G_2-81	G_3-243
polyalkynyl DOSY[a]	4.1	4.8	4.9
polyxylopyranoside DOSY[a]	4.4	5.2	8.5
polyalkynyl DLS[b]	/	6.2	6.6
polyxylopyranoside DLS[b]	/	/	7.1

[a] Diameter in nanometers obtained in $CDCl_3$ at 25 °C. [b] Hydrodynamic diameter in nanometers obtained in CH_2Cl_2 at 25 °C.

SCHEME 2. Size Progression in the Polyxylopyranoside Dendrimer Series Observed by SEC[a]



[a] Side bands at high masses increasing with the generation number are attributed to aggregated dendrimers.[3d]

As can be seen by IR spectroscopy (no visible alkyne or azide vibrating band for all these compounds), there is neither free alkyne branch in these molecules nor excess sugar. SEC indicates the size progression (Scheme 2) from **2** to **4** (retention time of 19.93, 18.85, and 18.18, respectively) and the low polydispersity (1.04 to 1.05). The size progression was also shown by the DOSY NMR data (in $CDCl_3$ at 25 °C: 4.4, 5.2, and 8.5 nm, respectively, for G_1-27-xylopyranoside, G_2-81-xylopyranoside, and G_3-243-xylopyranoside (Table 1)). Table 1 compares the characterizations of the precursor polylalkynyl dendrimers with those of the sugar-terminated dendrimers.

These values demonstrate the increase of the dendrimer size upon coupling the polyalkynyl cores with the sugar (from 4.1 to 4.4 nm for G_1-27, from 4.8 to 5.2 for G_2-81, and from 4.9 to 8.5 for G_3-243 under the same conditions). This increase also appears by DLS for the largest dendrimer G_3-243 (from 6.6 to 7.1 nm). These values are rather close to those obtained by the DOSY NMR technique (Table 1).

Moreover, the elemental analyses of the two dendrimers G_1-27-sugar **2** and G_2-81-sugar **3** are very good for such giant molecules (less than 0.3% difference between calculated and found for both carbon and hydrogen) and not so far for the largest dendrimer G_3-243-sugar **4** (MW > 130 000 Da and 0.7% difference between calculated and found for carbon). These results were obtained after more than 1 week under vacuum. After this period, the values obtained were stabilized, which is an indication of the strong encapsulation capacity of these dendrimers.

In this work, we have synthesized three generations of large to giant glycodendrimers containing 27, 81, and 243 xylopyranosides that have been characterized by standard spectroscopic and analytical techniques. The dendrimer size growth from G_1-27 to G_3-243 and also upon functionalization within each generation was shown using diffusion light scattering (DLS),

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DOSY NMR, and size exclusion chromatography (SEC), with a satisfactory agreement concerning size data among these methods.

Experimental Section

General Procedure for "Click" Coupling. To a solution of polyalkynyl dendrimer[16] (1.0 equiv) in a THF/water 1:1 (v/v) mixture were added 2′-azidoethyl 2,3,4-tri-*O*-acetyl-*β*-D-xylopyranoside **1**[15] (2.0 equiv per branch), $CuSO_4 \cdot 5H_2O$ (4.0 equiv per branch), and sodium ascorbate (8.0 equiv per branch). The mixture was stirred at room temperature under a nitrogen atmosphere for 12 h. The mixture was concentrated, and CH_2Cl_2 was added. The organic layer was washed with aqueous ammonium hydroxide until a colorless aqueous layer was obtained and then with water to neutrality. The organic phase was concentrated to dryness in vacuo. The crude product was purified by flash column chromatography with ethyl acetate and then an ethyl acetate/methanol 7:3 (v/v) mixture as eluents. The product obtained was dissolved in minimum CH_2Cl_2 and precipitated with excess diethylether and then with excess methanol. Glycodendrimers were obtained as off-white gums in 59, 62, and 51% yield for G_1-27, G_2-81, and G_3-243, respectively.

Data for dendrimer G_1-27, **2**, $C_{612}H_{795}O_{261}N_{81}Si_9$: MW 13 715.09 $g \cdot mol^{-1}$; yield 59%; off-white gum; δ_H (300 MHz, $CDCl_3$, 25 °C, TMS) 0.05 (s, 54H, Si−C*H*$_3$), 0.60 (s, 18H, CH_2−CH_2−C*H*$_2$−Si), 1.15 (s, 18H, CH_2−C*H*$_2$−CH_2−Si), 1.66 (s, 18H, C*H*$_2$−CH_2−CH_2−Si), 1.90−2.04 (m, 243H, C*H*$_3$ sugar), 3.31 (m, 27H, H_{5a} sugar), 3.46 (s, 18H, Si−C*H*$_2$−O), 3.92−3.99 (2m, 27H + 27H, $H_2 + H_4$ sugar), 4.03 (m, 27H, H_{5e} sugar), 4.45−4.55 (m, 27H + 54H, $H_{1\beta} + H_{2'}$ sugar), 4.85−4.89 (m, 18H + 54H, O−C*H*$_2$−C_{Ar} + $H_{1'}$ sugar), 5.08−5.16 (m, 27H + 54H, H_3 sugar + O−C*H*$_2$−$C_{triazole}$), 6.77−7.00 (m, 57H, H_{Ar}), 7.88 (s, 27H, $H_{triazole}$); δ_C (75.5 MHz, $CDCl_3$, 25 °C, TMS) −4.5 (CH_3), 14.2 (CH_2), 17.8 (CH_2), 20.6 (CH_3), 20.7 (CH_3), 20.8 (CH_3), 42.4 (CH_2), 44.3 (C), 49.7 (CH_2), 50.0 (CH_2), 60.9 (CH_2), 62.0 (CH_2), 62.1 (CH_2), 63.0 (CH_2), 63.0 (CH_2), 67.4 (CH_2), 67.5 (CH_2), 68.8 (CH), 70.5 (CH), 71.2 (CH), 71.3 (CH_2), 100.5 (CH), 100.6 (CH), 107.0 (CH), 114.8 (CH), 115.5 (CH), 116.2 (CH), 124.5 (CH), 125.1 (CH), 133.6 (C), 137.1 (C), 143.7 (C), 144.5 (C), 152.3 (C), 152.5 (C), 156.1 (C), 169.5 (C), 169.9 (C), 170.0 (C); no more azide or alkyne absorption in IR spectroscopy; *m/z* (MALDI-TOF) for $C_{612}H_{795}O_{261}N_{81}Si_9$-NaCu 13 801 $[M + NaCu]^+$, found 13 801. Anal. Calcd $C_{612}H_{795}O_{261}N_{81}Si_9$: C, 53.59; H, 5.84. Found: C, 53.29; H, 5.78. DOSY NMR gives $D = 1.85 \times 10^{-10}$ $m^2 \cdot s^{-1}$ in chloroform at 25 °C, which corresponds to a diameter of 4.4 nm; SEC shows the low polydispersity (1.04).

Data for dendrimer G_2-81, **3**, $C_{1935}H_{2541}O_{792}N_{243}Si_{36}$: MW 42 888.36 $g \cdot mol^{-1}$; yield 62%; off-white gum; δ_H (300 MHz, $CDCl_3$, 25 °C, TMS) 0.05−0.12 (s, 54H + 162H, Si−C*H*$_3$), 0.60 (s, 18H + 54H, CH_2−CH_2−C*H*$_2$−Si), 1.15 (s, 18H + 54H, CH_2−C*H*$_2$−CH_2−Si), 1.66 (s, 18H + 54H, C*H*$_2$−CH_2−CH_2−Si), 1.90−2.04 (m, 729H, C*H*$_3$ sugar), 3.31 (m, 81H, H_{5a} sugar), 3.38 (s, 54H, outer Si−C*H*$_2$−O), 3.47 (s, 18H, inner Si−C*H*$_2$−O), 4.04−4.07 (2m, 81H + 81H, $H_2 + H_4$ sugar), 4.19 (m, 81H, H_{5e} sugar), 4.45−4.55 (m, 81H + 162H, $H_{1\beta} + H_{2'}$ sugar), 4.85−4.89 (m, 54H + 162H, O−C*H*$_2$−C_{Ar} + $H_{1'}$ sugar), 5.08−5.16 (m, 81H + 162H, H_3 sugar + O−C*H*$_2$−$C_{triazole}$), 6.77−7.00 (m, 201H, H_{Ar}), 7.88 (s, 81H, $H_{triazole}$); δ_C (62.9 MHz, $CDCl_3$, 25 °C, TMS) −4.6 (CH_3), 14.2 (CH_2), 17.8 (CH_2), 20.6 (CH_3), 20.7 (CH_3), 20.8 (CH_3), 42.4 (CH_2), 44.3 (C), 50.0 (CH_2), 60.9 (CH_2), 62.1 (CH_2), 63.1 (CH_2), 67.4 (CH_2), 67.5 (CH_2), 68.8 (CH), 70.5 (CH), 71.2 (CH), 71.4 (CH_2), 100.6 (CH), 107.0 (CH), 114.9 (CH), 115.6 (CH), 116.2 (CH), 124.5 (CH), 125.1 (CH), 133.6 (C), 137.2 (C), 143.7 (C), 144.5 (C), 152.3 (C), 152.5 (C), 156.1 (C), 169.5 (C), 169.9 (C), 170.0 (C); no more azide or alkyne absorption in IR spectroscopy. Anal. Calcd for $C_{1935}H_{2541}O_{792}N_{243}Si_{36}$: C, 54.19; H, 5.97. Found: C, 54.14; H, 5.92%. DOSY NMR gives $D = 1.55 \times 10^{-10}$ $m^2 \cdot s^{-1}$ in chloroform at 25 °C, which corresponds to a size of 5.2 nm; SEC shows the low polydispersity (1.04).

Data for dendrimer G_3-243, **4**, $C_{5904}H_{7779}O_{2385}N_{729}Si_{117}$: MW 130 408.18 $g \cdot mol^{-1}$; yield 51%; off-white gum; δ_H (300 MHz, $CDCl_3$, 25 °C, TMS) 0.05−0.12 (m, 54H +162H + 486H, Si−C*H*$_3$), 0.60 (s, 18H + 54H + 162H, CH_2−CH_2−C*H*$_2$−Si), 1.15 (s, 18H + 54H + 162H, CH_2−C*H*$_2$−CH_2−Si), 1.66 (s, 18H + 54H + 162H, C*H*$_2$−CH_2−CH_2−Si), 1.90−2.04 (m, 2187H, C*H*$_3$ sugar), 3.30−3.47 (m, 18H + 54H + 162H + 243H, inner Si−C*H*$_2$−O + outer Si−C*H*$_2$−O + H_{5a} sugar), 3.9−4.2 (3m, 3 × 243H, $H_2 + H_4 + H_{5e}$ sugar), 4.45−4.55 (m, 243H + 486H, $H_{1\beta} + H_{2'}$ sugar), 4.85−4.89 (m, 162H + 486H, O−C*H*$_2$−C_{Ar} + $H_{1'}$ sugar), 5.08−5.16 (m, 243H + 486H, H_3 sugar + O−C*H*$_2$−$C_{triazole}$), 6.77−7.00 (m, 633H, H_{Ar}), 7.88 (s, 243H, $H_{triazole}$); δ_C NMR (62.9 MHz, $CDCl_3$, 25 °C, TMS) −4.4 (CH_3), 14.6 (CH_2), 17.9 (CH_2), 20.7 (CH_3), 20.8 (CH_3), 20.8 (CH_3), 42.4 (CH_2), 44.3, 49.7 (CH_2), 50.0 (CH_2), 61.0 (CH_2), 62.0 (CH_2), 62.2 (CH_2), 63.1 (CH_2), 67.4 (CH_2), 67.5 (CH_2), 68.8 (CH), 70.5 (CH), 71.2 (CH), 71.8 (CH_2), 100.5 (CH), 100.6 (CH), 107.0 (CH), 114.8 (CH), 115.6 (CH), 116.3 (CH), 124.5 (CH), 125.6 (CH), 134.1 (C), 137.2 (C), 143.8 (C), 144.5 (C), 152.3 (C), 152.5 (C), 156.1 (C), 169.9 (C), 170.0 (C), 170.1 (C); no more azide or alkyne absorption in IR spectroscopy. Anal. Calcd for $C_{5904}H_{7779}O_{2385}N_{729}Si_{117}$: C, 54.38; H, 6.01. Found: C, 53.65; H, 6.35. DOSY NMR gives $D = 9.5 \times 10^{-11}$ $m^2 \cdot s^{-1}$ in chloroform at 25 °C, which corresponds to a size of 8.5 nm; DLS gives a size of 7.1 ± 0.9 nm in dichloromethane at 25 °C; SEC shows the low polydispersity (1.05).

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Supporting Information Available: General data, spectroscopic data including ^1H NMR, $^{13}C\{^1H\}$ NMR, IR and mass spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

JO900554B

Supporting Information

"Click" Glycodendrimers Containing 27, 81 and 243 Modified Xylopyranoside Termini

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1. General. All operations were performed under nitrogen atmosphere using standard Schlenk techniques. Whenever mentioned, CH_2Cl_2 was dried over calcium hydride and freshly distilled under a nitrogen atmosphere. All other reagents were obtained from commercial sources and used without further purification. All glassware was previously dried in an oven and cooled under a nitrogen flow.

Parts 2 to 6 of this SI describe syntheses that are already known and adapted from ref 15 of the main text. The spectra that we have obtained are shown here.

Parts 7 to 9 of this SI describe the characterizations of the three new compounds (for the syntheses see main text).

2. Synthesis of the 1,2,3,4-tetra-*O*-acetyl-β-D-xylopyranose

A mixture of D-xylose **1** (8 g, 53.20 mmol, 1.0 equiv), $NaOAc.3H_2O$ (7.25 g, 53.20 mmol, 1.0 equiv) and acetic anhydride (60 mL, 639 mmol, 12 equiv) was heated to 100°C for 24 h. The mixture was then cooled, mixed with crushed ice and extracted using diethylether (200 mL). The organic layer was washed with saturated aqueous $NaHCO_3$ and then with water to neutrality. Organics were collected, dried over anhydrous $MgSO_4$ and concentrated to dryness in vacuo. The yellow solid was recristallized in absolute ethanol.

Yield 54%; white crystals; Rf = 0.35 (Ethyl acetate/Petroleum ether 4:1 (v/v)); mp 125-128 °C; δ_H (300 MHz; $CDCl_3$; 25°C; TMS) 2.00-2.20 (4 x s, 12H, COCH_3), 3.35 (dd, 1H, J=8.5 Hz J=12.0 Hz, H_{5a}), 4.16 (dd, 1H, J=4.9 Hz J=12.0 Hz, H_{5e}), 4.93-5.10 (m, 2H, H_2 and H_4), 5.22 (t, 1H, J=8.2 Hz, H_3), 5.73 (d, 1H, J=6.8 Hz, $H_{1\beta}$); δ_C (75.5 MHz, $CDCl_3$, 25°C; TMS) 20.7, 20.8, 20.8, 20.9 (4 x CH_3 (OAc)), 62.9 (C_5), 68.4 (C_4), 69.6 (C_2), 71.0 (C_3), 92.1 ($C_{1\beta}$), 169.1, 169.4, 169.9, 169.9 (4 x quat. *C* (OAc)); m/z (TOF^+ HRMS) for $C_{13}H_{18}O_9Na$ 341.0849 $[M + Na]^+$, found 341.0840; IR spectroscopy 2967 (w), 2888 (w), 1745 (s), 1380 (m), 1221 (s), 1083 (m), 1041 (m); elemental analysis calcd for $C_{13}H_{18}O_9$ C 49.06%, H 5.66%, found C 49.00%, H 5.56%.

Figure SI1. ^{1}H NMR spectrum

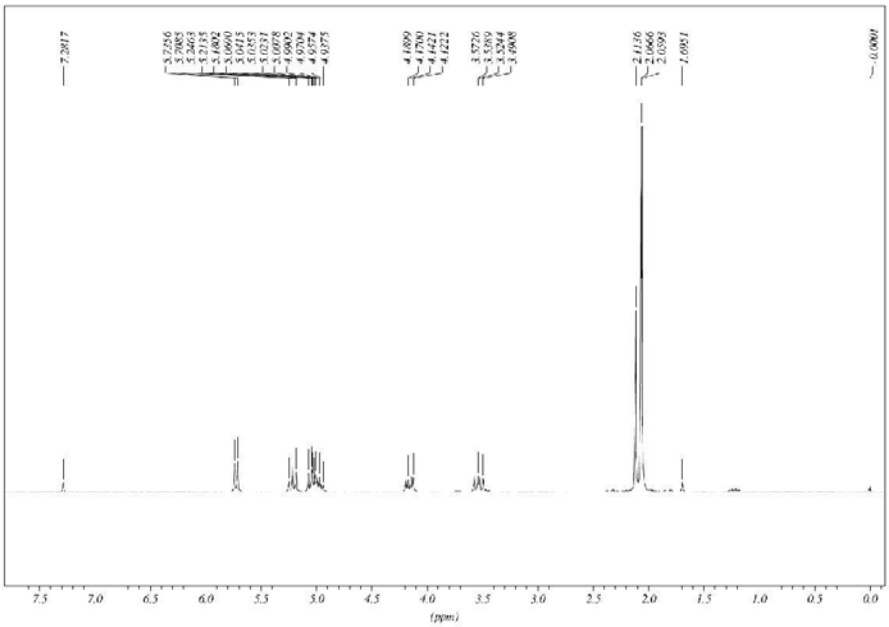
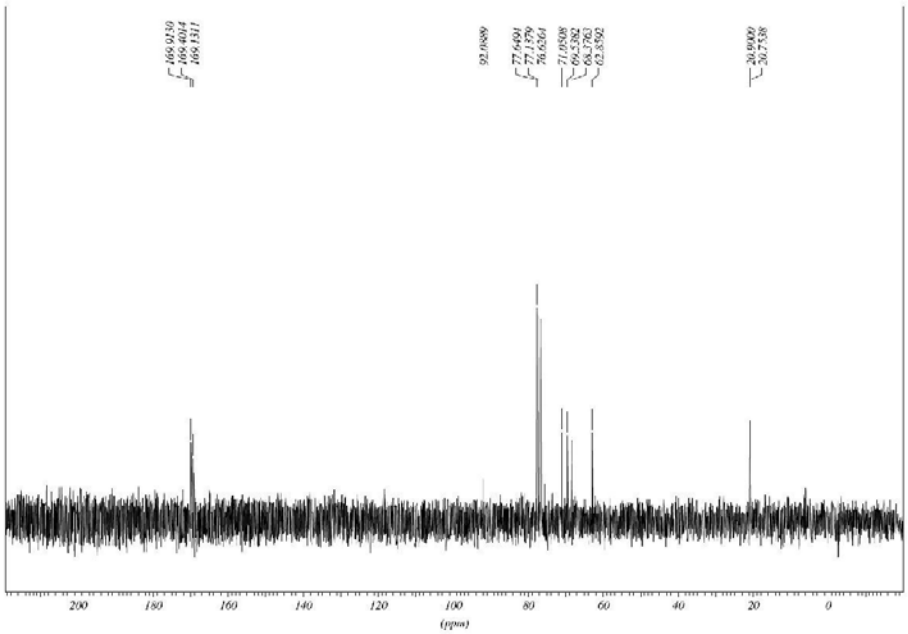
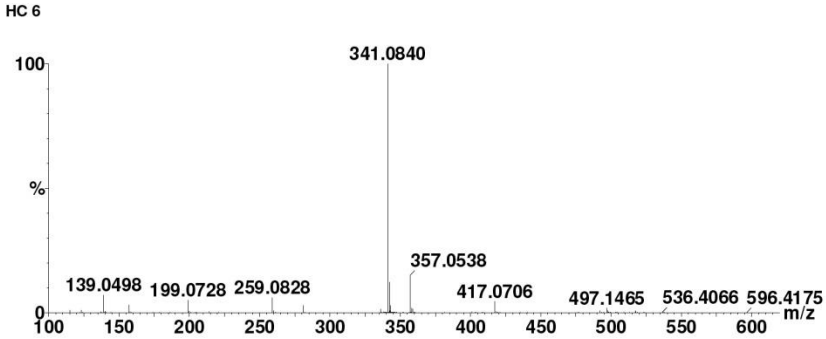


Figure SI2. ^{13}C{^{1}H} NMR spectrum



SI5

Figure SI3. High resolution mass spectrum



3. Synthesis of the 2,3,4-tri-*O*-acetyl-α-D-xylopyranosyl bromide

To a solution of 1,2,3,4-tetra-*O*-acetyl-β-D-xylopyranose (2.05 g, 9.43 mmol, 1.0 equiv) in CH_2Cl_2 (40 mL) under an argon atmosphere at 0°C was added dropwise a solution of HBr 33% in acetic acid (8.1 mL, 47.15 mmol, 5 equiv). The mixture was stirred at room temperature for 24 h and then CH_2Cl_2 (60 mL) was added. The solution was cooled and mixed with crushed ice. The organic layer was washed with saturated aqueous $NaHCO_3$ (4 x 50mL) and then with water (4 x 50 mL). Organics were collected, dried over anhydrous $MgSO_4$, and concentrated to dryness in vacuo. The 2,3,4-tri-*O*-acetyl-α-D-xylopyranosyl bromide was immediately engaged in the next step.

Yield 83%; off-white crystals; Rf = 0.73 (Ethyl acetate/Petroleum ether 7:3 (v/v)); δ_H (300 MHz; $CDCl_3$; 25°C; TMS) 2.00-2.15 (3 x s, 9H, COCH_3), 3.86 (d, 1H, J=11.3 Hz, H_{5a}), 4.08 (dd, 1H, J=6.0 Hz J=11.3 Hz, H_{5e}), 4.75 (dd, 1H, J=4.0 Hz J=9.9 Hz, H_2), 4.95-5.15 (m, 1H, H_4), 5.58 (t, 1H, J=9.9 Hz, H_3), 6.60 (d, 1H, J=4.0 Hz, $H_{1\alpha}$); δ_C (75.5 MHz; $CDCl_3$; 25°C; TMS) 20.6, 20.7, 20.7 (3 x CH_3 (OAc)), 62.5 (C_5), 68.1 (C_4), 69.5 (C_3), 70.1 (C_2), 87.7 ($C_{1\alpha}$), 169.8, 169.9, 169.9 (3 x quat. *C* (OAc)).

Figure SI4. ^{1}H NMR spectrum

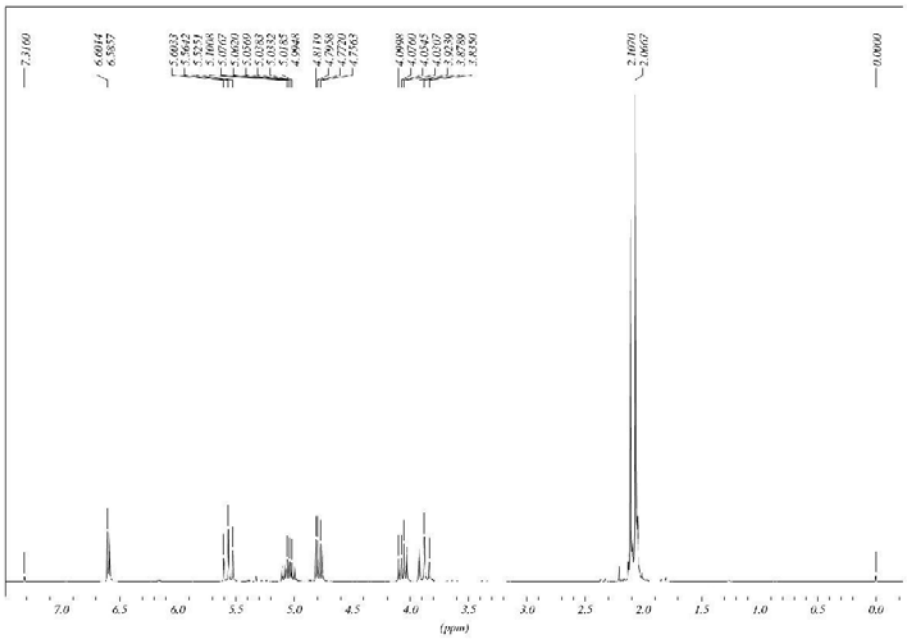
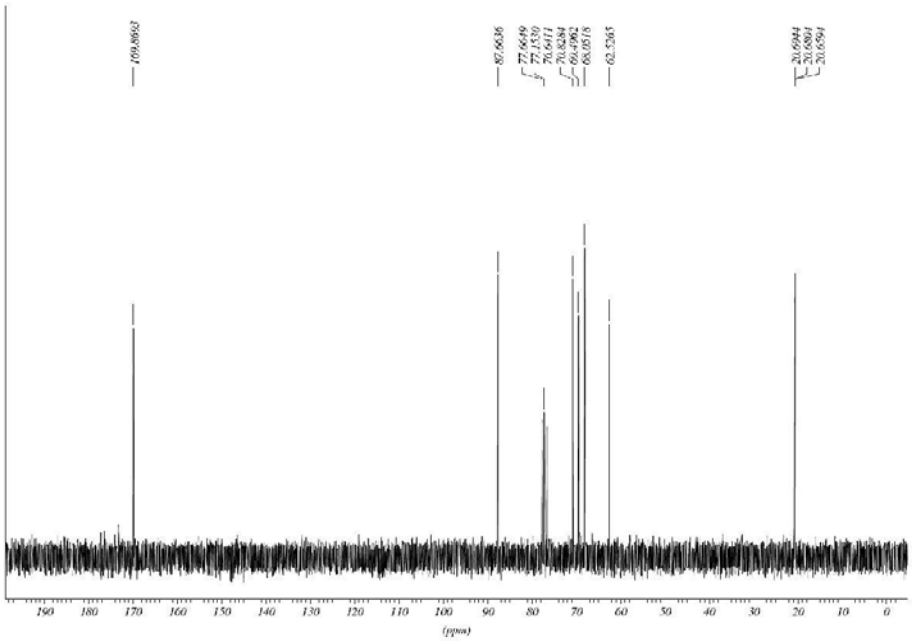


Figure SI5. ^{13}C{^{1}H} NMR spectrum



SI8

4. Synthesis of the 2'-hydroxyethyl 2,3,4-tri-*O*-acetyl-β-D-xylopyranoside

To a solution of 2,3,4-tri-*O*-acetyl-α-D-xylopyranosyl bromide (2.45 g, 7.21 mmol, 1.0 equiv) in CH_2Cl_2 (45 mL) were added Ag_2O (1.67 g, 7.21 mmol, 1.0 equiv), $CaSO_4$ (1 g, 7.35 mmol, 1.1 equiv) and ethylene glycol (2 mL, 36.05 mmol, 5 equiv). The mixture was stirred at room temperature under an argon atmosphere for 48 h.

Eluent for column chromatography ethyl acetate/petroleum ether 9:1 (v/v); yield 57%; white solid; Rf = 0.48 (Ethyl acetate/Petroleum ether 4:1 (v/v)); δ_H (300 MHz; $CDCl_3$; 25°C; TMS) 1.90-2.10 (3 x s, 9H, COCH_3), 3.35 (dd, 1H, J=9.3 Hz J=11.6 Hz, H_{5a}), 3.55-3.85 (m, 4H, $H_{1'}$ and $H_{2'}$), 4.05 (dd, 1H, J=5.3 Hz J=11.6 Hz, H_{5e}), 4.50 (d, 1H, J=7.1 Hz, $H_{1\beta}$), 4.80-4.95 (m, 2H, H_2 and H_4), 5.15 (t, 1H, J=8.9 Hz, H_3); δ_C (75.5 MHz; $CDCl_3$; 25°C; TMS) 20.6, 20.7, 20.7 (3 x CH_3 (OAc)), 61.3 ($C_{2'}$), 61.9 (C_5), 68.6 ($C_{1'}$), 70.7 (C_4), 73.3 (C_2), 73.4 (C_3), 100.9 ($C_{1\beta}$), 169.4, 169.7, 169.9 (3 x quat; *C* (OAc)); m/z (TOF$^+$ HRMS) for $C_{13}H_{20}O_9Na$ 343.1005 $[M + Na]^+$, found 343.0908; IR spectroscopy 3525 (s), 2955 (w), 2889 (w), 1748 (s), 1369 (m), 1224 (s), 1068 (m), 1051 (m); elemental analysis calcd for $C_{13}H_{20}O_9$ C 48.75%, H 6.25%, found C 48.51%, H 6.13%.

Figure SI6. ^{1}H NMR spectrum

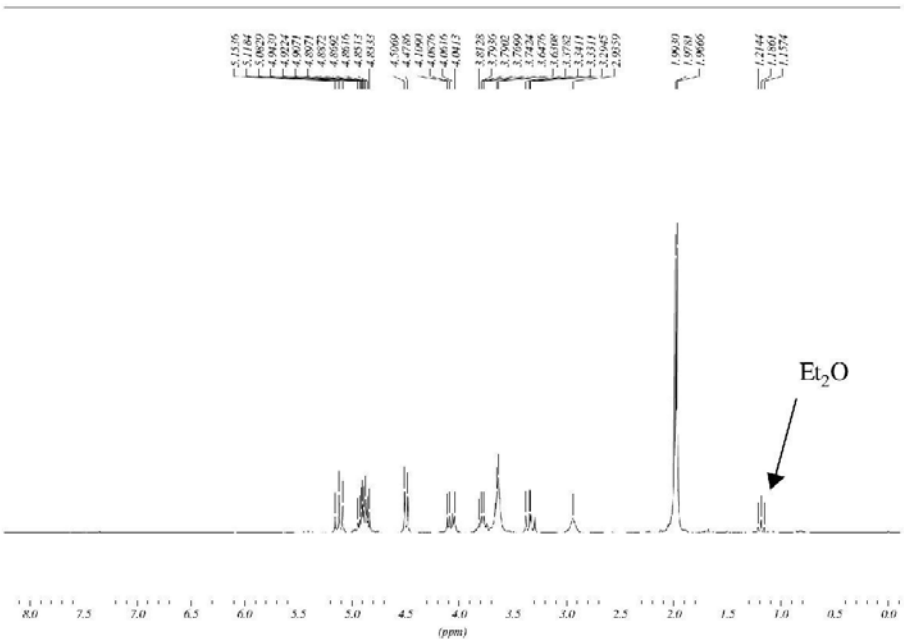
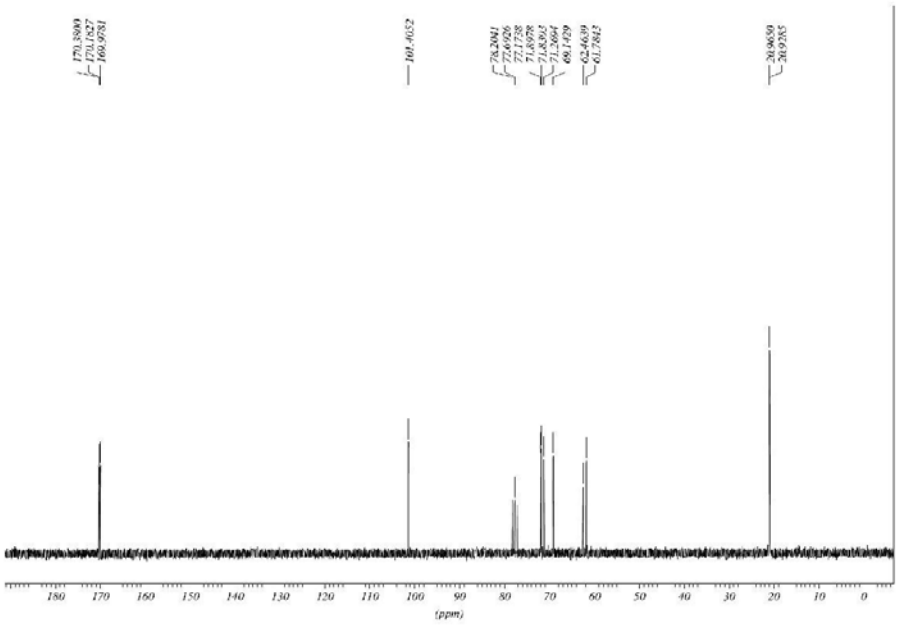


Figure SI7. ^{13}C{^{1}H} NMR spectrum



5. Synthesis of the 2'-methanesulfonyloxyethyl 2,3,4-tri-*O*-acetyl-β-D-xylopyranoside

To a solution of 2'-hydroxyethyl 2,3,4-tri-*O*-acetyl-β-D-xylopyranoside (1.66 g, 5.19 mmol, 1.0 equiv) in CH_2Cl_2 (25 mL) at 0°C under an argon atmosphere was added triethylamine (1.1 mL, 7.78 mmol, 1.5 equiv). The mixture was stirred for 15 minutes and methanesulfonyl chloride (0.51 mL, 6.49 mmol, 1.25 equiv) was added. The mixture was stirred for another 2h at room temperature and water (20 mL) was added. The organic layer was washed with water to neutrality, dried over anhydrous $MgSO_4$ and concentrated to dryness in vacuo.

Eluent for column chromatography ethyl acetate/petroleum ether 9:1 (v/v); yield 96%; yellow oil; Rf = 0.60 (Ethyl acetate/Petroleum ether 1:1 (v/v)); δ_H (300 MHz; $CDCl_3$; 25°C; TMS) 1.75-1.92 (3 x s, 9H, $COCH_3$), 2.81 (s, 3H, SO_2CH_3), 3.23 (dd, 1H, J=8.8 Hz J=11.9 Hz, H_{5a}), 3.56-3.69 (m, 1H, $H_{1'}$), 3.81-3.91 (m, 1H, $H_{1'}$), 3.94 (dd, 1H, J=5.2 Hz J=11.9 Hz, H_{5e}), 4.12-4.20 (m, 2H, $H_{2'}$); 4.40 (d, 1H, J=6.9 Hz, $H_{1\beta}$), 4.71 (dd, 1H, J=6.9 Hz J=8.7 Hz, H_2), 4.68-4.82 (m, 1H, H_4), 4.92 (t, 1H, J=8.7 Hz, H_3); δ_C (75.5 MHz; $CDCl_3$; 25°C; TMS) 20.4, 20.5, 20.5 (3 x CH_3 (OAc)), 37.2 (CH_3 (OMs)), 61.8 (C_5), 66.8 ($C_{1'}$), 68.5 (C_4), 68.8 ($C_{2'}$), 70.3 (C_2), 70.9 (C_3), 100.5 ($C_{1\beta}$), 169.3, 169.6, 169.7 (3 x quat. *C* (OAc)); m/z (TOF^+ HRMS) for $C_{14}H_{22}O_{11}SNa$ 421.0781 $[M + Na]^+$, found 421.0778; IR spectroscopy 2941 (w), 1747 (s), 1433 (s), 1353 (s), 1226 (s), 1066 (m); elemental analysis calcd for $C_{14}H_{22}O_{11}S$ C 42.22%, H 5.53%, S 8.04%, found C 42.20%, H 5.62%, S 8.02%.

Figure SI8. ^{1}H NMR spectrum

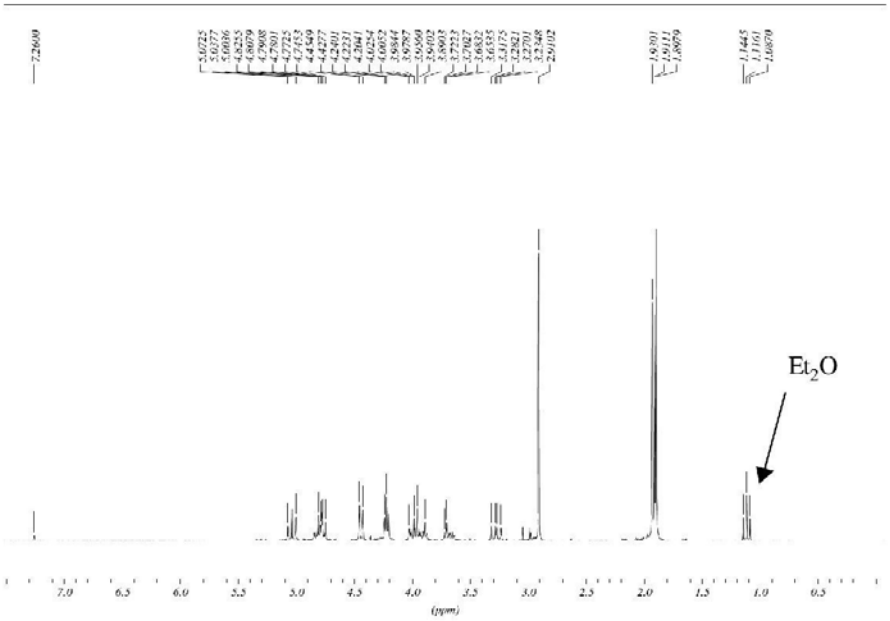


Figure SI9. ^{13}C{^{1}H} NMR spectrum

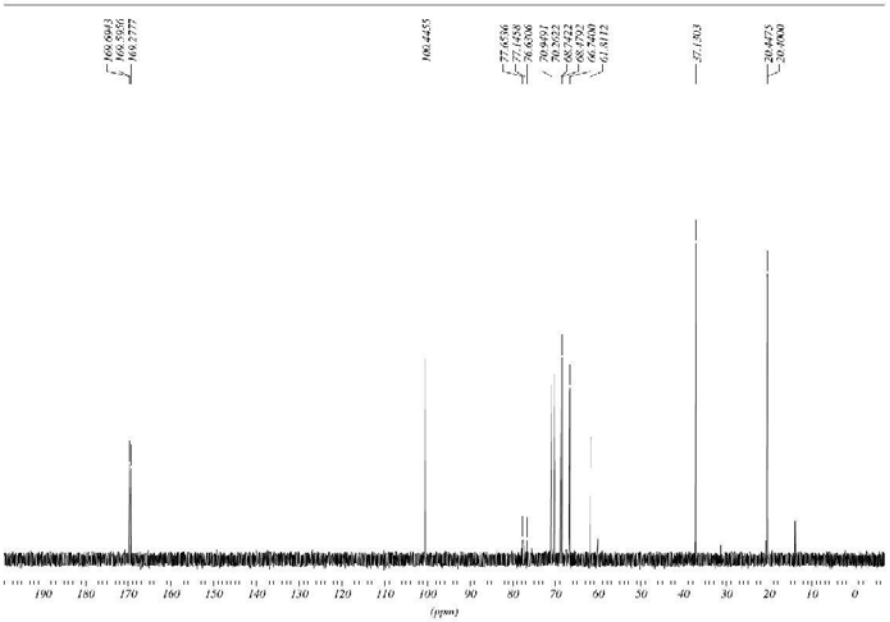
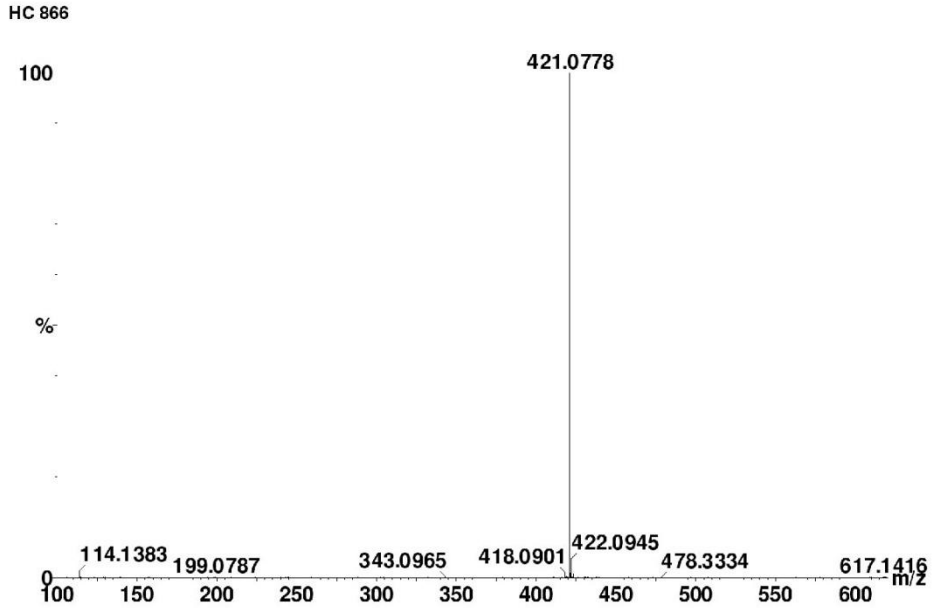


Figure SI10. High resolution mass spectrum



6. Synthesis of the 2'-azidoethyl 2,3,4-tri-*O*-acetyl-β-D-xylopyranoside 1

To a solution of sodium azide (975 mg, 15.0 mmol, 3.0 equiv) in DMF (20 mL) at room temperature under an argon atmosphere was added dropwise a solution of 2'-methanesulfonyloxyethyl 2,3,4-tri-*O*-acetyl-β-D-xylopyranoside (1.99 g, 5.0 mmol, 1.0 equiv) in DMF (2 mL). The mixture was stirred at 80°C for 24 h. The mixture was concentrated and diethylether (20 mL) was added. The organic layer was washed with water (2 x 20 mL) and with saturated aqueous NaCl (20 mL). Organics were collected, dried over anhydrous $MgSO_4$ and concentrated to dryness in vacuo.

Yield 73%; off-white solid; Rf = 0.68 (Ethyl acetate/Petroleum ether 1:1 (v/v)); δ_H (300 MHz, CD_3COCD_3; 25°C; TMS), 1.92-2.16 (m, 9H, CH_3), 3.58 (dd, 1H, $J_{5a/4}$=9.4 Hz, J_{5a5e}=11.7 Hz, H_{5a}), 3.54-3.60 (m, 2H, $H_{1'}$), 3.69 (dd, 1H, J=3.6 Hz, J=7.1 Hz, $H_{2'}$), 3.95 (ddd, 1H, J=3.6 Hz, J=5.5 Hz, J=11.0 Hz, $H_{2'}$), 4.45 (dd, 1H, $J_{5e/4}$=5.3 Hz, $J_{5a/5e}$=11.7 Hz, H_{5e}), 4.70 (d, 1H, $J_{1/2}$=7.3 Hz, $H_{1\beta}$), 4.84 (dd, 1H, $J_{2/1}$=7.3 Hz, $J_{2/3}$=9.1 Hz, H_2), 4.80-4.92 (m, 1H, H_4), 5.16 (t, 1H, J=9.1 Hz, H_3); δ_C (75.5 MHz, CD_3COCD_3; 25°C; TMS) 20.5, 20.6, 20.7 (3 x CH_3 (OAc)), 51.1 ($C_{2'}$), 62.9 (C_5), 68.9 ($C_{1'}$), 69.6, 71.5 (C_4 and C_2), 72.3 (C_3), 101.3 ($C_{1\beta}$), 169.6, 170.1, 170.2 (3 x quat. *C* (OAc)); m/z (TOF$^+$ HRMS) for $C_{13}H_{19}O_8N_3Na$ 368.1070 $[M + Na]^+$, found 368.1067; IR spectroscopy 2947 (w), 2874 (w), 2103 (s), 1752 (s), 1432 (w), 1371 (w), 1226 (s), 1048 (m), 1034 (m); elemental analysis calcd for $C_{13}H_{19}O_8N_3$ C 45.21%, H 5.51%, N 12.17%, found C 44.97%, H 5.56%, N 12.04%.

Figure SI11. ^{1}H NMR spectrum of compound 1

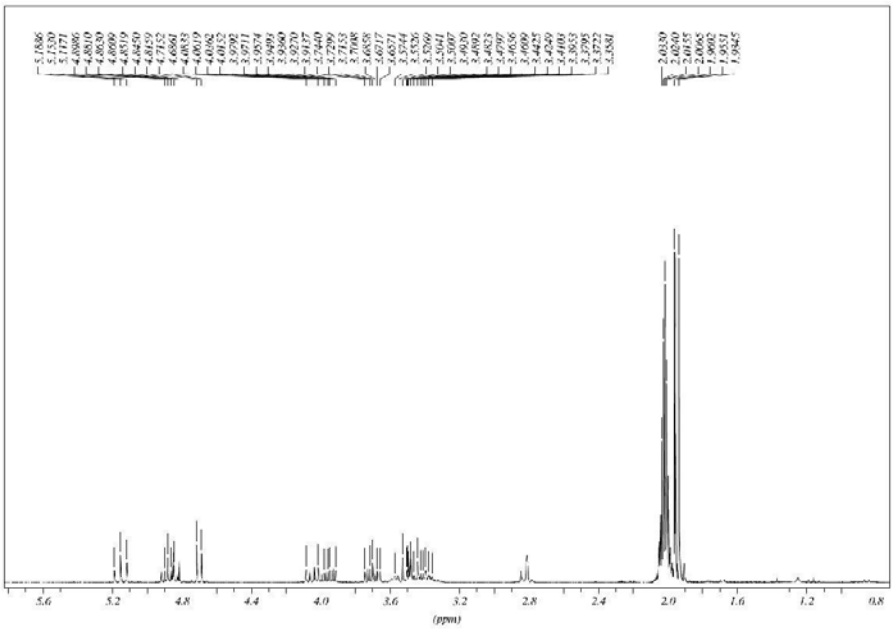
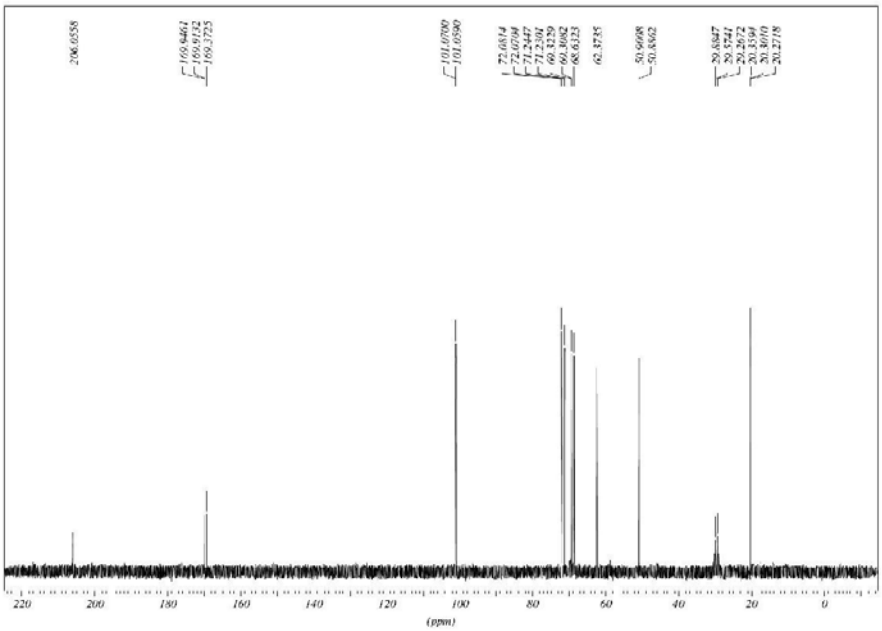
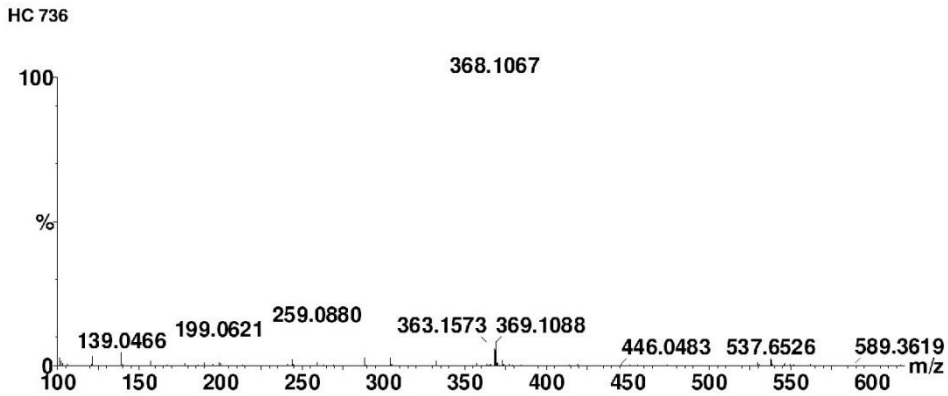


Figure SI12. ^{13}C{^{1}H} NMR spectrum of compound 1



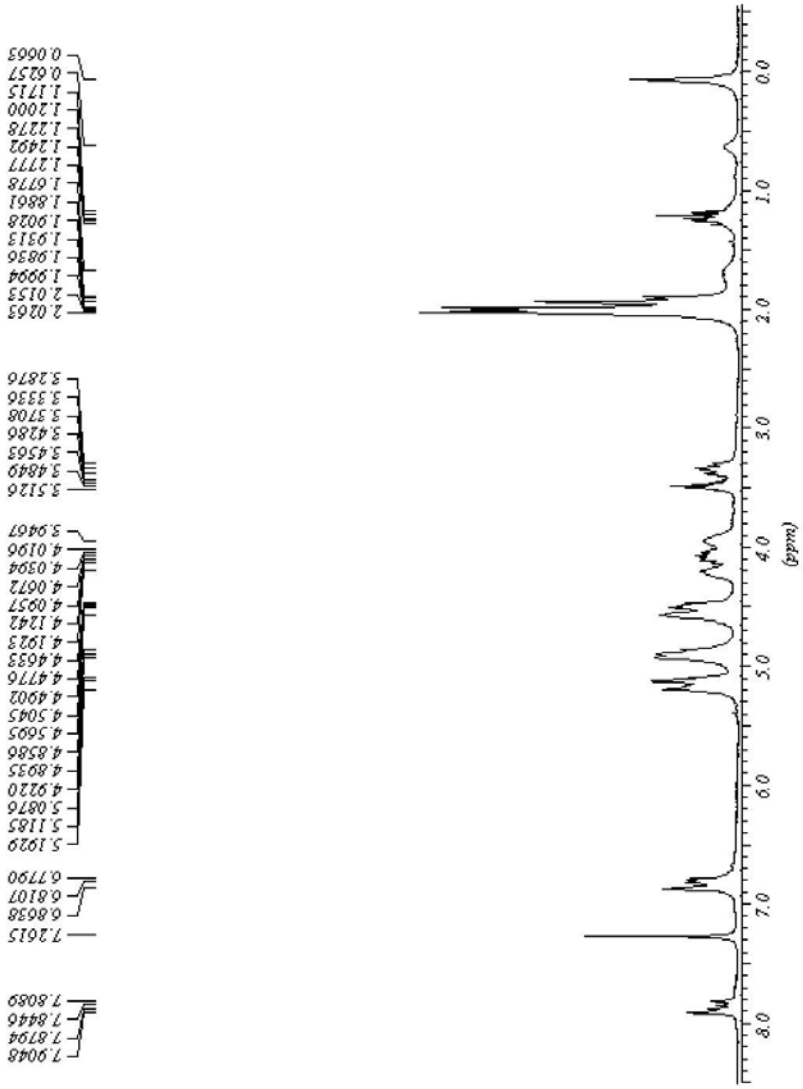
SI15

Figure SI13. High resolution mass spectrum of compound 1



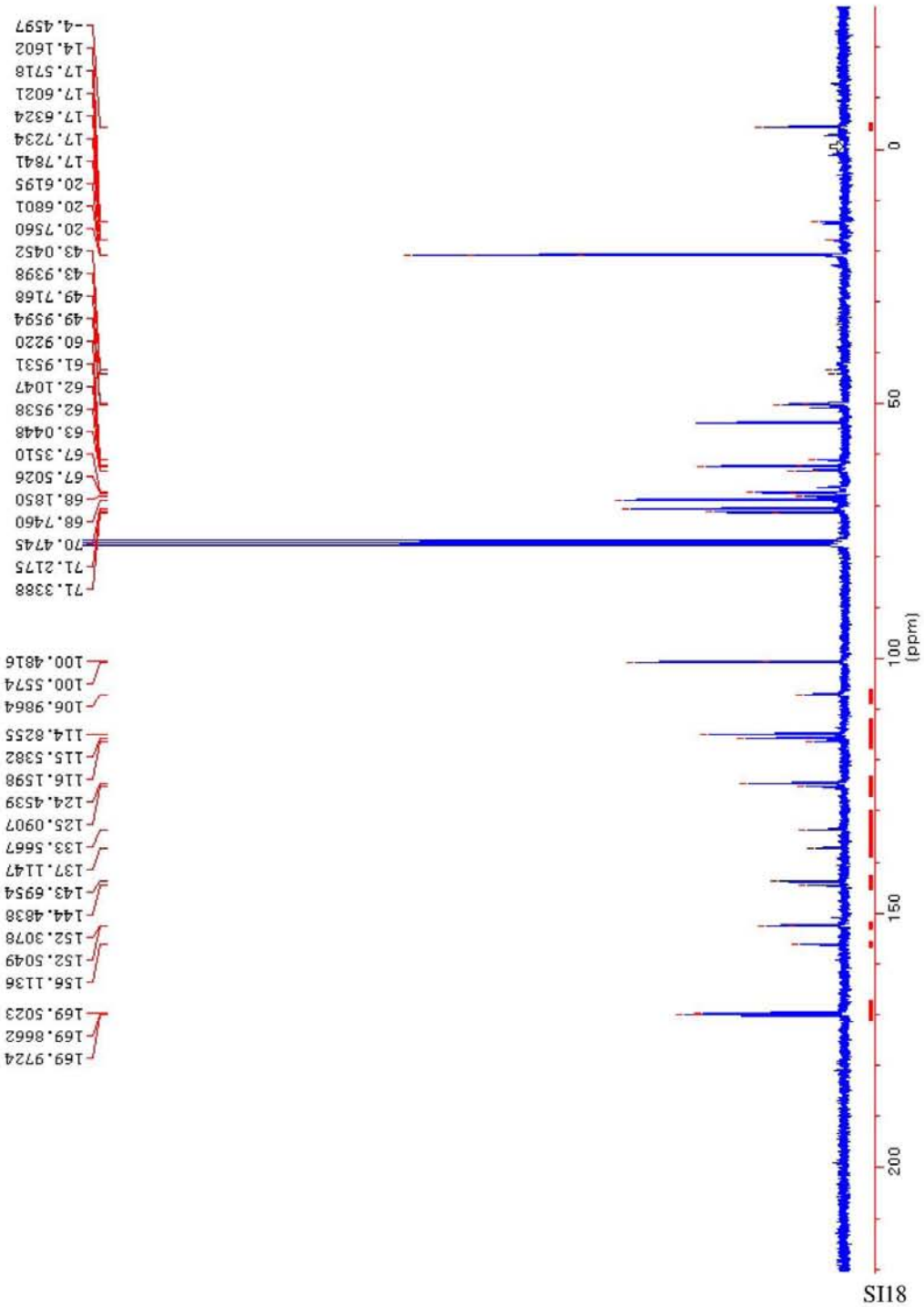
7. Data for G_1-27 xylopyranoside 2

Figure SI14. ^{1}H NMR spectrum of compound 2



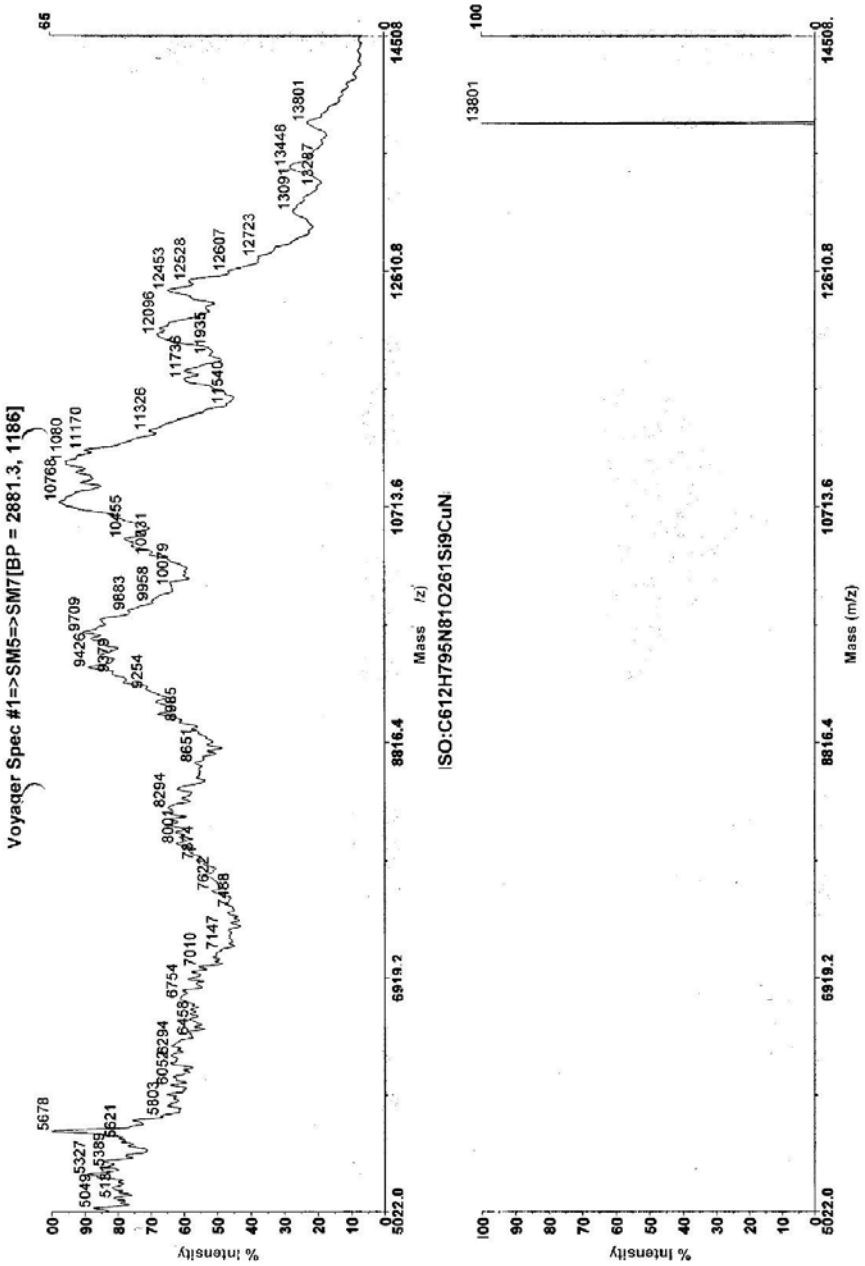
SI17

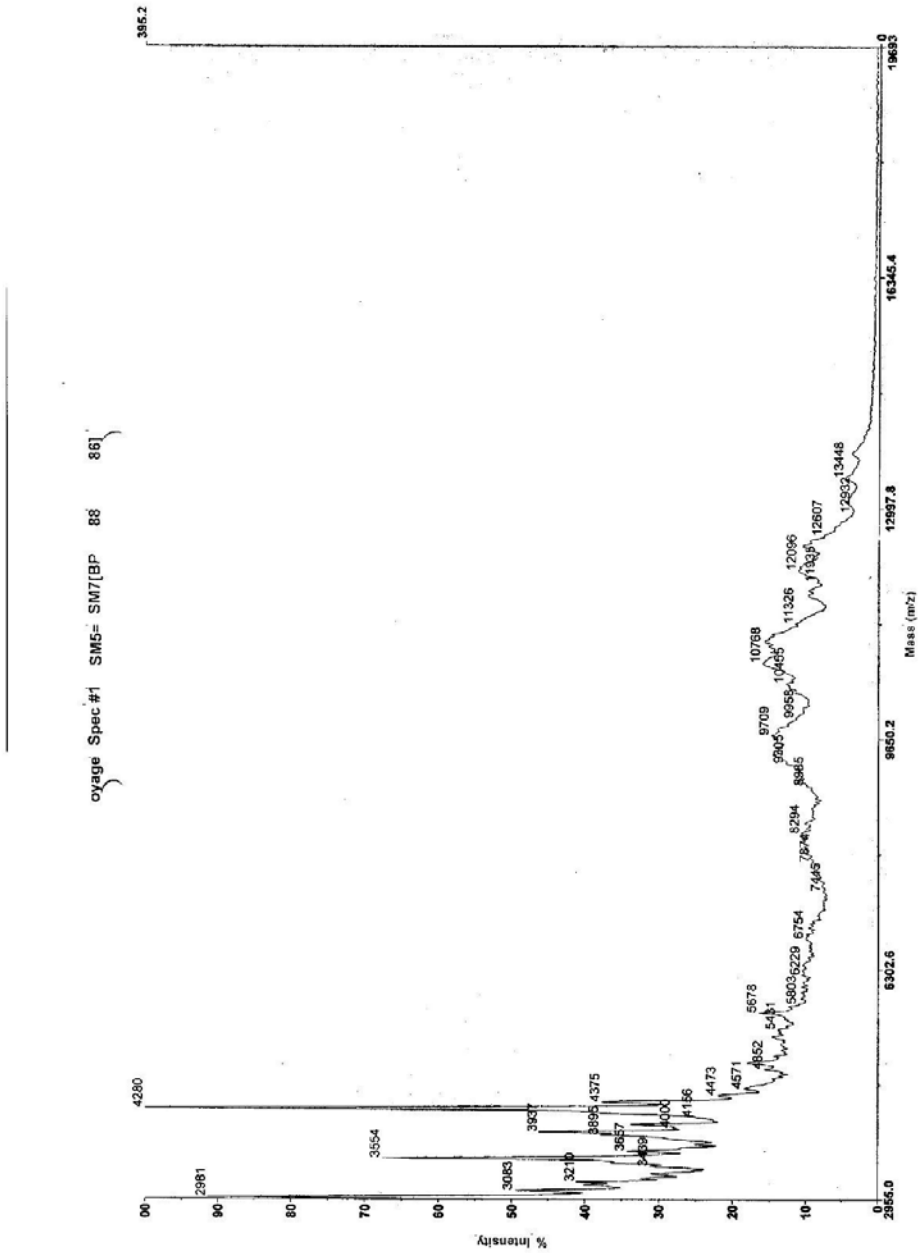
Figure SI15. $^{13}C\{^{1}H\}$ NMR spectrum of compound 2



SI18

Figure SI16. Maldi-Tof mass spectrum of compound 2

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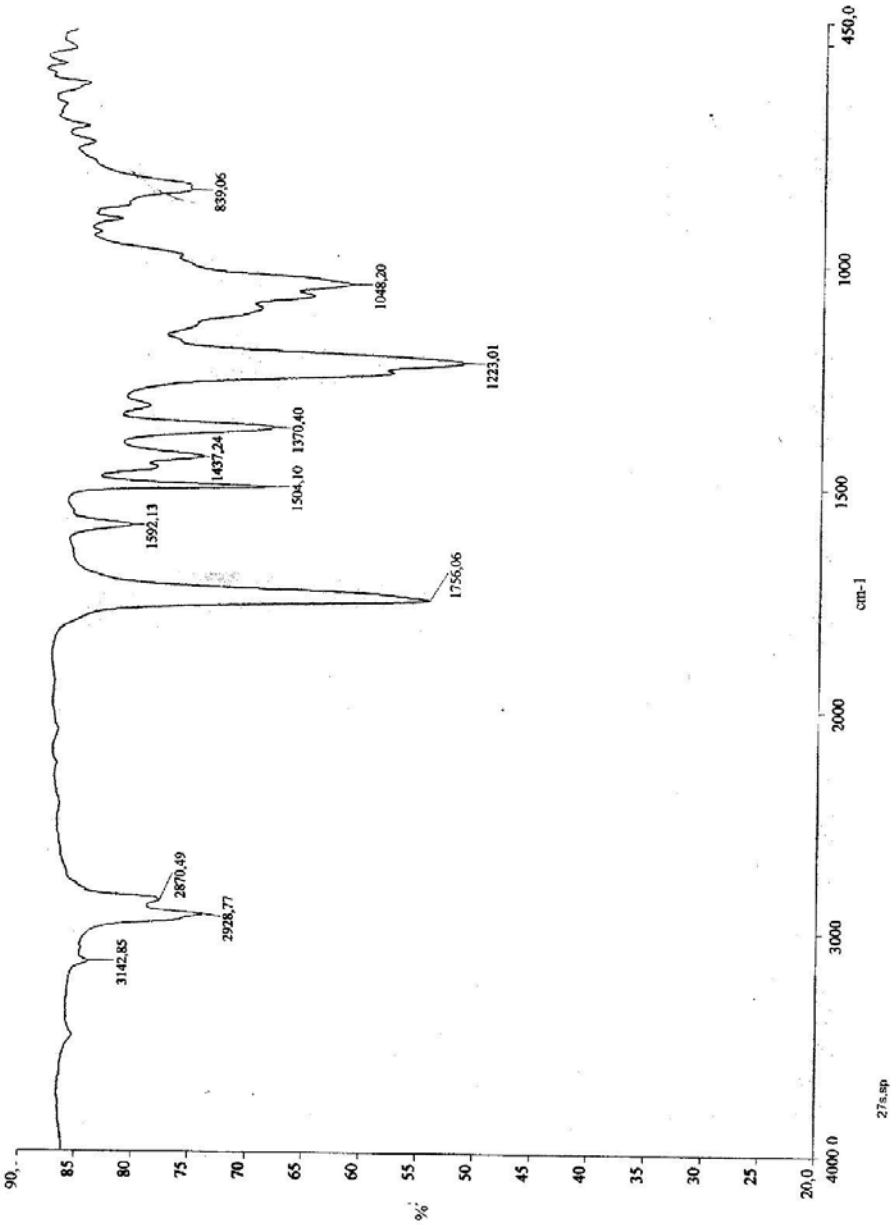
% Intensity
Mass (m/z)
395.2
4280
2981
3554
3083
3937
3210
3895
4375
3657
4400
4156
4473
4571
4652
5678
5451
5803
5229
6754
7449
8294
9709
9958
10768
11326
12096
12607
13448
12933
2955.0
6302.6
9650.2
12997.8
16345.4
19693

SI20

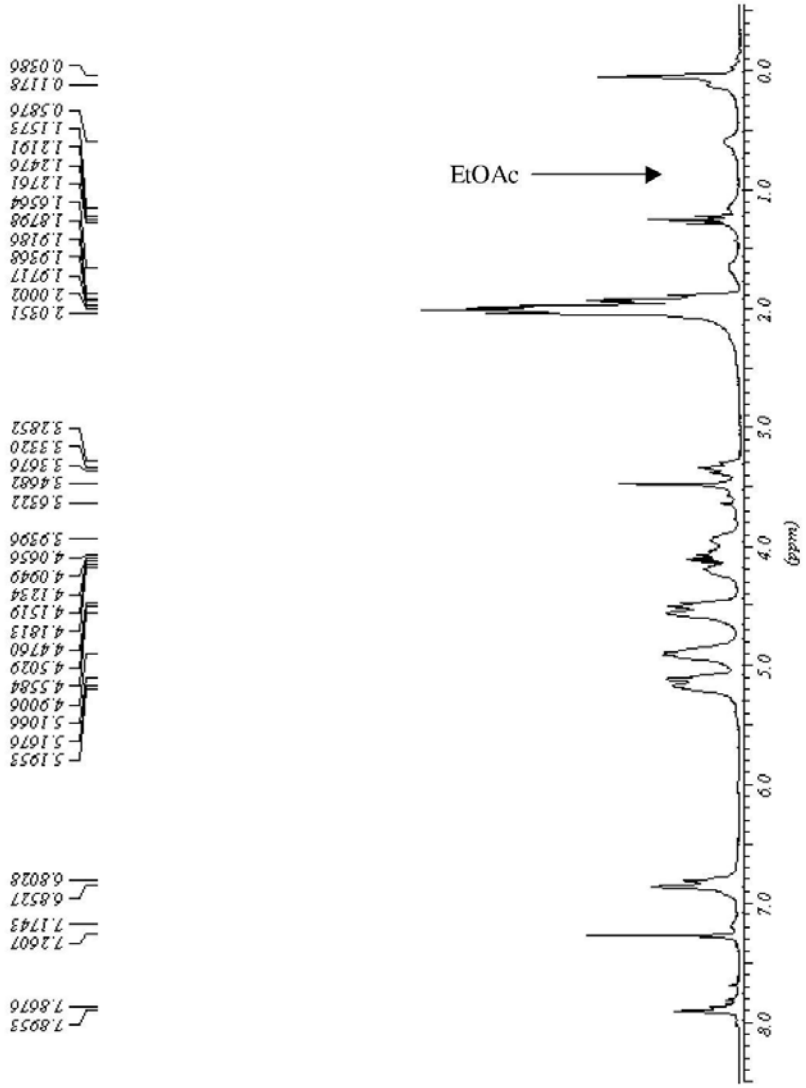
Figure SI17. IR spectrum of compound 2



SI21

8. Data for G_2-81 xylopyranoside 3

Figure SI18. ^{1}H NMR spectrum of compound 3



SI22

Figure SI19. $^{13}C\{^{1}H\}$ NMR spectrum of compound 3

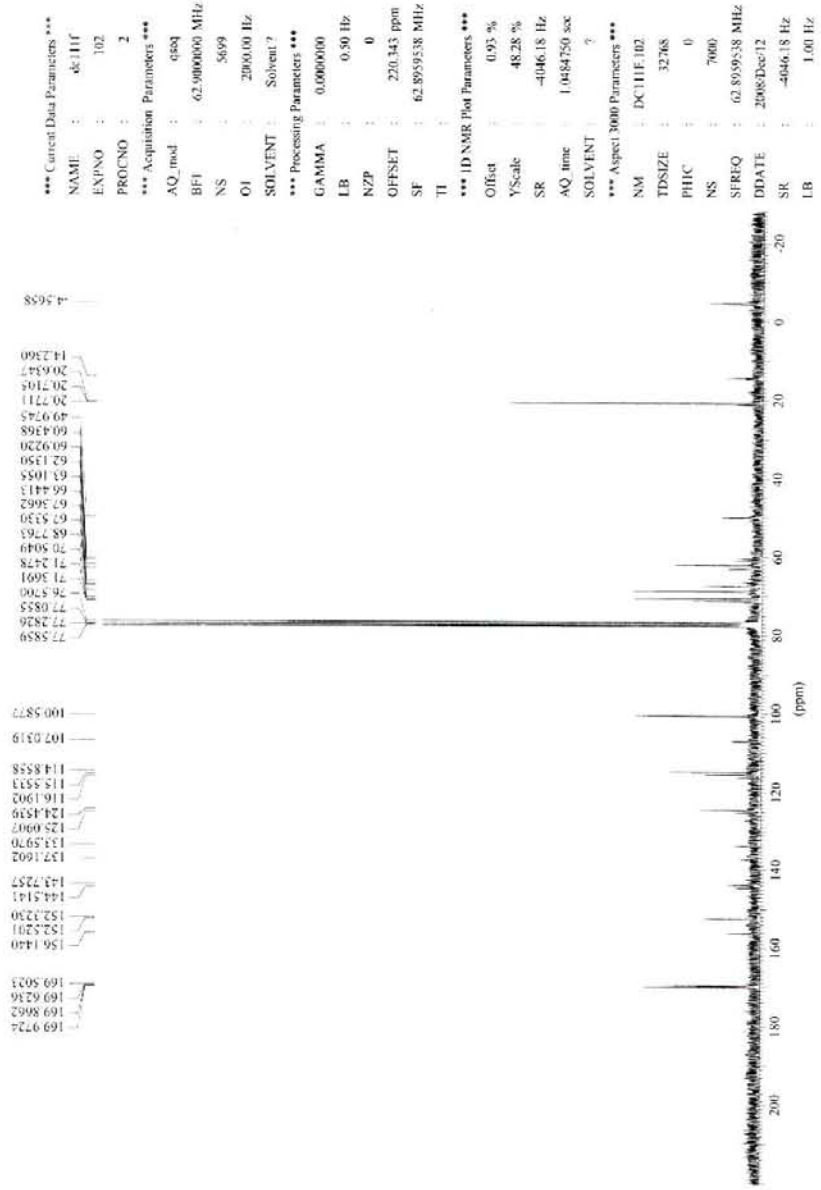
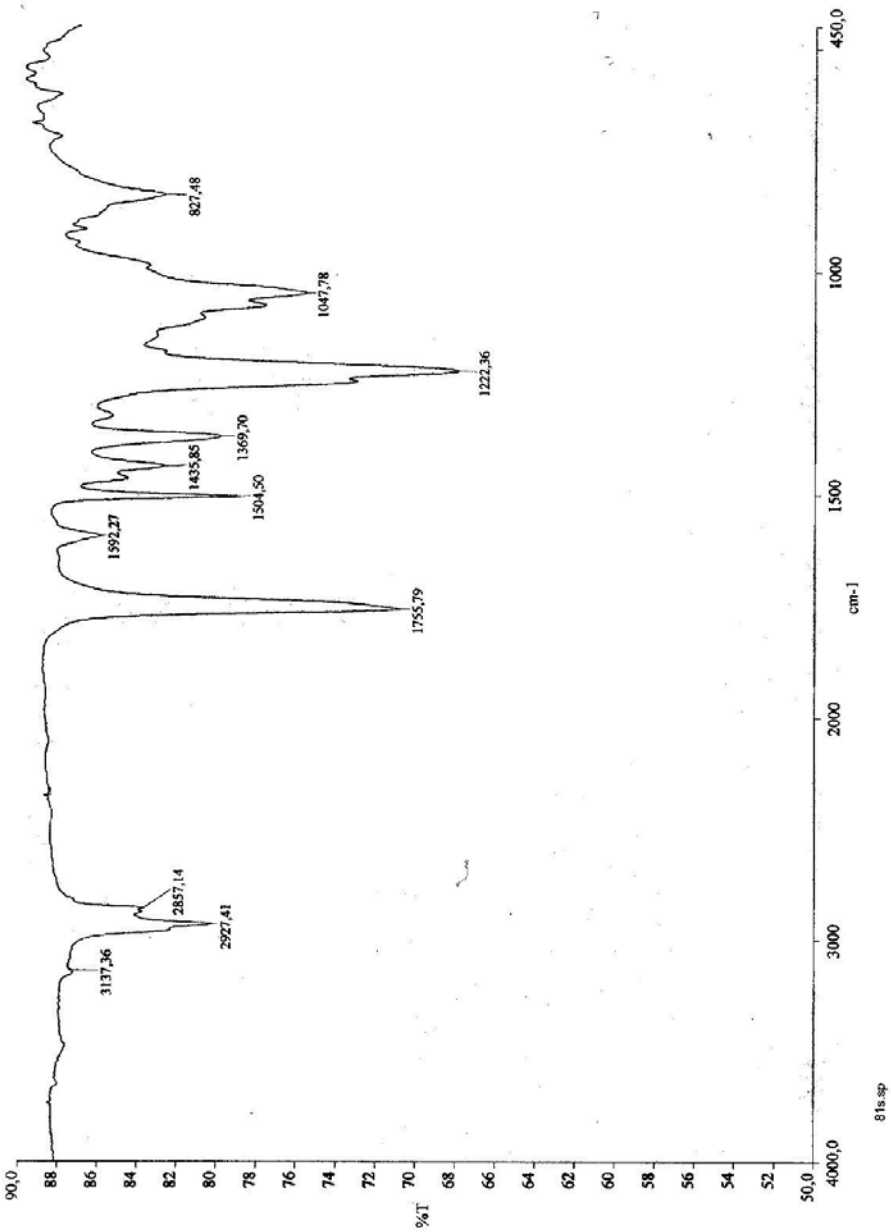


Figure SI20. IR spectrum of compound 3



SI24

9. Data for G_3-243 xylopyranoside 4

Figure SI21. ^{1}H NMR spectrum of compound 4

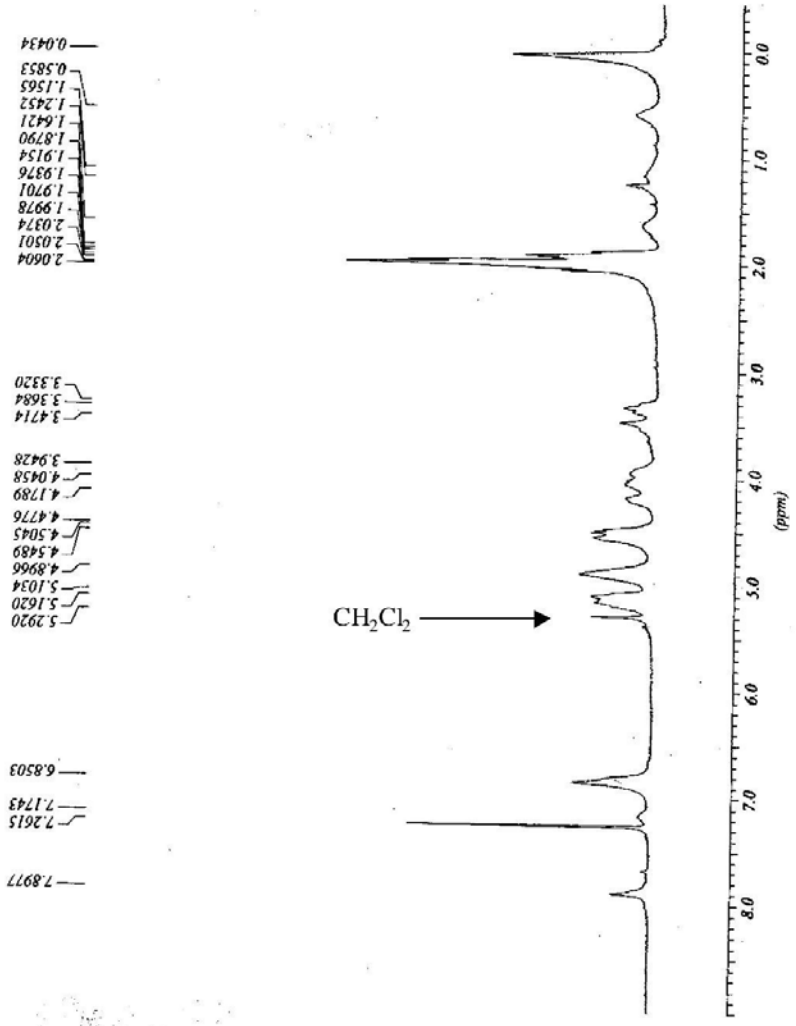


Figure SI22. $^{13}C\{^{1}H\}$ NMR spectrum of compound 4

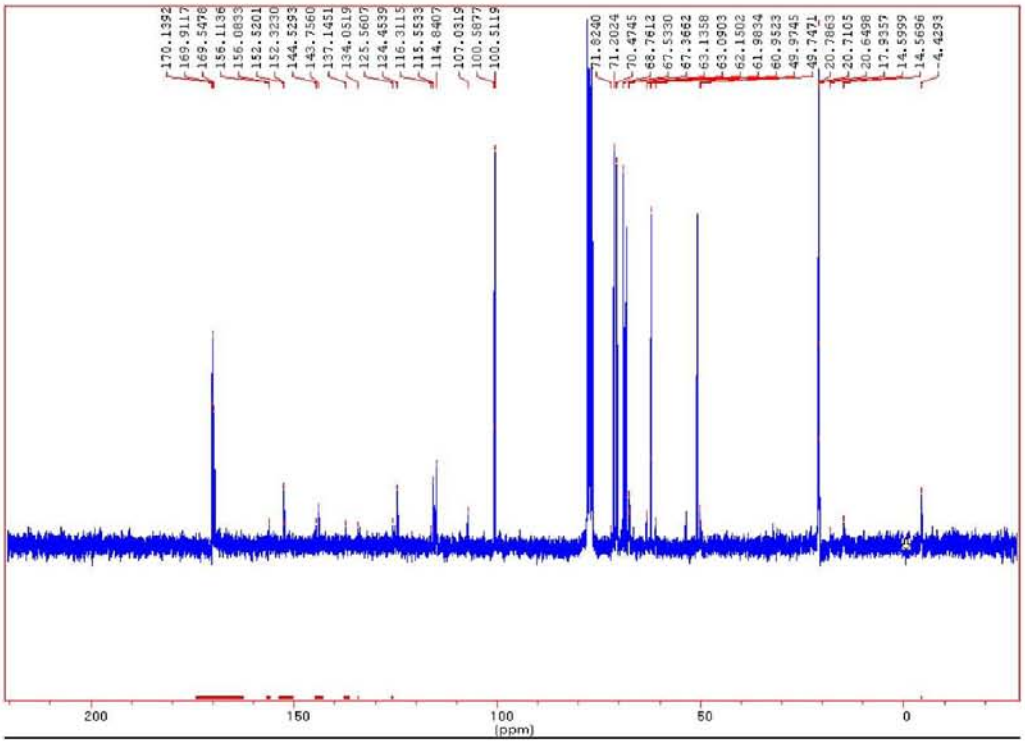
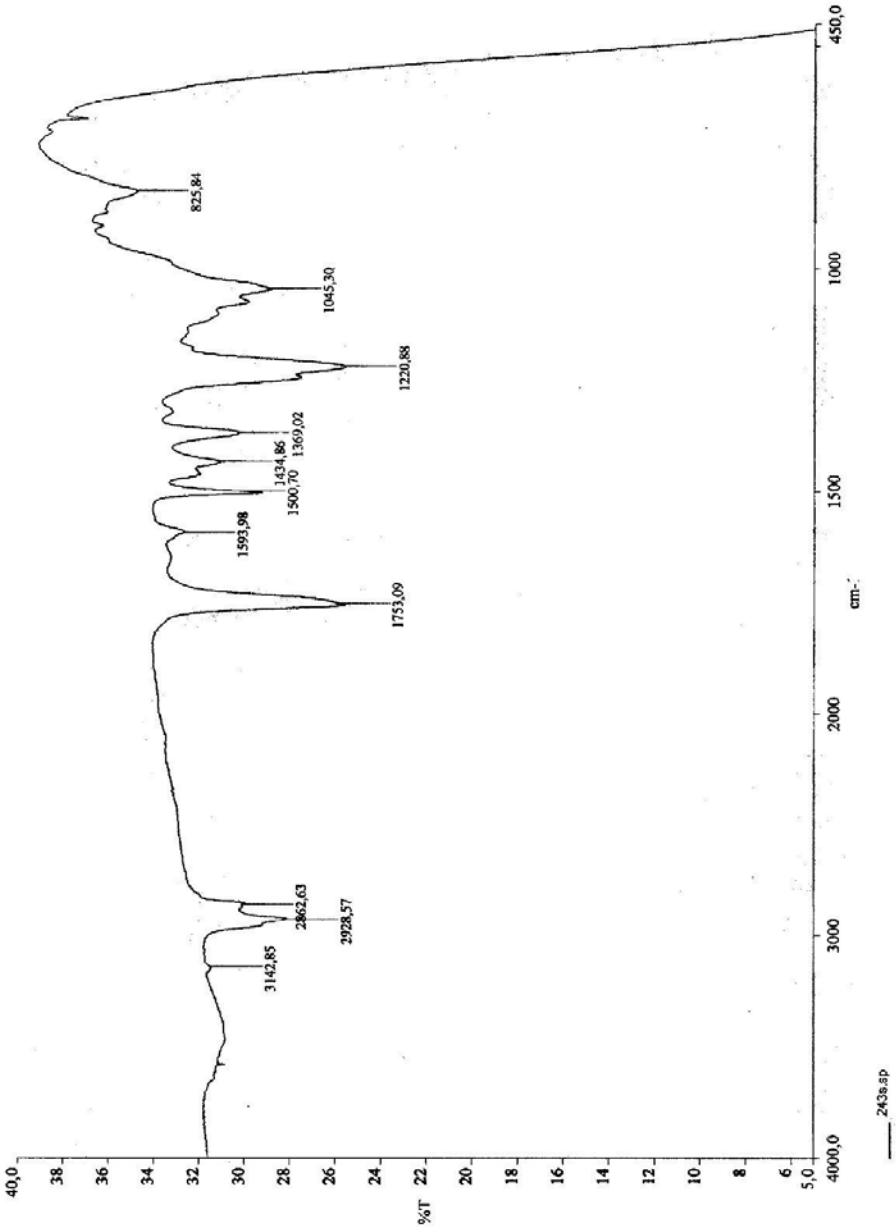


Figure SI23. IR spectrum of compound 4



SI27

Chapitre 3

Chapitre 3 : Synthèse de petits dendrimères comportant des β-cyclodextrines modifiées en périphérie, pour la catalyse et le transport de médicaments

Chapitre 3 : Synthèse de petits dendrimères comportant des β-cyclodextrines modifiées en périphérie, pour la catalyse et le transport de médicaments

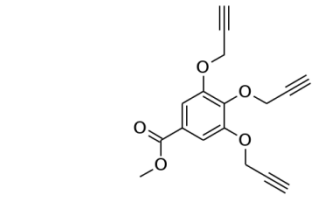
Les cyclodextrines possèdent une solubilité dans l'eau relativement bonne. De plus, cette solubilité peut être améliorée par des modifications chimiques, dont la méthylation aléatoire. Ainsi, la RAME-β-cyclodextrine, avec une moyenne de 12.6 groupements méthyl par cyclodextrine, a une solubilité dans l'eau supérieure à $500 g.L^{-1}$, soit 30 fois plus forte que la β-cyclodextrine native.

Ces molécules, en forme de tronc de cône, comportent une cavité hydrophobe de taille définie permettant de réaliser des complexes d'inclusion. Cependant, les limites des cyclodextrines classiques sont assez vite atteintes. Il est admis que l'utilisation de polycyclodextrines permet d'améliorer l'interaction avec la molécule hôte, l'espaceur entre deux cyclodextrines jouant alors le rôle d'une pseudo-cavité supplémentaire.

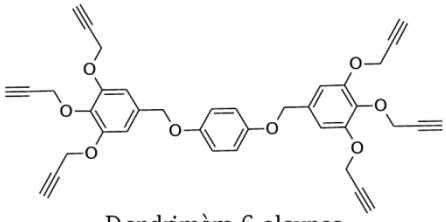
Ces molécules peuvent alors être utilisées pour améliorer la solubilité dans l'eau de molécules hydrophobes comme des médicaments ou des catalyseurs. De plus, dans le cas de la RAME-β-cyclodextrine, sa présence importante à l'interface phase aqueuse/phase organique, améliore le transfert de matière en catalyse biphasique.

Les premiers essais, pour synthétiser de tels objets, ont été réalisés en utilisant de l'azido-β-cyclodextrine hydroxylée et le cœur dendritique comportant 27 branches alcynes. La réaction « click » a conduit à l'obtention d'un produit totalement insoluble que ce soit dans l'eau ou en milieu organique. Notre choix s'est donc tourné vers l'utilisation de l'azido-RAME-β-cyclodextrine afin d'améliorer la solubilité du composé final.

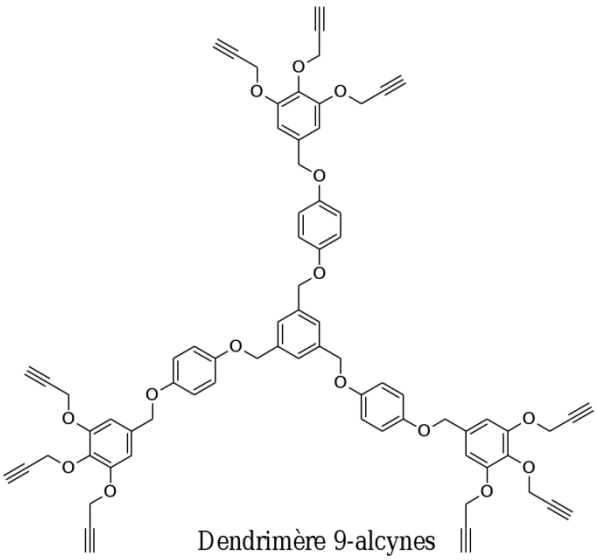
Cette dernière a alors été couplée à différents objets dendritiques comportant des alcynes périphériques (Schéma 2). Cependant, même en diminuant le nombre de branches, tous les produits obtenus se sont trouvés être insolubles.



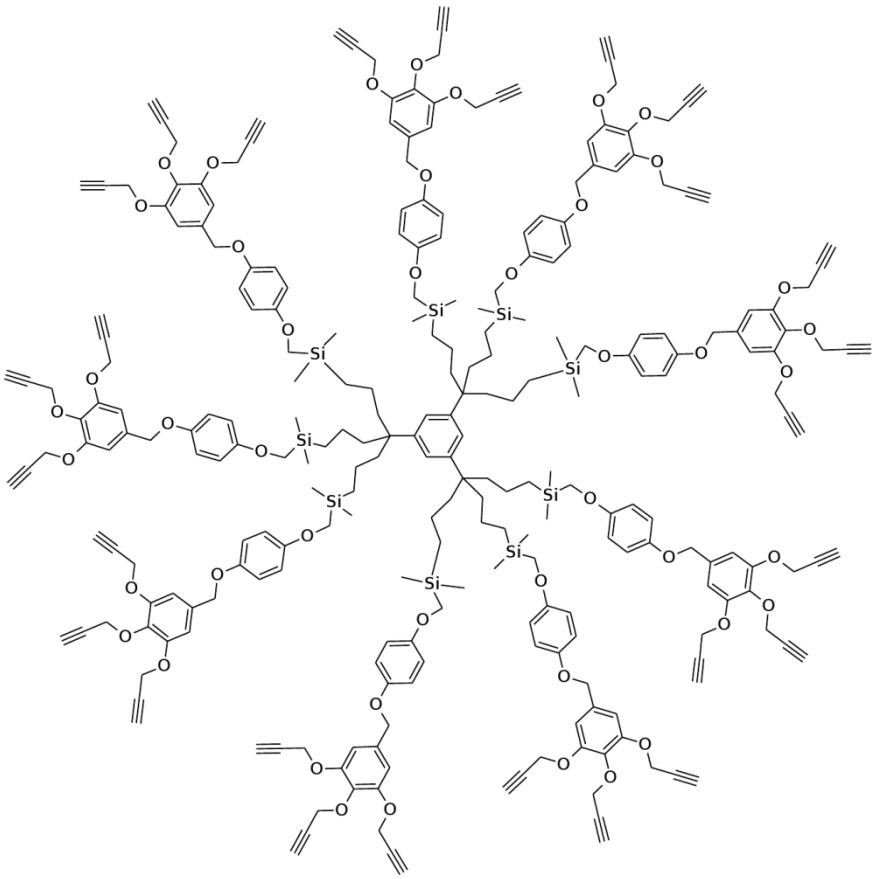
Dendron tris alcyne



Dendrimère 6-alcynes



Dendrimère 9-alcynes



Dendrimère 27-alcynes

Schéma 2. Différents cœurs dendritiques polyalcynes utilisés

Afin de diminuer la congestion stérique en périphérie, nous avons développé des cœurs en étoile comportant 4 et 6 branches terminées par des alcynes (Schéma 3). Les couplages par chimie « click » ont été réalisés. Cependant, la robustesse des cœurs dendritiques n'autorisait pas la fonctionnalisation totale de toutes les branches. Le meilleur résultat obtenu (Schéma 4) n'a pas pu être confirmé par spectrométrie de masse, et la reproductibilité a été médiocre.

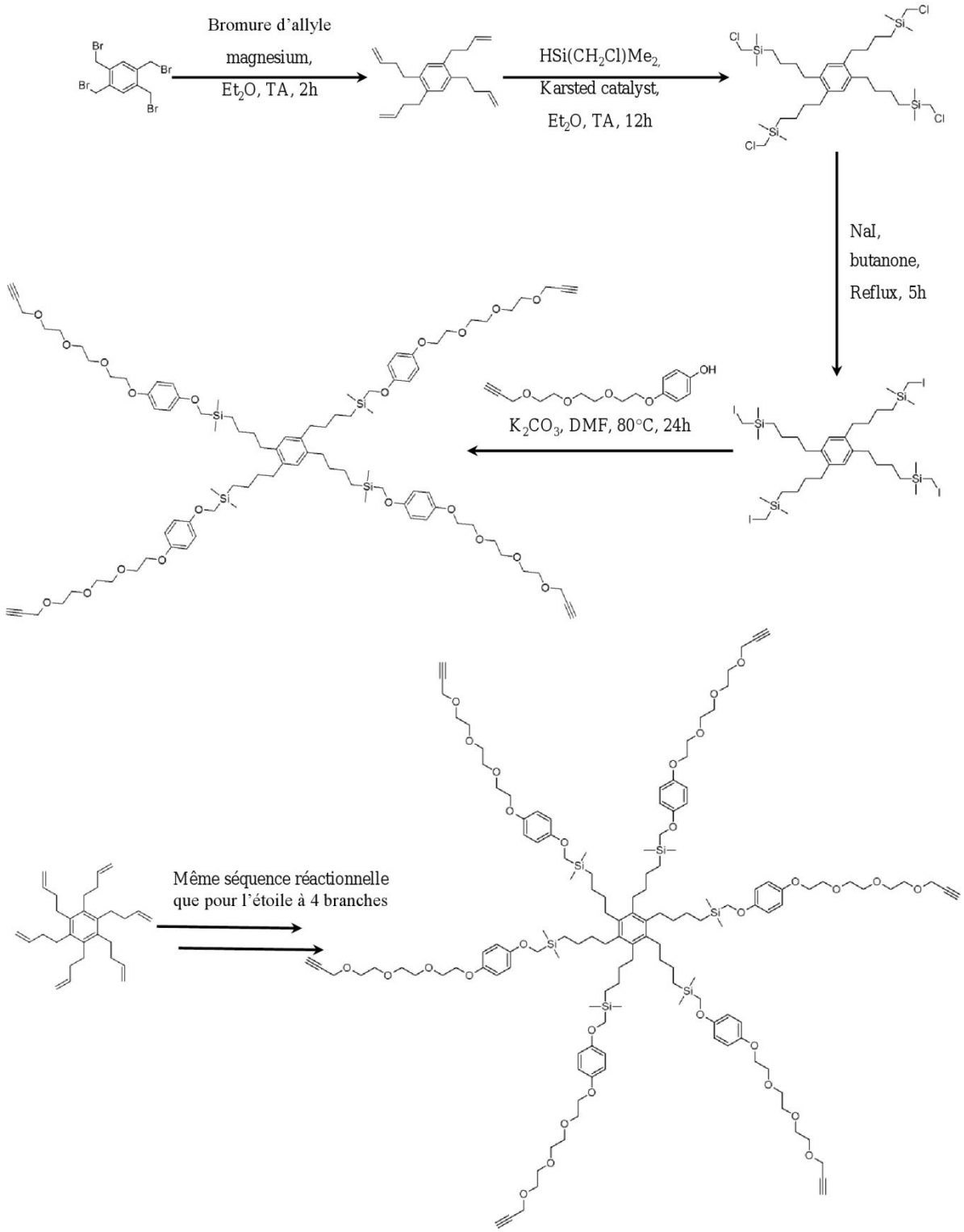


Schéma 3. Synthèse des étoiles comportant 4 et 6 branches alcynes

Nous nous sommes alors tournés vers la synthèse de petits dendrimères plus robustes comportant 4 et 6 branches. Une investigation rapide de la faisabilité de la génération supérieure a également été menée. Une étude de stabilité menée sur ces deux dendrimères polyalcynes a montré qu'ils supportent, sans dégradation visible en RMN ^{1}H, plusieurs jours en solution à une température de 100°C ou encore deux semaines en milieu basique.

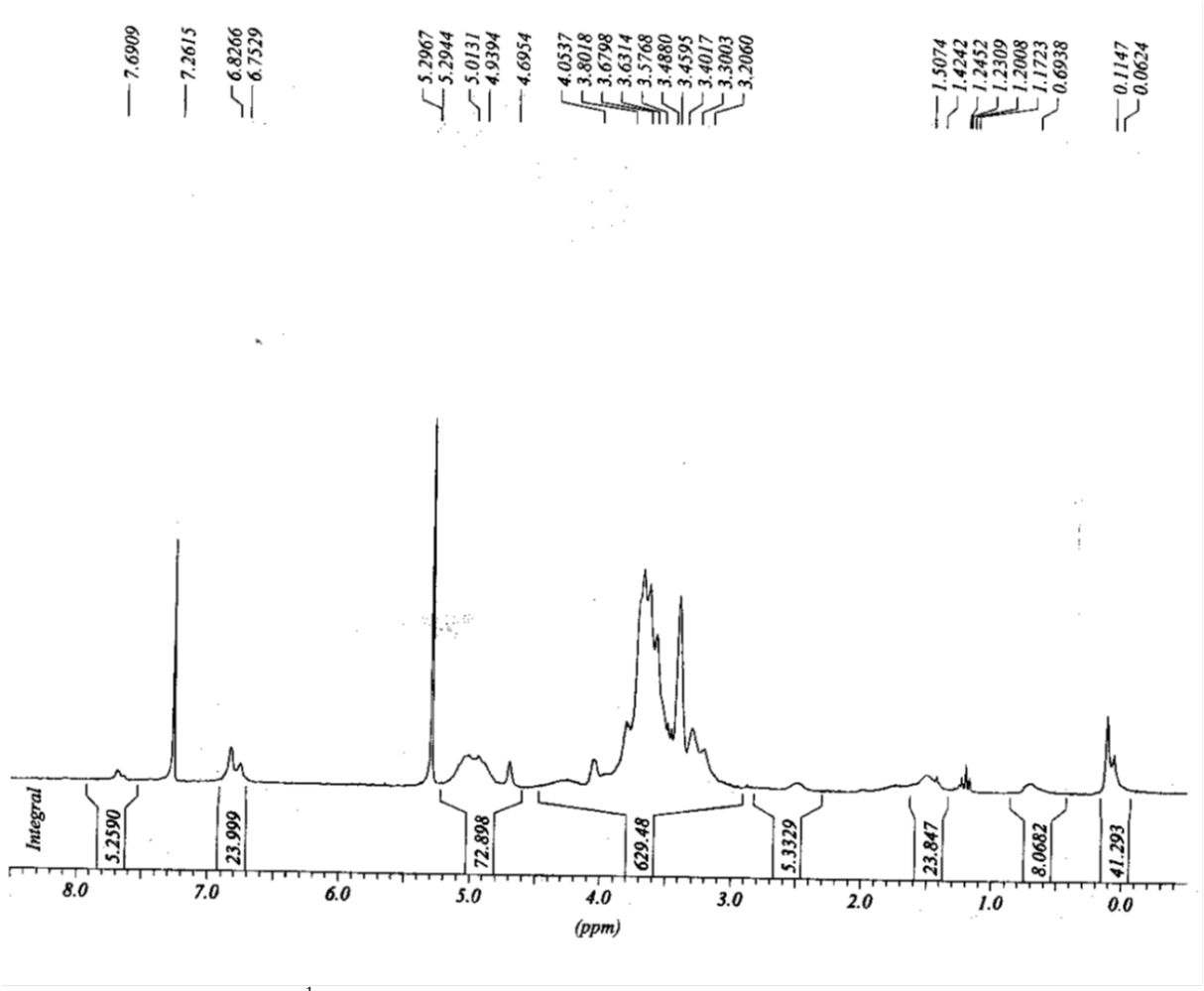


Schéma 4. RMN ^{1}H du meilleur résultat obtenu lors du greffage d'azido-RAME-β-cyclodextrine sur l'étoile à 6 branches

La fonctionnalisation par chimie « click » a donc pu être forcée, sans risques pour la structure dendritique, en augmentant légèrement la température, le temps de réaction et en procédant à l'ajout d'un supplément de catalyseur à mi-réaction.

Le produit obtenu est parfaitement substitué, ce qui a été confirmé par spectrométrie de masse. La solubilité est bonne en milieu organique, ce qui prouve que la stratégie d'allongement des branches a bien été fructueuse. Cependant, la solubilité dans l'eau du produit obtenu est nulle, il faudra donc construire d'autres cœurs sur ce modèle en limitant leur hydrophobicité.

RAME-β-cyclodextrin containing dendrimers with 4 and 6 branches

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First published on the web Xth XXXXXXXXX 200X
DOI: 10.1039/b000000x

This article reports the whole synthesis of new easily accessible dendritic cores. These dendrimers are robust and allow their use in many fields of chemistry due to the rich chemistry of terminal alkynes. Their functionalization with azido-RAME-β-cyclodextrins by "click" chemistry is also reported. This novel series is characterized by standard NMR technics including 2D-NMR, mass spectrometry, DOSY NMR, and GPC/SEC.

Introduction

Cyclodextrins are well known for their capacity to form inclusion complexes with a wide variety of molecules.[1] These properties can be improved by using polytopic cyclodextrin containing molecules.[2] The strengh of the interaction is very structure depending, but in general, the linker between two cyclodextrins acts like an additionnal pseudo-cavity. This cooperativity could have beneficial effects compared to many single cyclodextrins.

The use of randomly methylated β-cyclodextrins is very interesting, particularly because of their enhanced water solubility compared to native cyclodextrin.[3] The synthesis of polytopic RAME-β-cyclodextrin[4] is more difficult however than hydroxylated ones.[4,5]

We report here the synthesis of a new family of polytopic RAME-β-cyclodextrin by click chemistry, starting from a new family of poly alkynyl dendritic cores.

Results and discussion

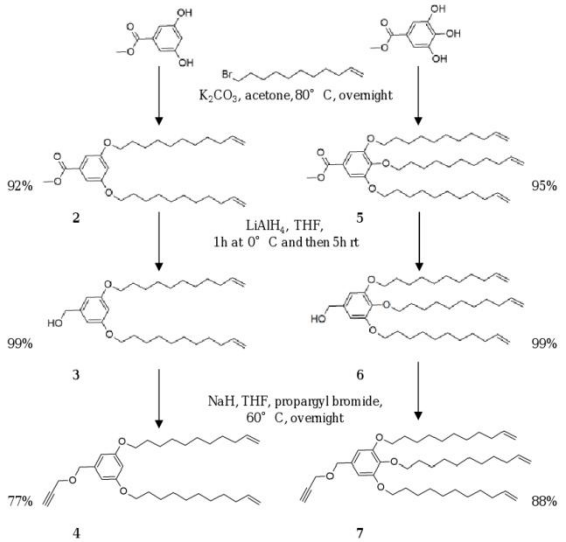
Synthesis of the different dendrons

The bis (**4**) and the tris alkenyl (**7**) dendrons were prepared in three steps starting from commercially available methyl 3,5-dihydroxybenzoate and methyl 3,4,5-trihydroxybenzoate respectively (Scheme 1).

The phenol groups were functionnalized by classical Williamson reaction, using the commercial 11-bromo-1-undecene and potassium carbonate in acetone. Excess of bromo derivative is easily removed by flash column chromatography on silica gel yielding the ester dendrons (**2**) and (**5**) (Scheme 1).

The ester at the focal point of these dendrons was then reduced using lithium aluminium hydride in anhydrous tetrahydrofuran (THF). The alcohol obtained (**3**) and (**6**) (Scheme 1) could be used for the next step without further purification.

A propargyl group was then introduced at the focal point using sodium hydride and a propargyl bromide solution in anhydrous THF. The alkynyl dendrons (**4**) and (**7**) (Scheme 1) were obtained after a flash column chromatography on silica gel in a good overall yield.



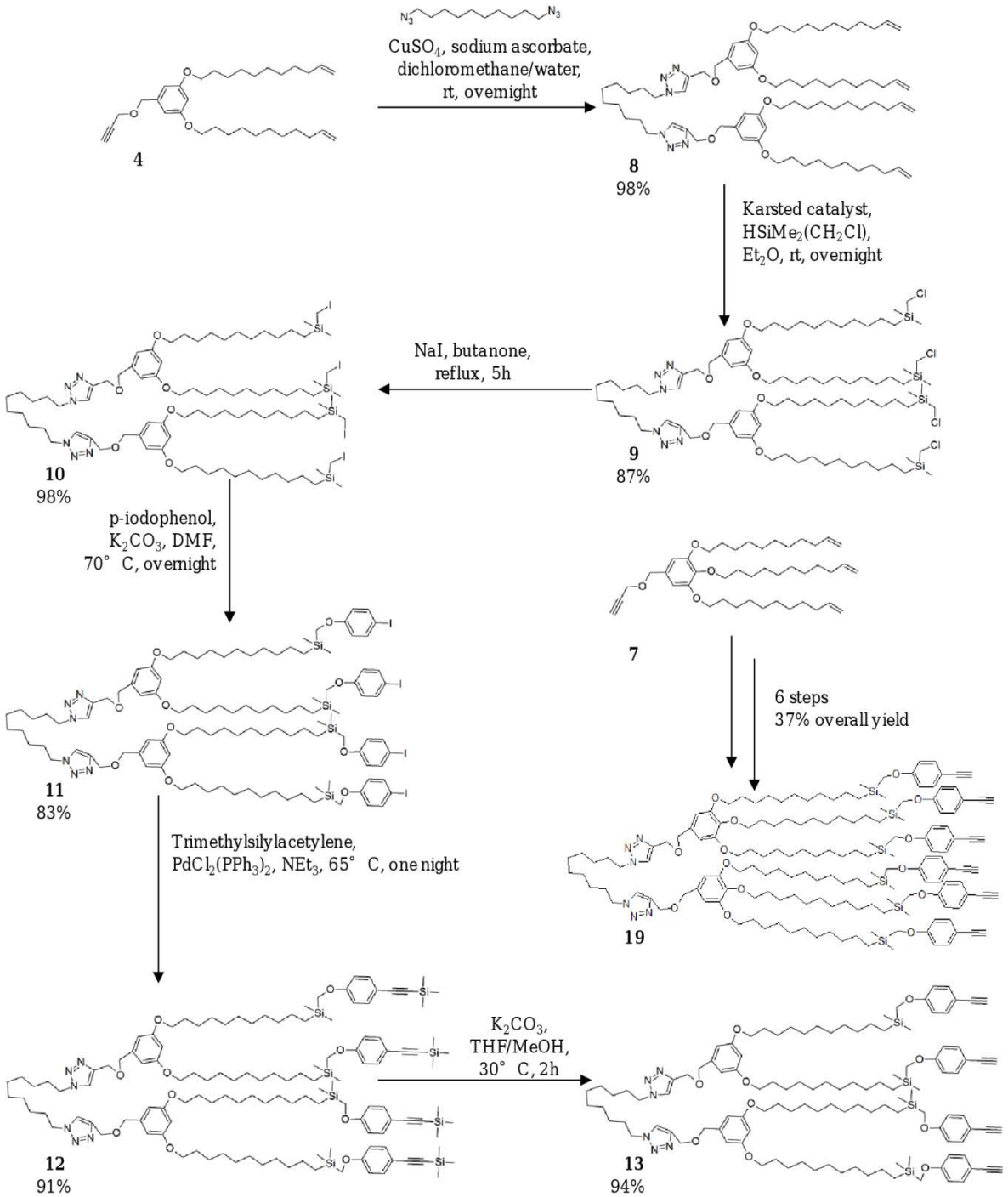
Scheme 1. Synthesis of the different dendrons

All these dendrons were characterized by ^{1}H NMR, ^{13}C NMR, IR spectroscopy, and mass spectrometry. 2D-NMR technics have been used if needed.

Synthesis of the polyalkynyl dendritic cores

Commercially available 1,10-dibromodecane was first stirred with sodium azid in anhydrous dimethylformamide (DMF) to yield the 1,10-diazidodecane (**1**).

The tetra (**8**) and hexa alkenyl (**14**) first generation dendrimers were synthesized by coupling compound (**1**) with respectively dendron (**4**) and dendron (**7**) by a classical Huisgen 1,3-dipolar cycloaddition reaction[6] (Scheme 2). In the case of dendrimers, the Cu^{I} catalyst is used in stoechiometric amount and the reaction is carried out under a nitrogen atmosphere to enhance the yield of the reaction.[7]



Scheme 2. Synthesis of the poly alkynyl dendritic cores

Hydrosilylation of the terminal olefinic bonds of (**8**) and (**14**) was carried out using $HSiMe_2(CH_2Cl)$ and the Karsted catalyst. This reaction pioneered in dendrimer synthesis by van Leeuwen et al.[8] regioselctively gives the chloromethyl intermediates (**9**) and (**15**) (Scheme 2).

A quantitative halogen exchange is then carried out using sodium iodide in butanone. After a flash column chromatography, iodomethyl intermediates (**10**) and (**16**) are obtained (Scheme 2). The NMR investigations for these molecules was showing artefacts in 2D-NMR (both in HMQC and HMBC) at different chemical shift for the $SiCH_2I$ signal. A 135-DEPT NMR analysis showed that these signals were wrong. The solution of this problem came from the enlargement of the spectral window. In fact, the ^{13}C NMR signal resulting from the $SiCH_2I$ appears to be very low (around -13 ppm) and was outside the classical spectral windows used for 2D-NMR. HSQC and HMBC were performed with enlarged spectral windows and we notice the disappearance of the artefact signal.

A Williamson reaction was then carried out in conditions inspired from what was developped in the case of dendritic syntheses.[9] Coupling of p-iodophenol on the iodomethyl dendrimers (**10**) and (**16**) yields the tetra (**11**) and the hexa iodophenyl (**17**) dendrimers containing respectively 4 and 6 branches (Scheme 2).

Alkynyl functions were then introduced by a Sonogashira reaction using trimethylsilylacetylene followed by a deprotection step. This reaction was first performed at 100°C using toluene as solvent and triethylamine in stoechiometric amount for two days. The use of triethylamine alone as solvent authorized now to obtain better yields (up to 91% yield) at lower temperature (65°C) in reduced time (one night). Trimethylsilyl dendrimers (**12**) and (**18**) were then obtained after a flash column chromatography. Removing of the trimethylsilyl group was carried out in a THF/MeOH 1/1 mixture in presence of a stoechiometric amount of potassium carbonate for 2h. After a flash column chromatography and a precipitation step, the poly alkynyl dendrimers (**13**) and (**19**) were obtained (Scheme 2).

All these dendrimers were characterized by ^{1}H NMR, ^{13}C NMR, ^{29}Si NMR (except for those who do not have any silicon atom), 2D-NMR, and different technics of mass spectrometry depending on the molecular weight. DOSY NMR were performed on the two polyalkynyl dendrimers, but the difference of size for the two compounds shows the limits of this technic.

The robustness of these dendritic cores was also tested. No significant modification in ^{1}H NMR spectra were visible after several days in solution at 100°C or after two weeks in solution stirred together with potassium carbonate.

Functionnalization of the dendritic cores by click coupling

Click coupling using azido-RAME-β-cyclodextrin were performed under nitrogen atmosphere and with a stoechiometric amount of copper. Cyclodextrin was introduced in little excess per alkynyl branch. The reaction was carried out in a biphasic dichloromethane/water mixture for two days. Another amount of catalyst was added after 14h of reaction.

The purification was first performed by dialysis versus water. This method was abandonned because the product was precipitating in water while the free cyclodextrin and the copper were removed.

The purification was now based on the difference of water solubility of the excess RAME-β-cyclodextrin and the polytopic compounds. Removal of not fully substituted dendrimers was performed by precipitation in excess methanol yielding the tetra RAME-β-cyclodextrin compound (**20**) and the hexa RAME-β-cyclodextrin compound (**21**).

Conclusion

We have reported the synthesis of a new family of robust polyalkynyl dendrimers well characterized for each step, including their functionnalization by click chemistry.

Well defined tetra and hexa RAME-β-cyclodextrins were obtained even if the solubility in water of these compounds is very far from what was expected.

This strategy of synthesis must be used with less hydrophobic chains to developp better compounds.

Notes and references

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†Electronic Supplementary Information (ESI) available: [^{1}H NMR, ^{13}C NMR, JMOD NMR, 2D NMR ^{29}Si NMR, IR spectroscopy and mass spectrometry were given]. See DOI: 10.1039/b000000x/

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RAME-β-cyclodextrin containing dendrimers with 4 and 6 branches

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General

Whenever mentioned, reagent grade tetrahydrofuran (THF), and diethyl ether were predried over Na foil and distillated from sodium-benzophenone anion under nitrogen atmosphere immediately prior to use. Triethylamine (TEA) was predried over CaH_2 and distillated under nitrogen atmosphere immediately prior to use. All other chemicals were used as received. All manipulations were carried out using Schlenk techniques or a nitrogen-filled Vacuum Atmosphere drylab (glove-box).

NMR Spectroscopy:

^{1}H NMR spectra were recorded at 25°C with a Bruker DPX 400 (400 MHz), a Bruker Avance 300 (300 MHz) or with a Bruker DPX 200 (200 MHz) spectrometer.

^{13}C NMR, JMOD and 135DEPT spectra were obtained at 25°C in the pulse FT mode at 75.0 MHz with a Bruker Avance 300 spectrometer or at 50.3 MHz with a Bruker DPX 200 spectrometer.

^{29}Si NMR spectra were obtained at 25°C at 59.6 MHz with a Bruker Avance 300 spectrometer.

COSY, HMQC and HMBC spectra were recorded at 25°C with a Bruker Avance 300 spectrometer or with a Bruker DPX 400 spectrometer.

DOSY NMR spectra were recorded at 25°C with a Bruker DPX 400 spectrometer.

All chemical shifts are reported in parts per million (δ, ppm) with reference to $SiMe_4$ (TMS).

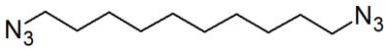
Mass spectrometry:

The mass spectra reported in this Supporting Information were recorded with a Waters AutoSpec with EBEqQ geometry (Milford, MA) mass spectrometer for small molecules. MALDI mass spectra were recorded with a PerSeptive Biosystems Voyager Elite (Framingham, MA) time-of-flight mass spectrometer for the other molecules. This instrument is equipped with a nitrogen laser (337 nm), a delayed extraction, and a reflector. It was operated at an accelerating potential of 20 kV in both linear and reflection modes. The mass spectra shown represent an average over 256 consecutive laser shots (3 Hz repetition rate). Peptides were used to calibrate the mass scale using the two points calibration software 3.07.1 from PerSeptive Biosystems. Mentioned m/z values correspond to monoisotopeak masses. The dendrimer solutions (10-3 M) were prepared in chloroform. Matrix compounds were from Sigma (France) and used without further purification. The matrices, 2-5-dihydroxybenzoic acid (2.5-DHB), 1,8-dihydroxy-9[10H]-anthracenone (dithranol), 6-azathiothymine, 2,4,6-trihydroxyacetophenon, 7-hydroxycoumarin, or 2-anthramine, were also dissolved in chloroform (10 g.L-1). One microliter of dendrimer solution was mixed with 50 microliter of matrix solution. One microliter of the final solution was dissolved onto the sample stage and allowed to dry in air.

IR spectroscopy:

IR spectra were recorded at 25°C with a Perkin Elmer spectrum 100 FTIR spectrometer on KBr windows.

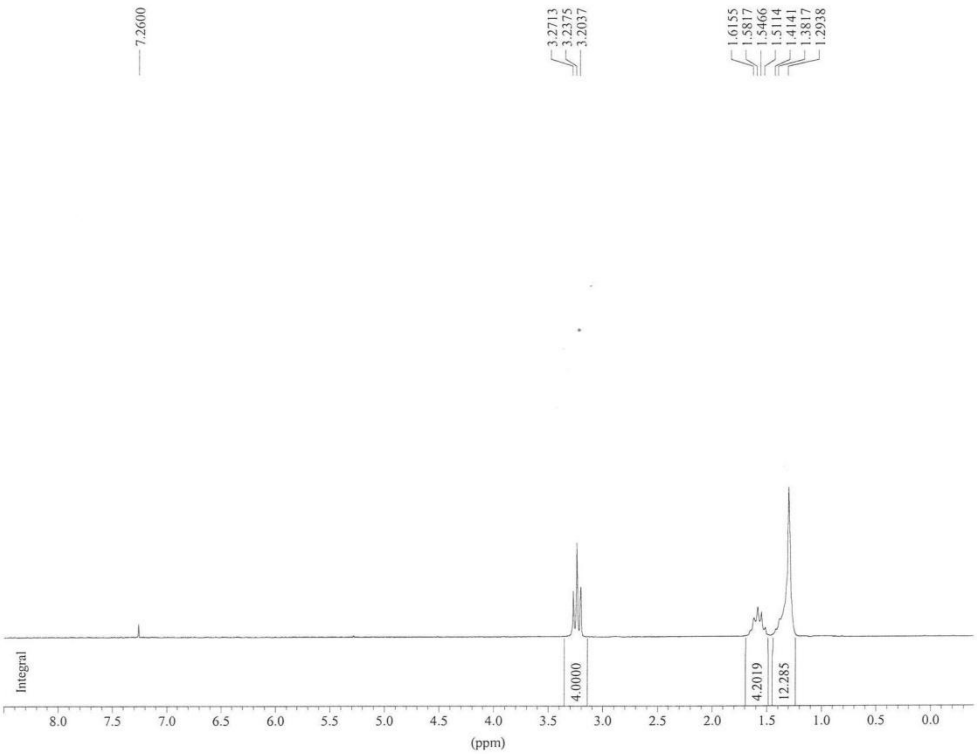
Synthesis of the 1,10-diazidodecane 1



To a solution of 1,10-dibromodecane (1g, 3.33mmol, 1eq) in 10mL of dry DMF was added sodium azide (0.86g, 13.3mmol, 4eq). The medium was stirred at 65°C for one night. The medium was cooled to room temperature. Diethylether and water were then added. The organic phase was washed three times with water, dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*.
1,10-diazidodecane was obtained as a colorless oil quantitatively.

^{1}H NMR ($CDCl_3$ 200MHz): 3.23 ppm (t, -C*H*$_2$-N_3, ^{3}J = 7Hz, 4H); 1.58 ppm (m, -C*H*$_2$-CH_2-N_3, 4H); 1.29 ppm (m, -(C*H*$_2$)$_6$-CH_2-CH_2-N_3, 12H)
JMOD NMR (CDCl3 50,33MHz): 51.36 ppm (-*C*H_2-N_3); 29.24, 28.98, 28.73 and 26.58 ppm (-(*C*H_2)$_8$-CH_2-N_3)
IR spectroscopy (cm-1): 3332.3 ; 2934.8 ; 2861.5 ; 2093.4 ; 1464.3 ; 1263.7
HRMS: calculated for $[M+Ag]^+$, m/z = 331.0794 found m/z = 331.0788

^{1}H NMR spectrum

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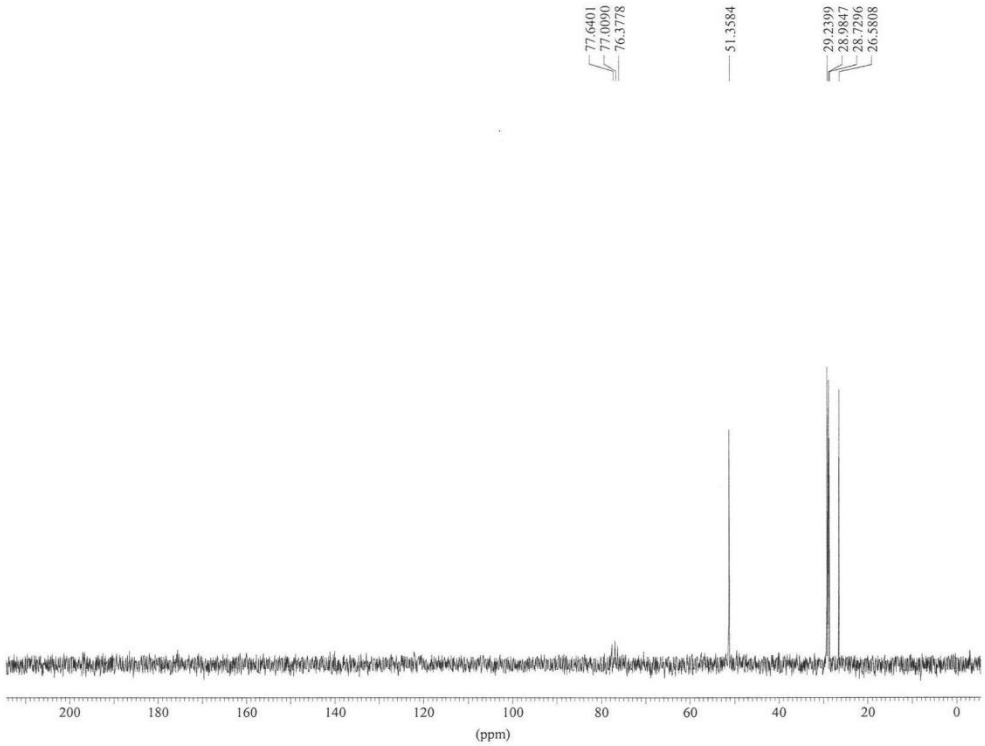
JMOD NMR spectrum

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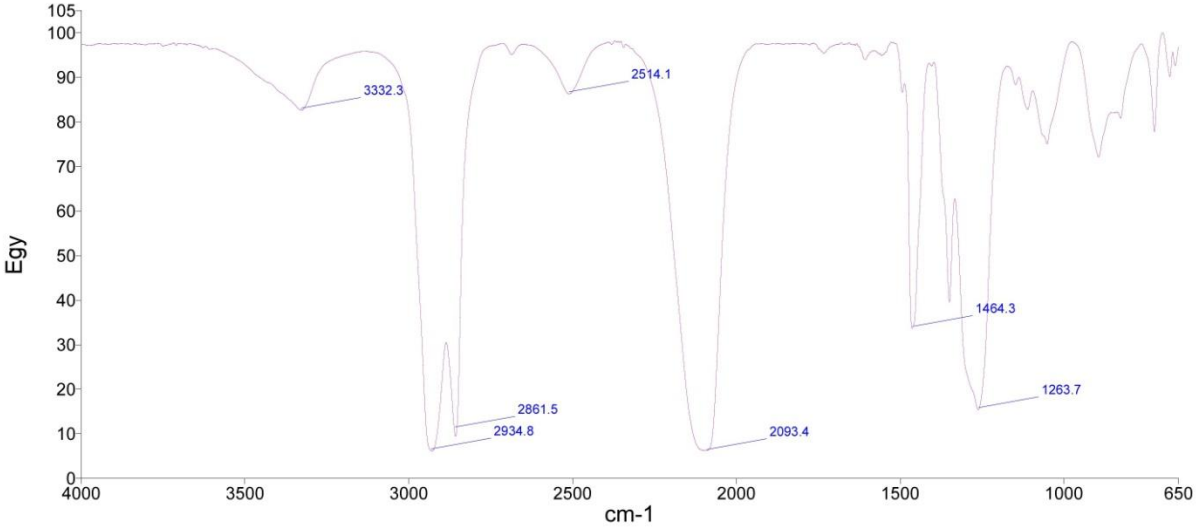
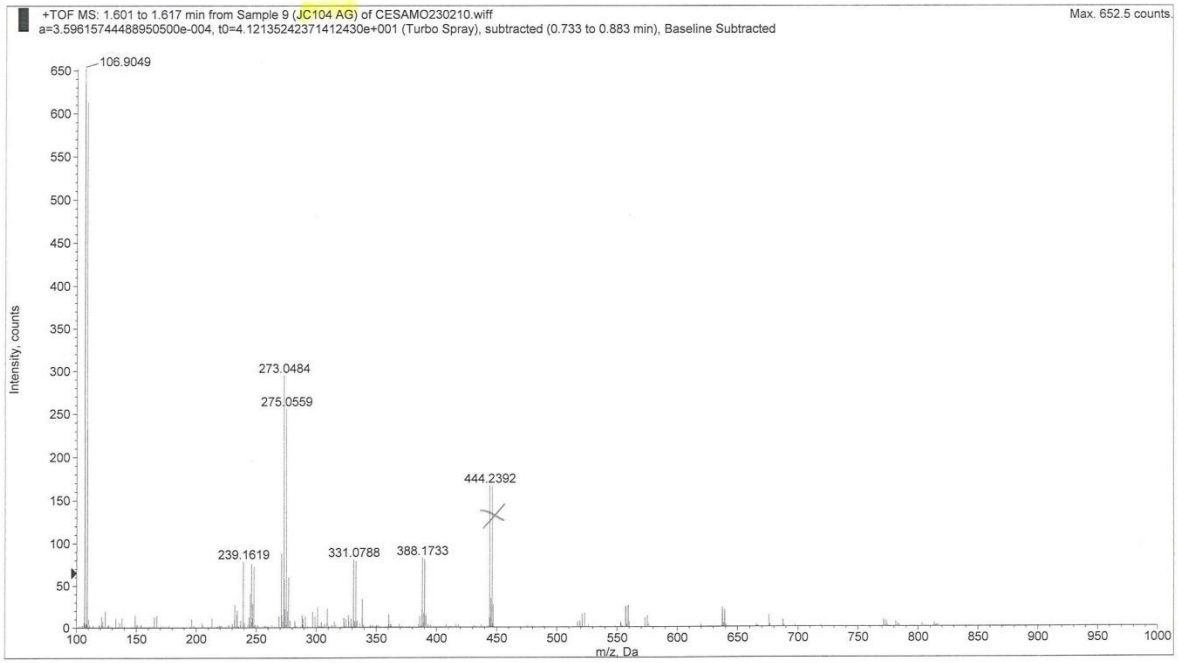
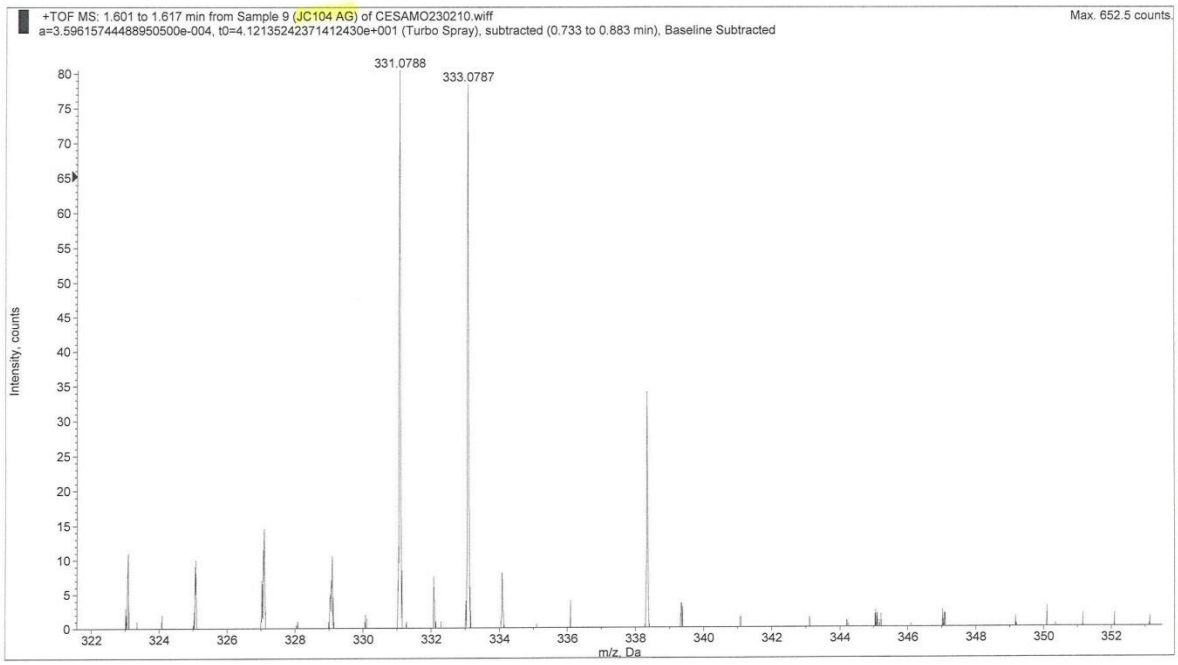


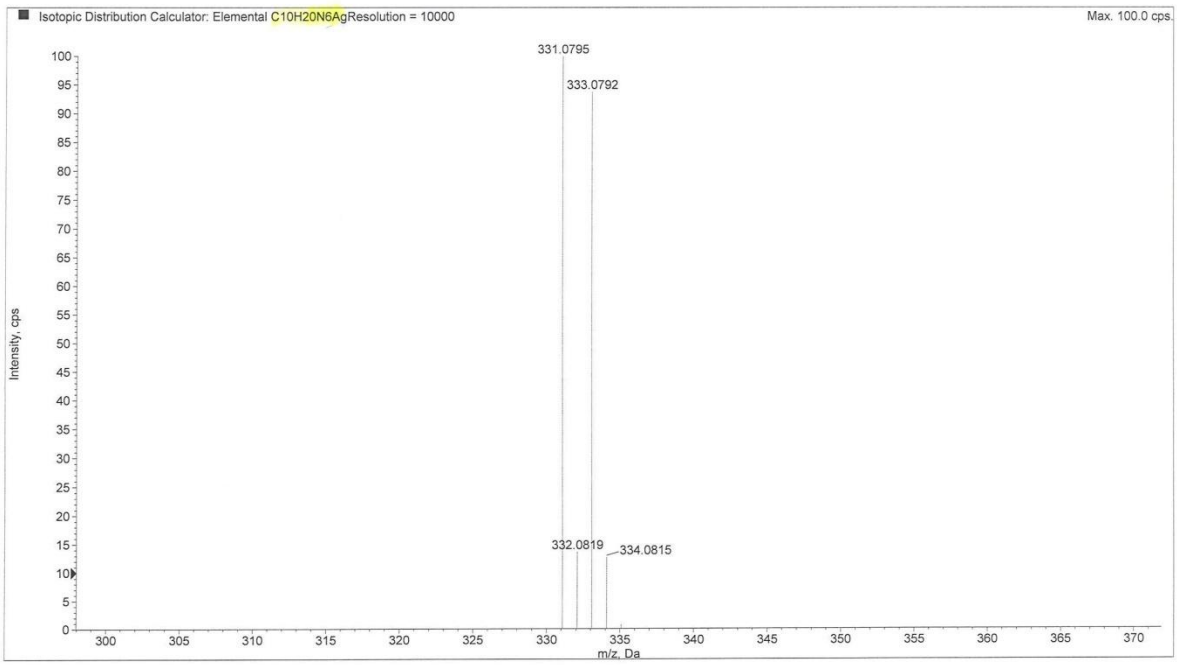
Mass spectrum (1/4)



Mass spectrum (2/4)



Mass spectrum (3/4 Simulation)



Elemental composition calculator

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Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAMO230210.wiff

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4	Cl	0	0
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6	Fe	0	0
7	H	0	1000
8	I	0	0
9	K	0	0
10	N	0	6

	Elements	Min Number	Max Number
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12	O	0	0
13	P	0	0
14	S	0	0
15	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
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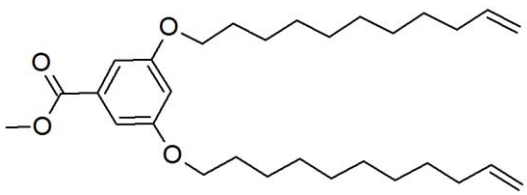
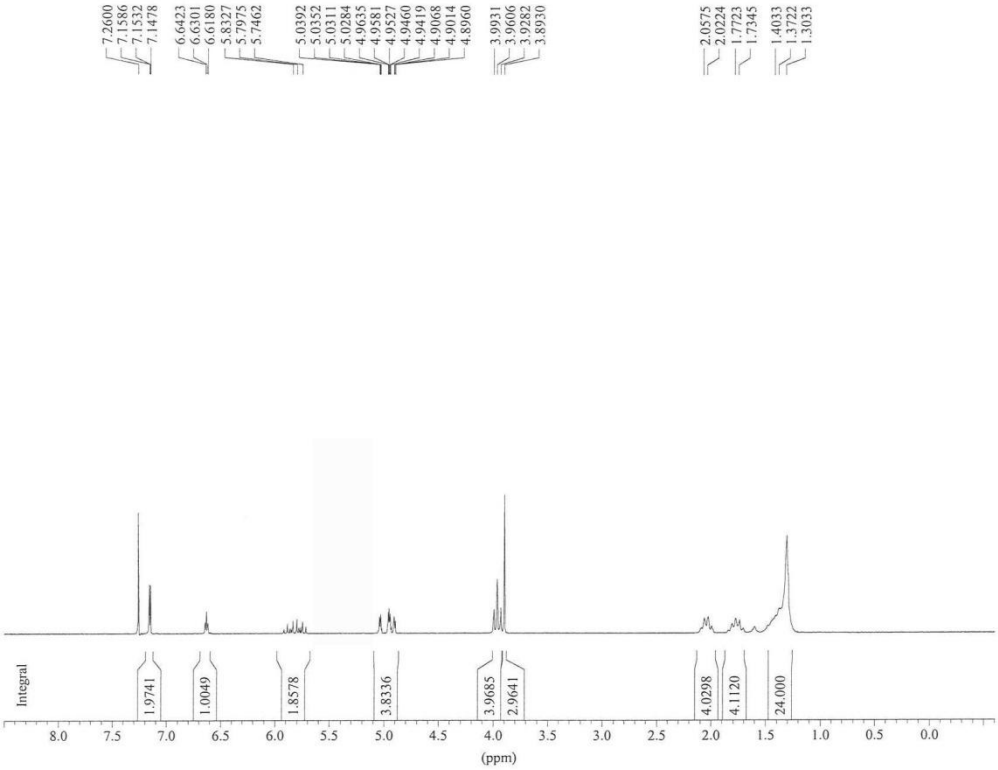
Synthesis of the methyl 3,5-bis(10-undecen-1-yloxy)benzoate 2



To a solution of methyl 3,5-dihydroxybenzoate (3g, 17.84mmol, 1eq) and 11-bromo-1-undecene (12.5g, 53.5mmol, 3eq) in 200mL of acetone was added K_2CO_3 (14.8 g, 107 mmol, 6eq). The medium was stirred under reflux for one night. Acetone was removed *in vacuo*. Dichloromethane was then added and the medium was filtered. The crude product was purified by flash column chromatography using pentane and then dichloromethane as eluent.
The desired product was obtained as a colorless oil (7.75 g, 16.40mmol) in 92% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.15 ppm (d, H_{Ar}, ^{4}J = 1.1Hz, 2H); 6.63 ppm (t, H_{Ar}, ^{4}J = 2.4Hz, 1H); 5.79 ppm (m, -C*H*=CH_2, 2H); 5.03 to 4.89 ppm (m, -CH=CH_2, 4H); 3.96 ppm (t, -O-CH_2-, ^{3}J = 6.5Hz, 4H); 3.89 ppm (s, -CH_3, 3H); 2.02 ppm (m, -CH_2-CH=CH_2, 4H); 1.73 ppm (m, -O-CH_2-CH_2-, 4H); 1.50 to 1.25 ppm (m, -CH_2-, 24H)
JMOD NMR ($CDCl_3$ 50.3MHz): 166.83 ppm (*C*OOMe); 160.02 ppm (C_{ar}-O); 138.93 ppm (-*C*H=CH_2); 131.63 ppm (C_{ar}-COOMe); 114.06 ppm (-CH=*C*H_2); 107.41 and 106.31 ppm (C_{ar}-H); 68.06 ppm (-O-*C*H_2-); 51.96 ppm (-CH_3); 33.74, 29.45, 29.36, 29.29, 29.09, 29.05, 28.84 and 25.94 ppm (-*C*H_2-)
IR spectroscopy (cm-1): 2934.8 (Car-H) ; 2861.5 (C-H) ; 1730.6 (C=O)
HRMS: calculated for $[M+Ag]^+$, m/z = 579.2598 found m/z = 579.2600

^{1}H NMR spectrum

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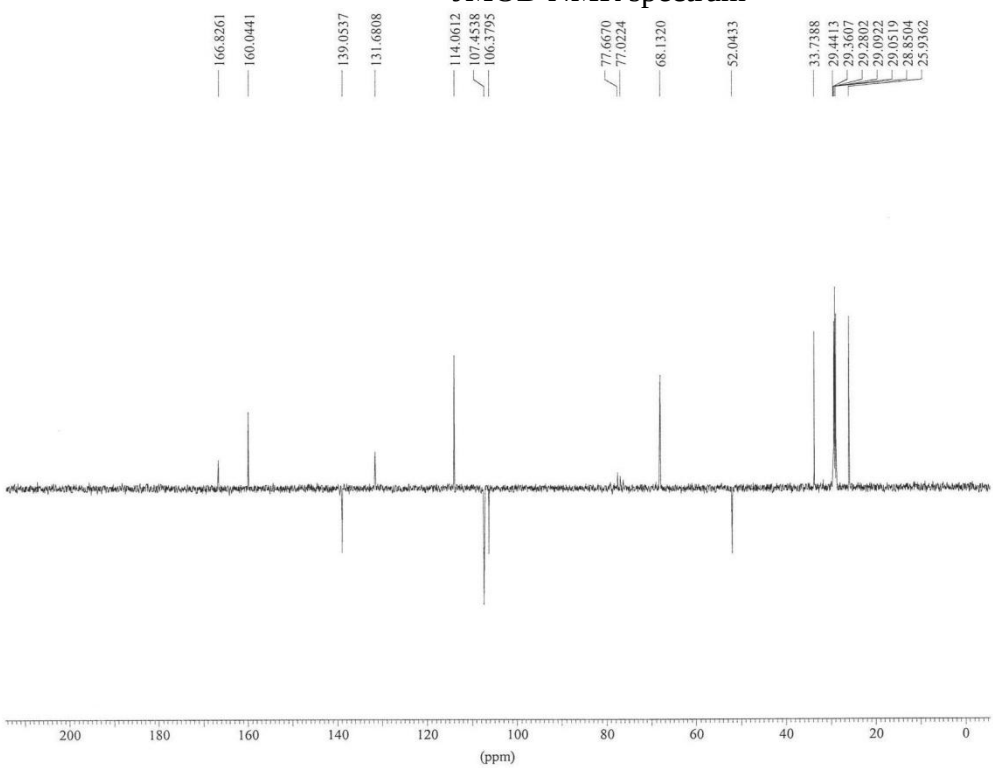
JMOD NMR spectrum

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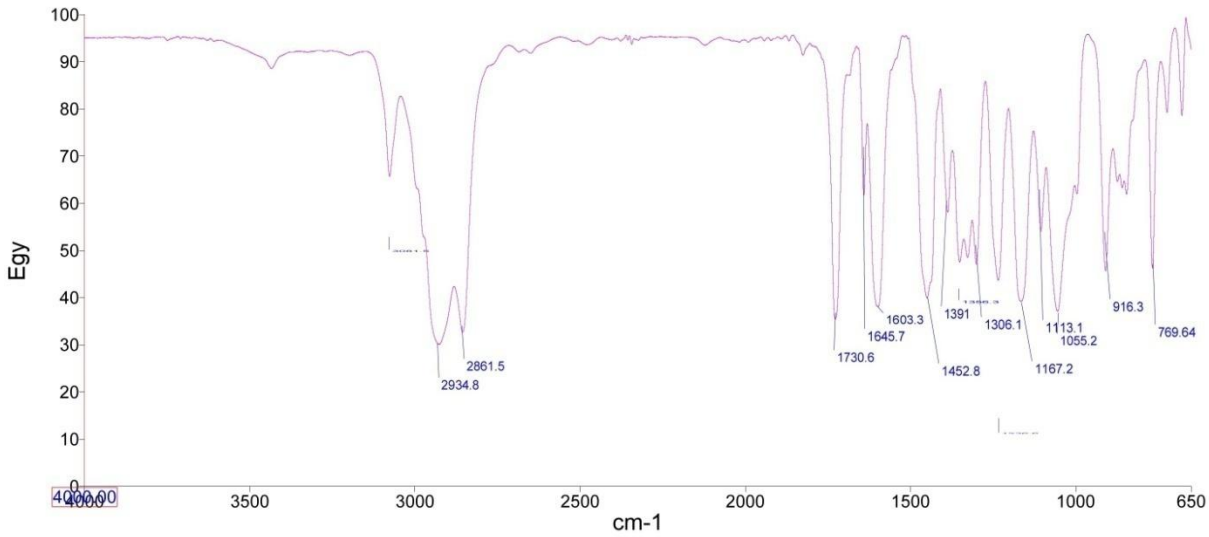
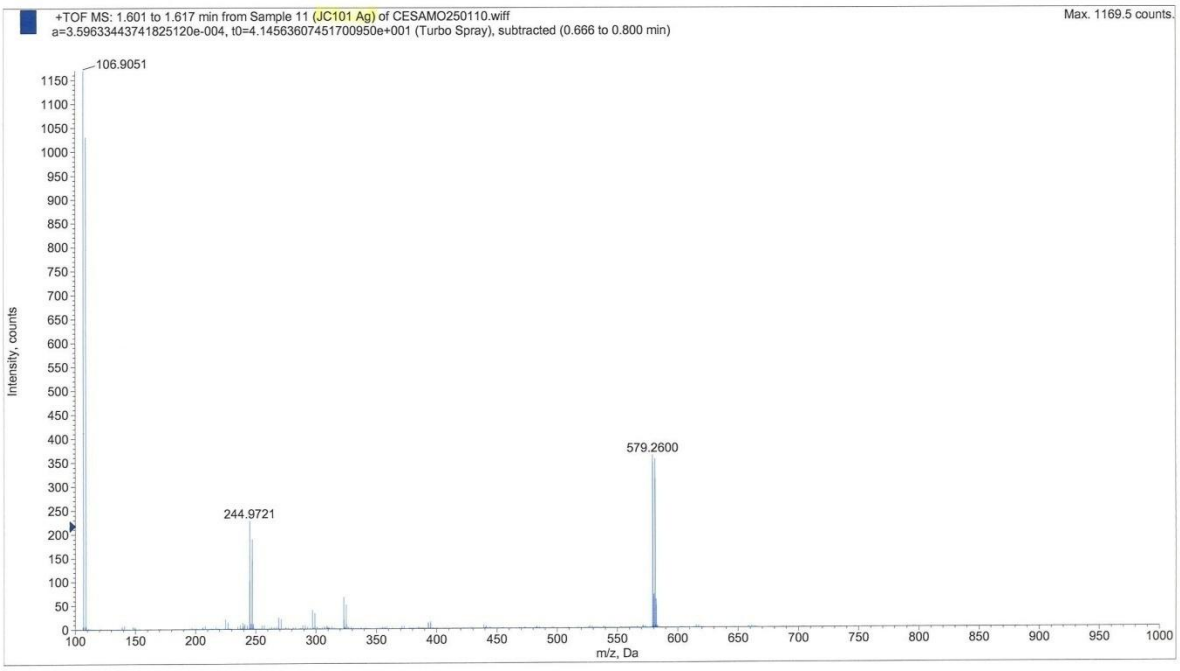
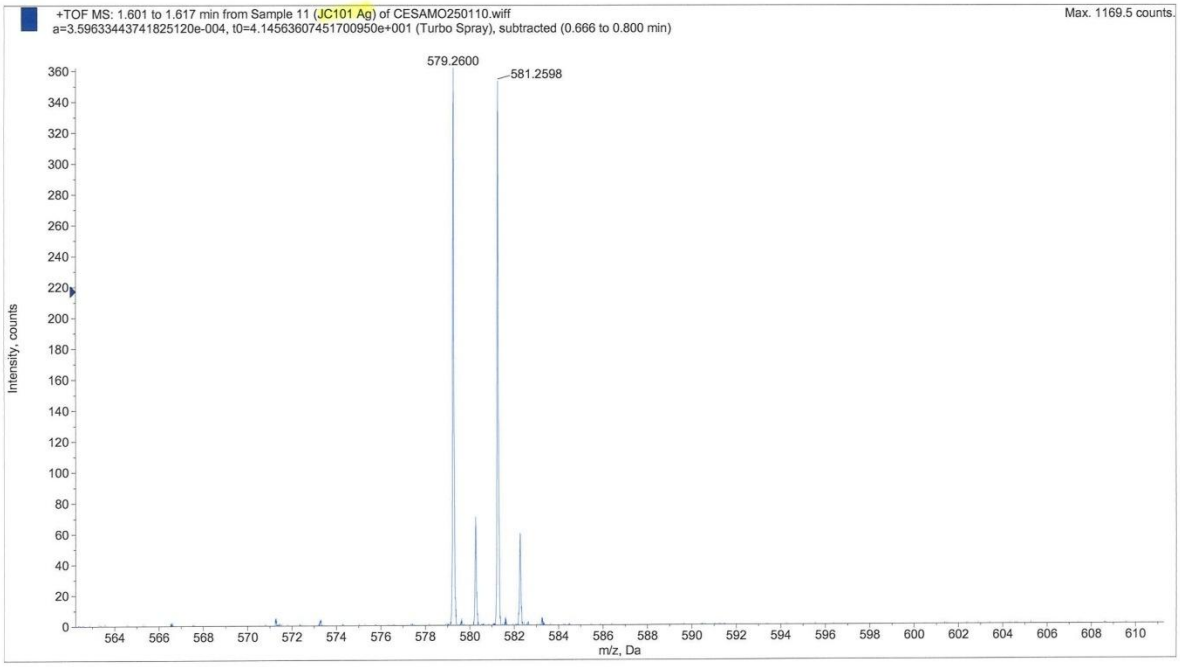


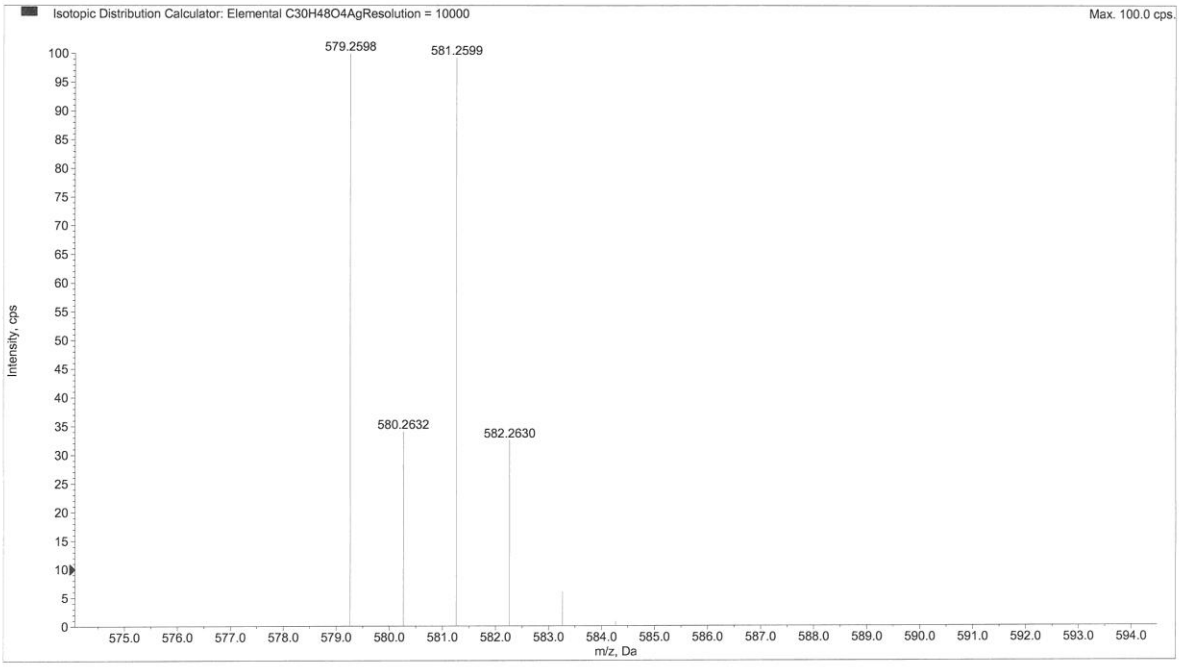
Mass spectrum (1/4)



Mass spectrum (2/4)



Mass spectrum (3/4 Simulation)



Elemental composition calculator

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Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: +0.0000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAMO250110.wiff

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6	H	0	1000
7	I	0	0
8	K	0	0
9	N	0	0
10	Na	0	0
11	O	0	4

	Elements	Min Number	Max Number
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13	S	0	0
14	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
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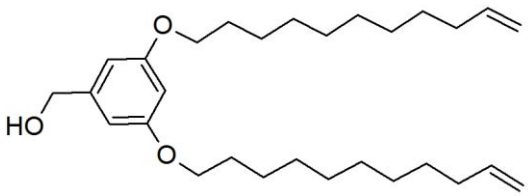
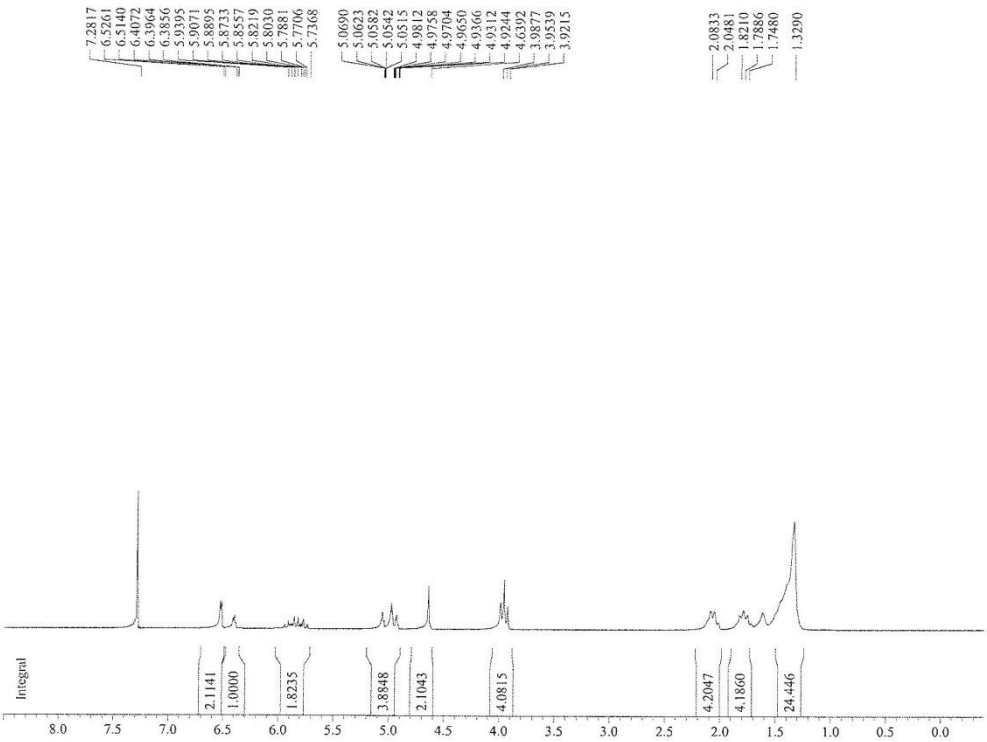
Synthesis of the [3,5-bis(10-undecen-1-yloxy)phenyl]methanol 3



To a solution of methyl 3,5-bis(10-undecen-1-yloxy)benzoate **2** (7.15g, 15.13mmol, 1eq) in distillated THF at -20°C, was added dropwise a suspension of $LiAlH_4$ (2.87g, 75.6mmol, 5eq) in distillated THF. The medium was stirred 1h at 0°C and then 5h at room temperature. The medium was then cooled to 0°C and a saturated solution of NH_4Cl was added carefully. The aqueous layer was extracted two times with diethyl ether. The organic layer was dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a colorless waxy product (6.7g, 15,02mmol) in 99% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 6.50 ppm (d, H_{Ar}, ^4J = 2.3Hz, 2H); 6.38 ppm (t, H_{Ar}, ^4J = 2.2Hz, 1H); 5.82 ppm (m, -C*H*=CH_2, 2H); 5.07 to 4.92 ppm (m, -CH=CH_2, 4H); 4.64 ppm (s, -CH_2-OH, 2H); 3.95 ppm (t, -O-CH_2-, ^3J = 6.6Hz, 4H); 2.06 ppm (m, -CH_2-CH=CH_2, 4H); 1.78 ppm (m, -O-CH_2-CH_2-, 4H); 1.50 to 1.25 ppm (m, -CH_2-, 24H)
JMOD NMR ($CDCl_3$ 50.3MHz): 160.38 ppm (C_{ar}-O); 143.19 (C_{ar}-CH_2-OH); 139.13 ppm (-*C*H=CH_2); 114.06 ppm (-CH=*C*H_2); 104.90 and 100.36 ppm (C_{ar}-H); 67.93 ppm (-O-*C*H_2-); 65.24 ppm (C_{ar}-*C*H_2-OH); 33.74, 29.45, 29.36, 29.31, 29.17, 29.05, 28.85 and 25.96 ppm (-*C*H_2-)
IR spectroscopy (cm-1) : 3355.5 (O-H) ; 2931.0 (Car-H) ; 2857.6 (C-H)
HRMS: calculated for $[M+Na]^+$, m/z = 467.3495 found m/z = 467.3507

^{1}H NMR spectrum

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PROCNO    :   1
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PROBHD    :   5 mm Multinuclear
SOLVENT   :   CDCl3
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SOLVENT   :   ?
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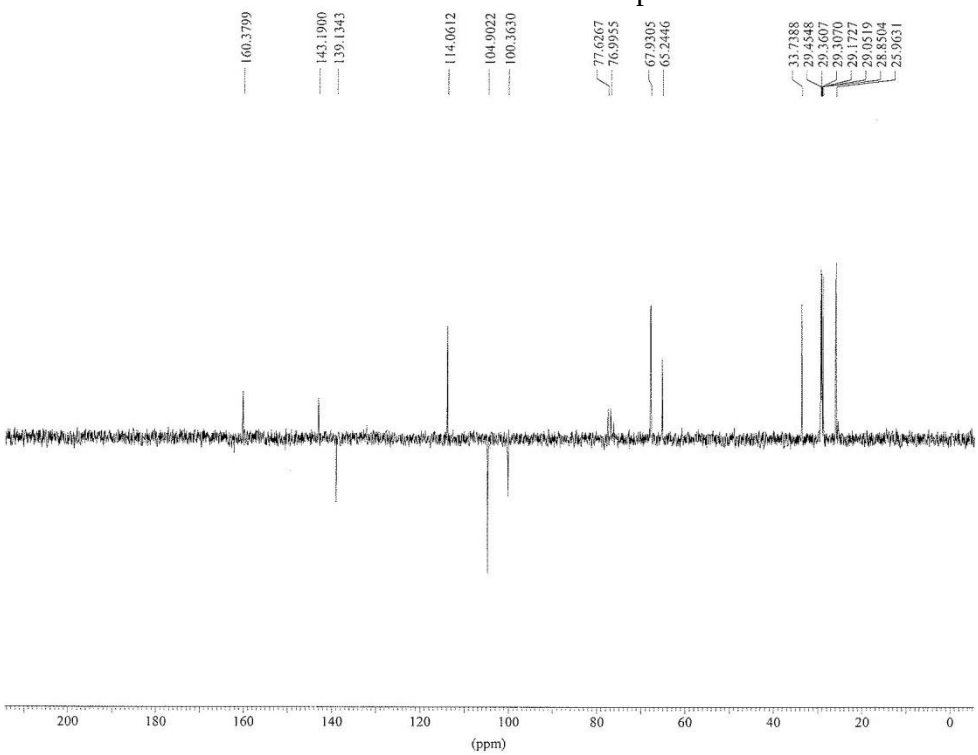
JMOD NMR spectrum

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PROBHD    :   5 mm Multinuclear
SOLVENT   :   CDCl3
*** Processing Parameters ***
AZFE      :   0.100 ppm
GAMMA     :   1.0000000
NZP       :   0
OFFSET    :   214.474 ppm
SF        :   50.3302792 MHz
TI        :
*** 1D NMR Plot Parameters ***
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SOLVENT   :   ?
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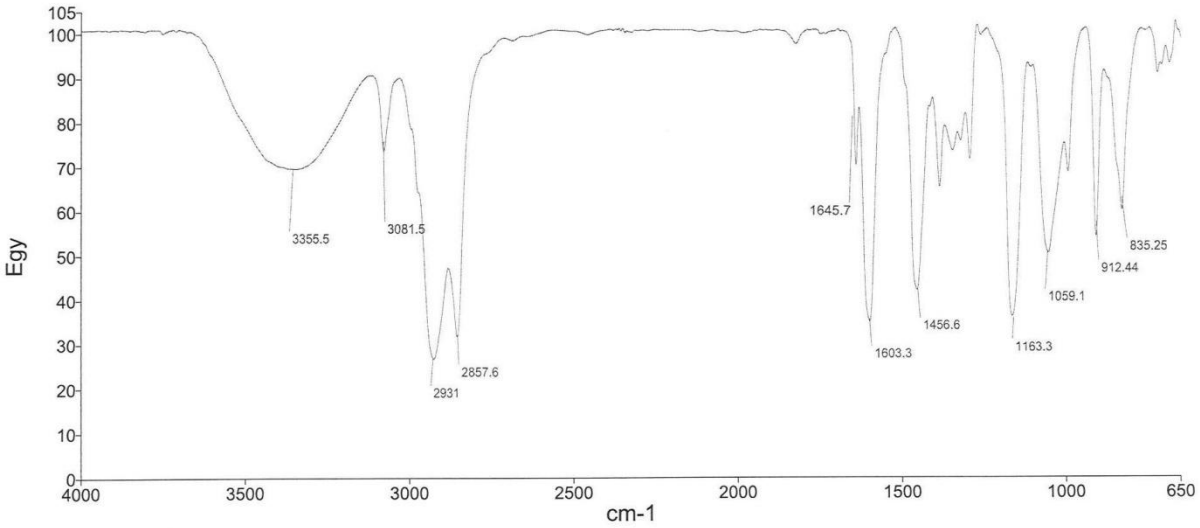
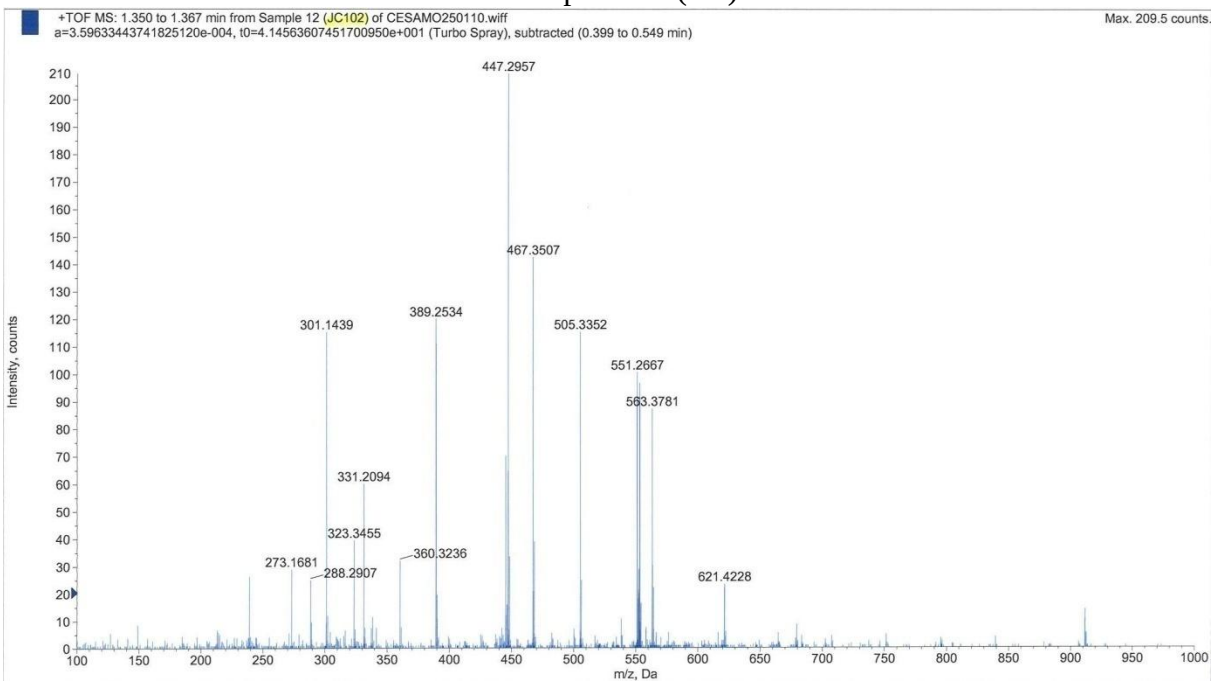
IR spectrum



Mass spectrum (1/2)



Mass spectrum (2/2 High Resolution)

Elemental composition calculator

Target m/z: +467.3507 Da
Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: +0.0000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAM0250110.wiff

	Elements	Min Number	Max Number
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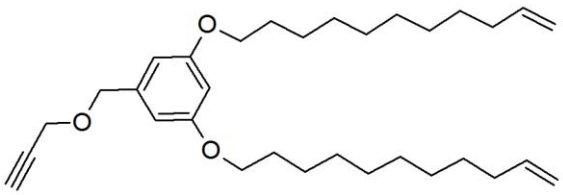
2	C	0	500
3	Cl	0	0
4	Cu	0	0
5	F	0	0
6	H	0	1000
7	I	0	0
8	K	0	0
9	N	0	0
10	Na	1	1
11	O	0	3

	Elements	Min Number	Max Number
12	P	0	0
13	S	0	0
14	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C29 H48 O3 Na	467.3495	1.1330	2.4243	5.5

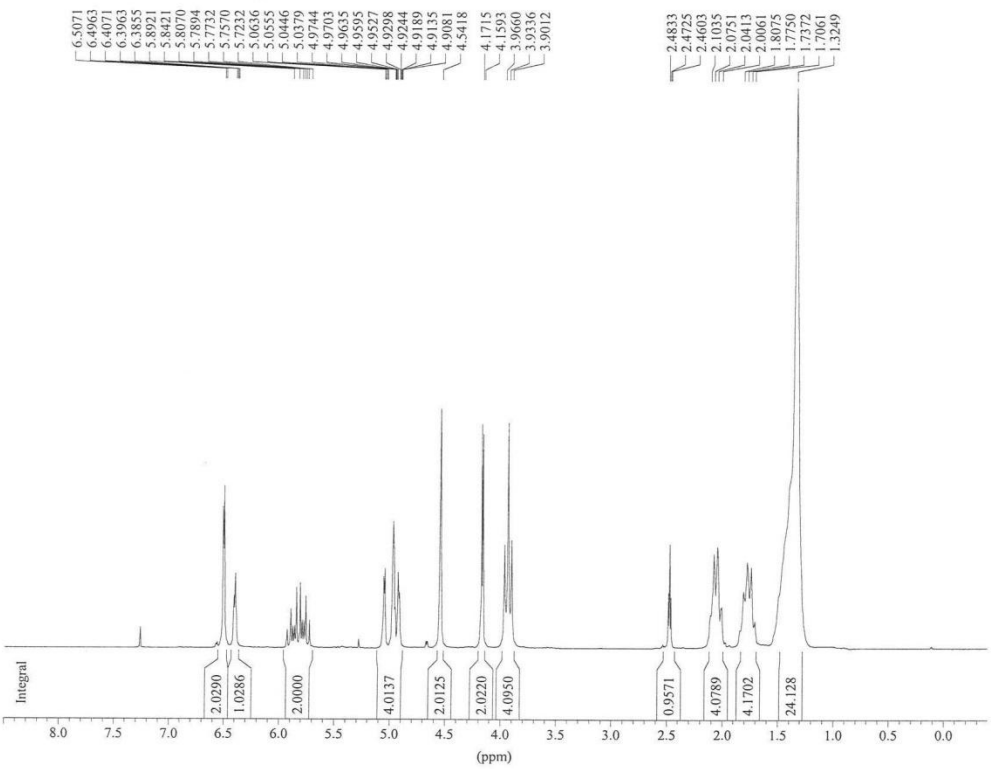
Synthesis of the 1,3-bis(10-undecen-1-yloxy)-5-[(2-propyn-1-yloxy)methyl]benzene 4



To a solution of [3,5-bis(10-undecen-1-yloxy)phenyl]methanol **3** (6.0g, 13.5mmol, 1eq) in 100mL of distillated THF, were added a 80% solution of propargyl bromide in xylene (4.5 mL, 40.5 mmol, 3eq) and NaH (1.6g, 67.5 mmol, 5eq). The medium was stirred for 1h at room temperature and then under reflux for one night. The reaction mixture was allowed to cool down and water was added. THF and excess propargyl bromide was removed *in vacuo*. The mixture was extracted two times with diethyl ether. The organic layer was dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane as eluent.
The desired product was obtained as a slightly yellow to light red oil (5.0g, 10.4mmol) in 77% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 6.50 ppm (d, H_{Ar}, ^{4}J = 2.2Hz, 2H); 6.40 ppm (t, H_{Ar}, ^{4}J = 2.2Hz, 1H); 5.80 ppm (m, -C*H*=CH_2, 2H); 5.07 to 4.90 ppm (m, -CH=CH_2, 4H); 4.54 ppm (s, C_{Ar}-CH_2-O-CH_2-C≡CH, 2H); 4.16 ppm (d, C_{Ar}-CH_2-O-CH_2-C≡CH, ^{4}J = 2.4Hz, 2H); 3.93 ppm (t, -O-CH_2-CH_2-, ^{3}J = 6.5Hz, 4H); 2.47 ppm (t, C_{Ar}-CH_2-O-CH_2-C≡C*H*, ^{4}J = 2.4Hz, 1H); 2.07 ppm (m, -CH_2-CH=CH_2, 4H); 1.80 ppm (m, -O-CH_2-CH_2-, 4H); 1.50 to 1.25 ppm (m, -CH_2-, 24H)
JMOD NMR ($CDCl_3$ 50.3MHz): 160.20 ppm (C_{ar}-O) ; 139.20 (C_{Ar}-CH_2-O-CH_2-C≡CH) ; 138.88 ppm (-*C*H=CH_2); 113.97 ppm (-CH=*C*H_2); 105.93 ppm (ortho C_{ar}-H) ; 100.60 ppm (para C_{ar}-H); 79.45 ppm (C_{Ar}-CH_2-O-CH_2-C≡*C*H); 74.41 ppm (C_{Ar}-CH_2-O-CH_2-*C*≡CH); 71.27 ppm (C_{Ar}-*C*H_2-O-CH_2-C≡CH); 67.73 ppm (-O-*C*H_2-CH_2-); 56.73 ppm (C_{Ar}-CH_2-O-*C*H_2-C≡CH); 33.61 ppm (-*C*H_2-CH=CH_2), 29.33, 29.23, 29.18, 29.07, 28.93, 28.73 and 25.85 ppm (-*C*H_2-)
IR spectroscopy (cm-1) : 3313.0 (≡C-H) ; 2931.0 (Car-H); 2857.6 (C-H); 2124.3 (C≡C)
HRMS: calculated for $[M+H]^+$, m/z = 483.3832 ; found m/z = 483.3844
$[M-OCH2C≡CH]^+$ m/z = 427.3590 $[M+H]^+$ m/z= 483.3844

^{1}H NMR spectrum

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PROBHD    : 5 mm Multinuclear
SOLVENT   :       CDCl3
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NZP       :            0
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SOLVENT   :          ?
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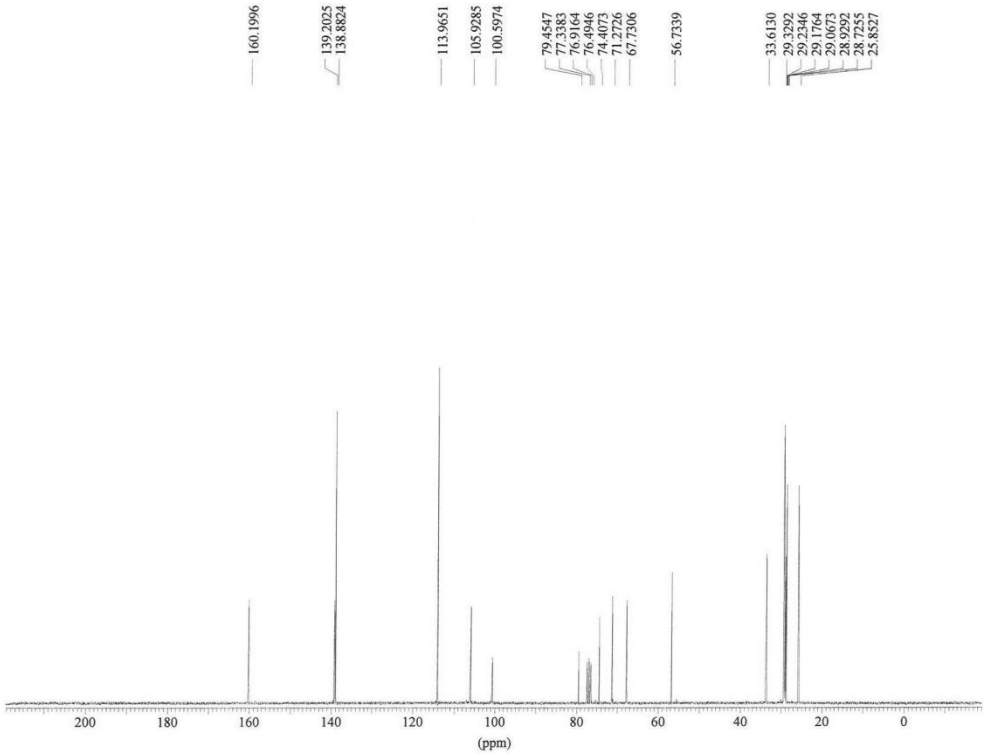
^{13}C NMR spectrum

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DATE_d    :    Feb 16 2010
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PULPROG   :       zgpg30
SOLVENT   :       CDCl3
SW        :   238.2980 ppm
SW_h      :  17985.612 Hz
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SF        :  75.4677490 MHz
SI        :        32768
WDW       :           EM
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EXPTYPE   :            ?
SOLVENT   :            ?
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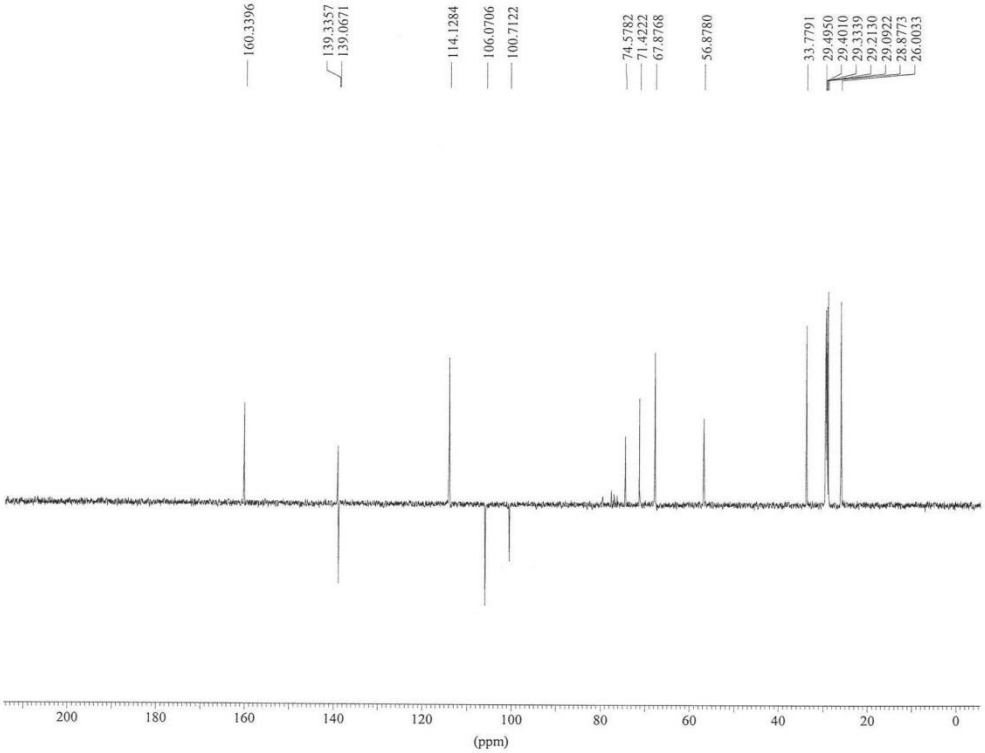
JMOD NMR spectrum



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PROBHD	:	5 mm Multinuclear
SOLVENT	:	CDCl3
*** Processing Parameters ***		
AZFE	:	0.100 ppm
GAMMA	:	1.0000000
NZP	:	0
OFFSET	:	214.474 ppm
SF	:	50.3302792 MHz
TI	:	
*** 1D NMR Plot Parameters ***		
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SR	:	27.22 Hz
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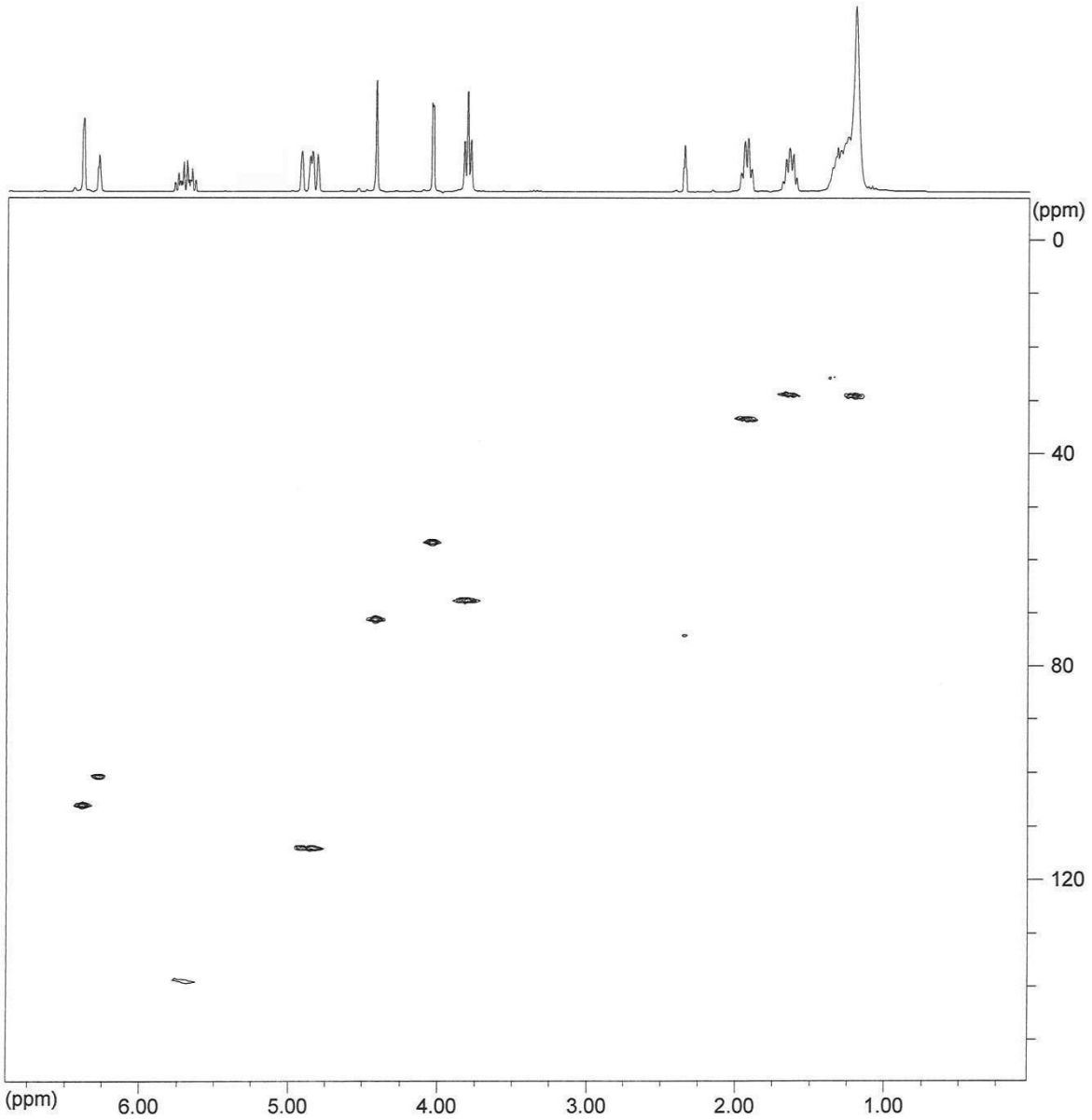
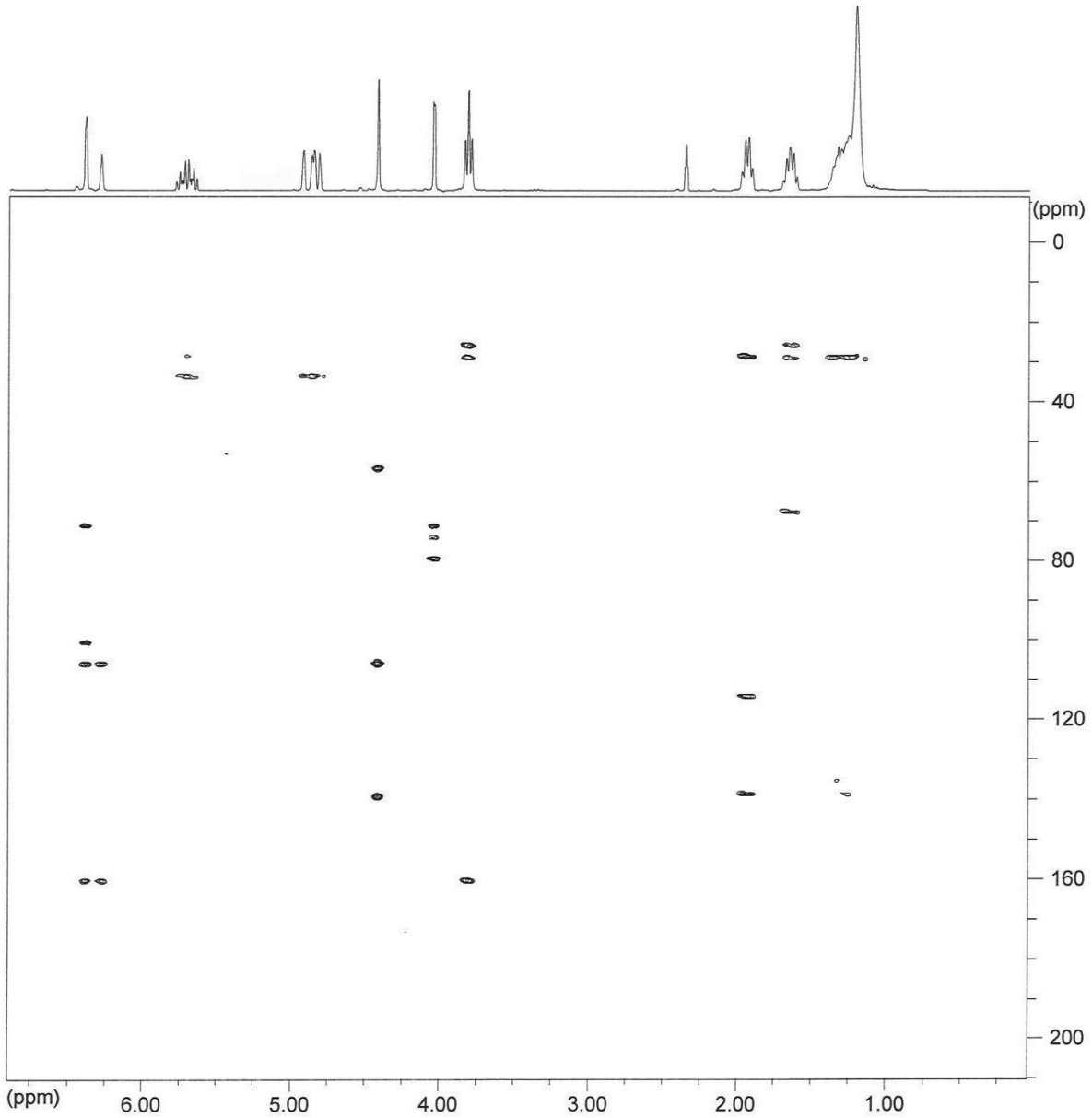
SOLVENT	:	?

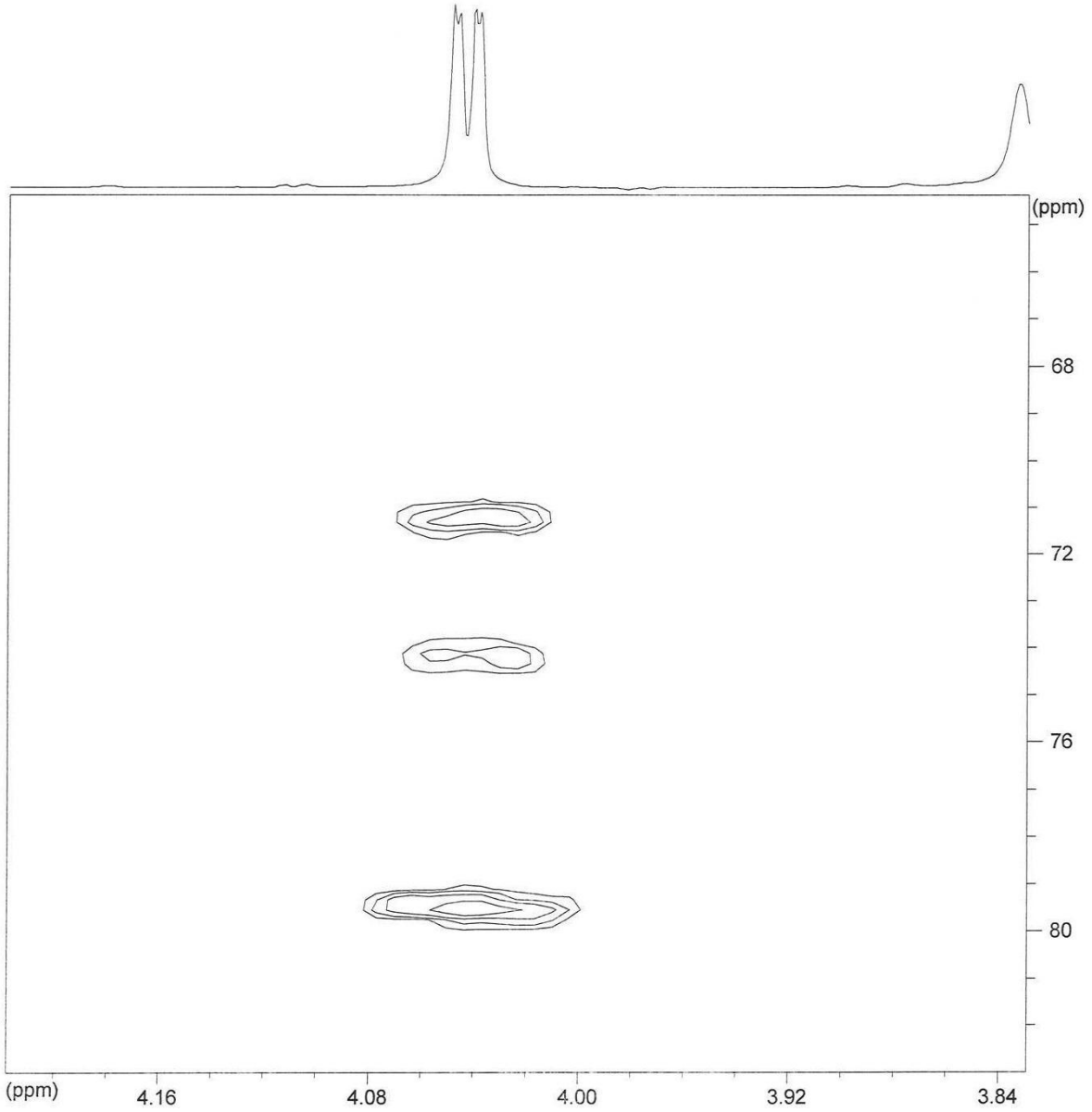
HMQC NMR spectrum



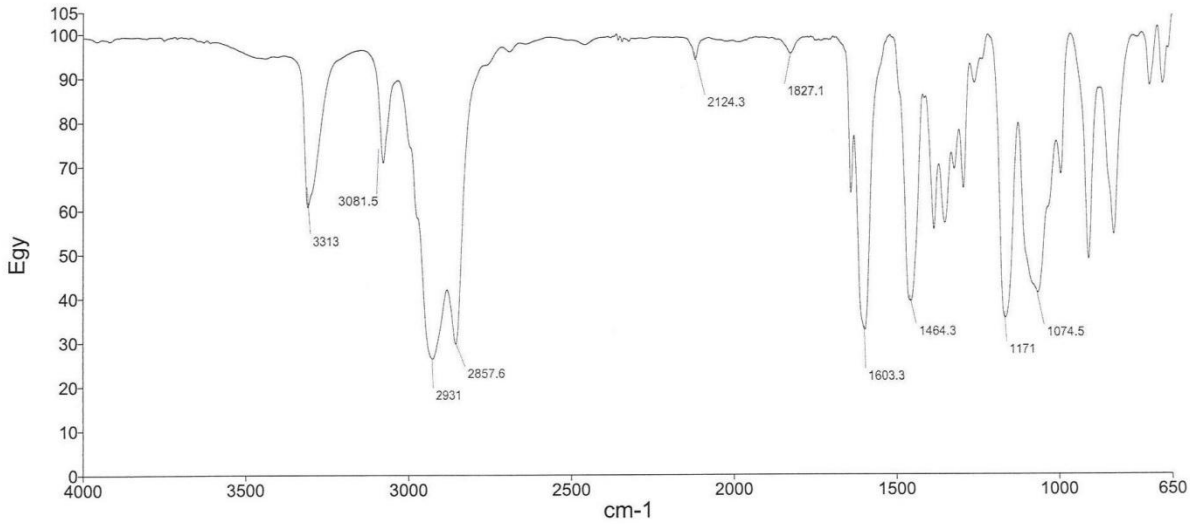
HMBC NMR spectrum



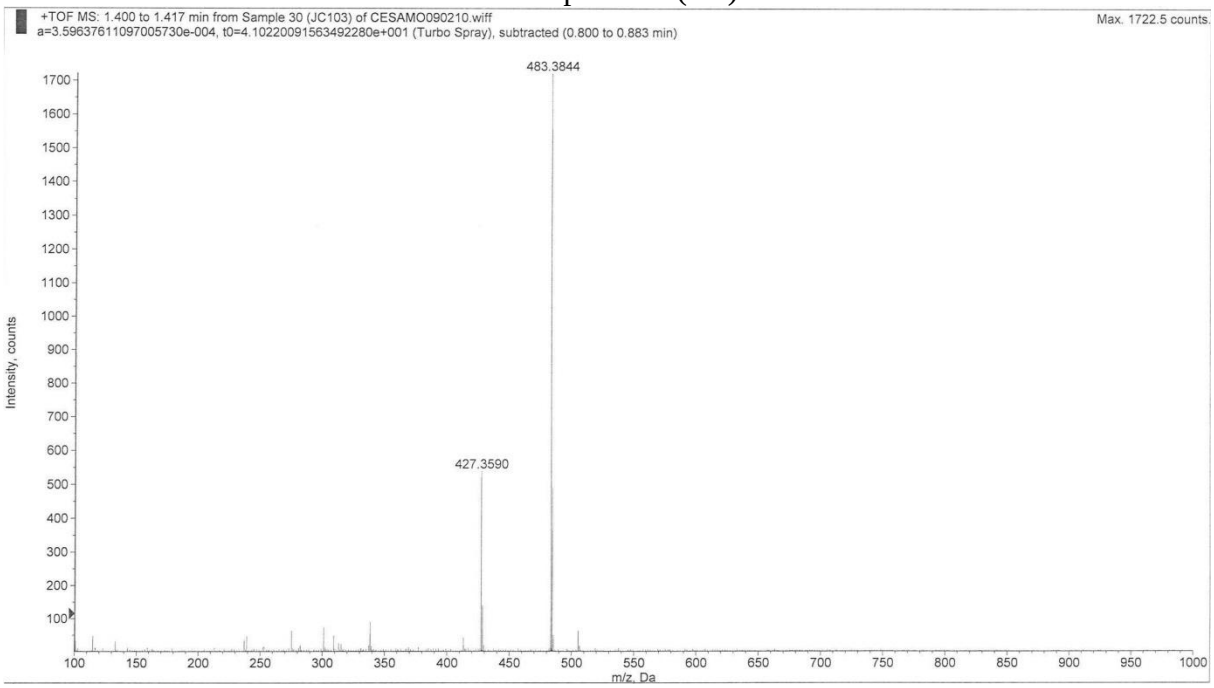
HMBC NMR spectrum (zoom)



IR spectrum



Mass spectrum (1/2)



Elemental composition calculator

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Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: -0.5000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAM0090210.wiff

	Elements	Min Number	Max Number
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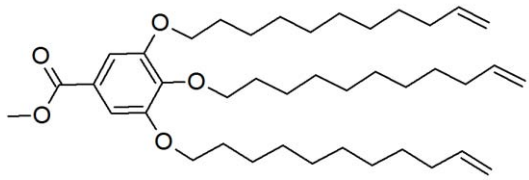
3	Cl	0	0
4	Cu	0	0
5	Fe	0	0
6	H	0	1000
7	I	0	0
8	K	0	0
9	N	0	1
10	Na	0	0

	Elements	Min Number	Max Number
11	O	2	3
12	S	0	0
13	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C32 H51 O3	483.3832	1.1276	2.3327	7.5

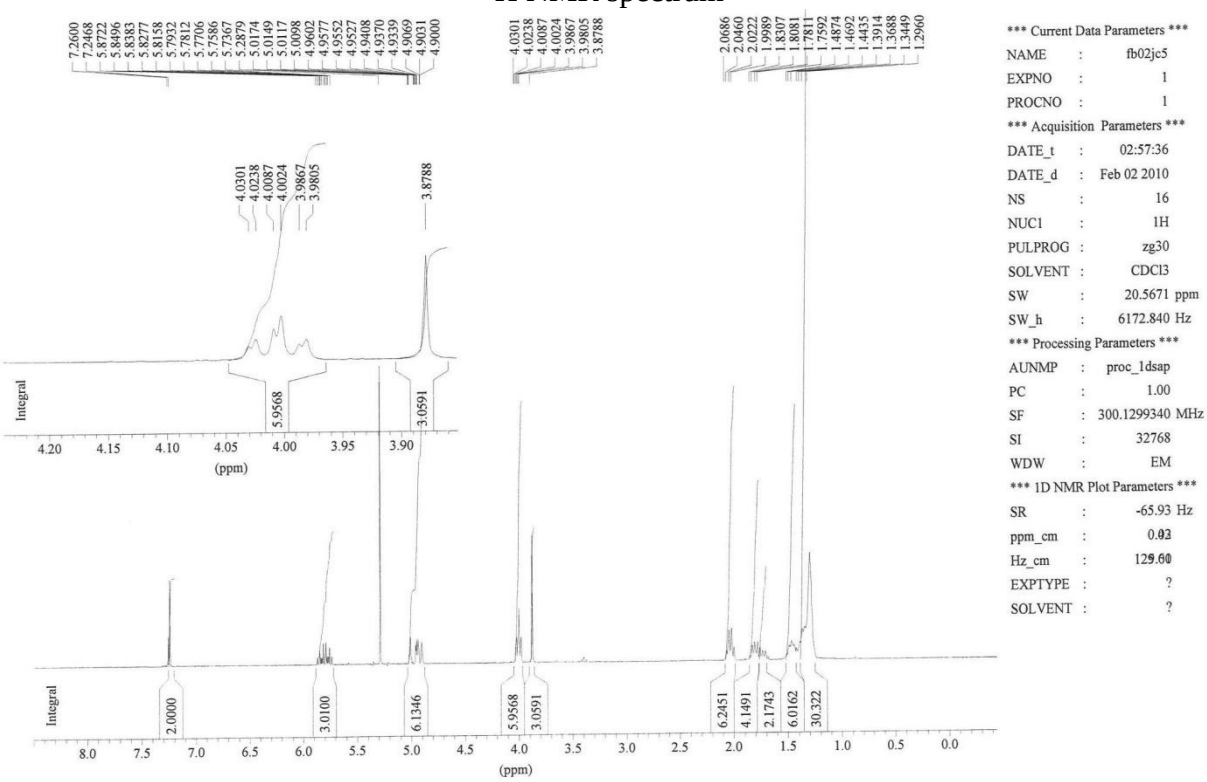
Synthesis of the methyl 3,4,5-tris(10-undecen-1-yloxy)benzoate 5



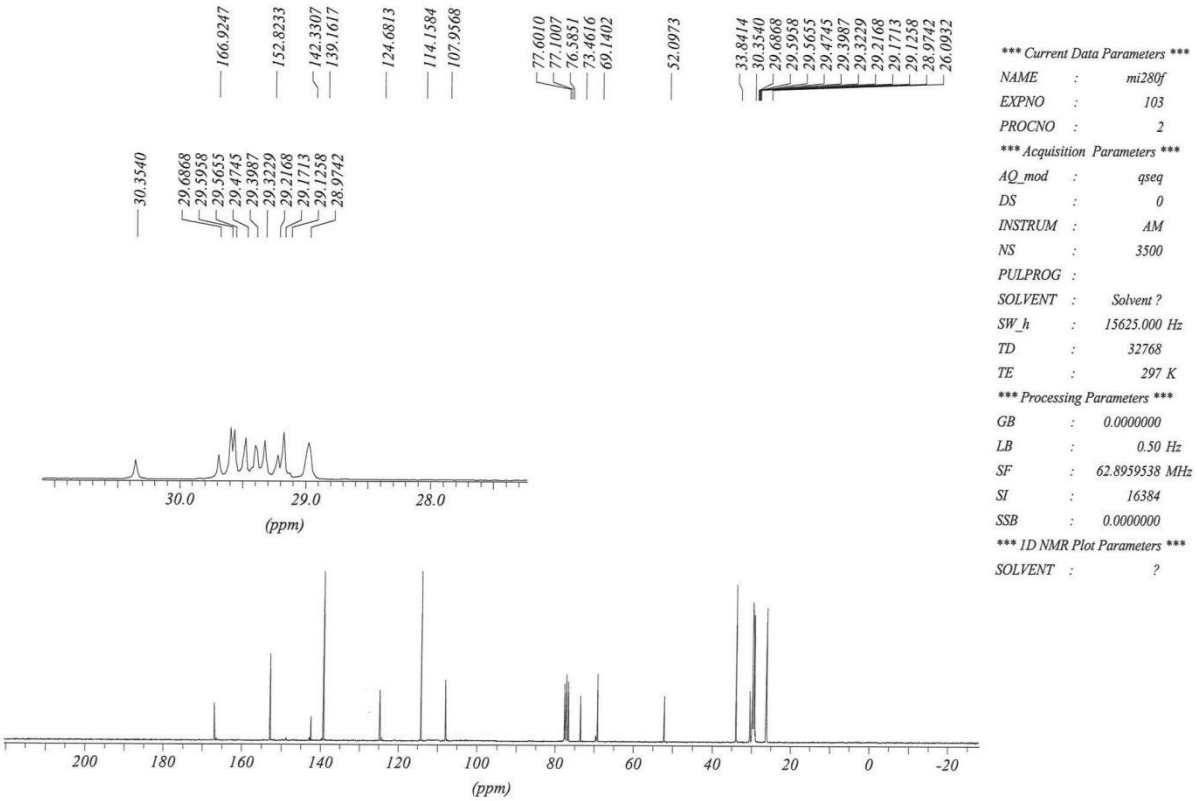
To a solution of methyl 3,4,5-trihydroxybenzoate (2.3g, 12.5mmol, 1eq) and 11-bromo-1-undecene (13.1g, 56.2mmol, 4.5eq) in 200mL of acetone was added K_2CO_3 (15.5g, 112.4 mmol, 9eq). The reaction mixture was stirred under reflux for one night. Acetone was removed *in vacuo*. Dichloromethane was then added and the medium was filtered. The crude product was purified by flash column chromatography using pentane and then dichloromethane as eluent.
The desired product was obtained as a colorless oil (7.6g, 11.8mmol) in 95% yield .

^{1}H NMR ($CDCl_3$ 200MHz): 7.25 ppm (s, H_{Ar}, 2H); 5.81 ppm (m, -C*H*=CH_2, 3H); 5.02 to 4.89 ppm (m, -CH=CH_2, 6H); 4.00 ppm (dt, para and meta -O-CH_2-, ^{3}J = 6.5Hz, 2H+4H); 3.88 ppm (s, -CH_3, 3H); 2.03 ppm (m, -CH_2-CH=CH_2, 6H); 1.83 to 1.75 ppm (m,para and meta -O-CH_2-CH_2-, 2H+4H); 1.50 to 1.25 ppm (m, -CH_2-, 36H)
JMOD NMR ($CDCl_3$ 62.9MHz): 166.92 ppm (*C*OOMe); 152.82 ppm (meta C_{ar}-O); 142.33 (para C_{ar}-O); 139.16 ppm (-*C*H=CH_2); 124.68 ppm (C_{ar}-COOMe); 114.16 ppm (-CH=*C*H_2); 107.96 ppm (C_{ar}-H); 73.46 (para -O-*C*H_2-); 69.14 ppm (meta -O-*C*H_2-); 52.10 ppm (-CH_3); 33.84, 30.35, 29.68, 29.60, 29.57, 29.47, 29.40, 29.32, 29.22, 29.17, 29.13, 28.97 and 26.09 ppm (-*C*H_2-)
IR spectroscopy (cm^{-1}) : 2934.8 (Car-H); 2853.7 (C-H) ; 1726.8 (C=O)
HRMS: calculated for $[M+Na]^+$, m/z = 663.4958, found m/z = 663.4934

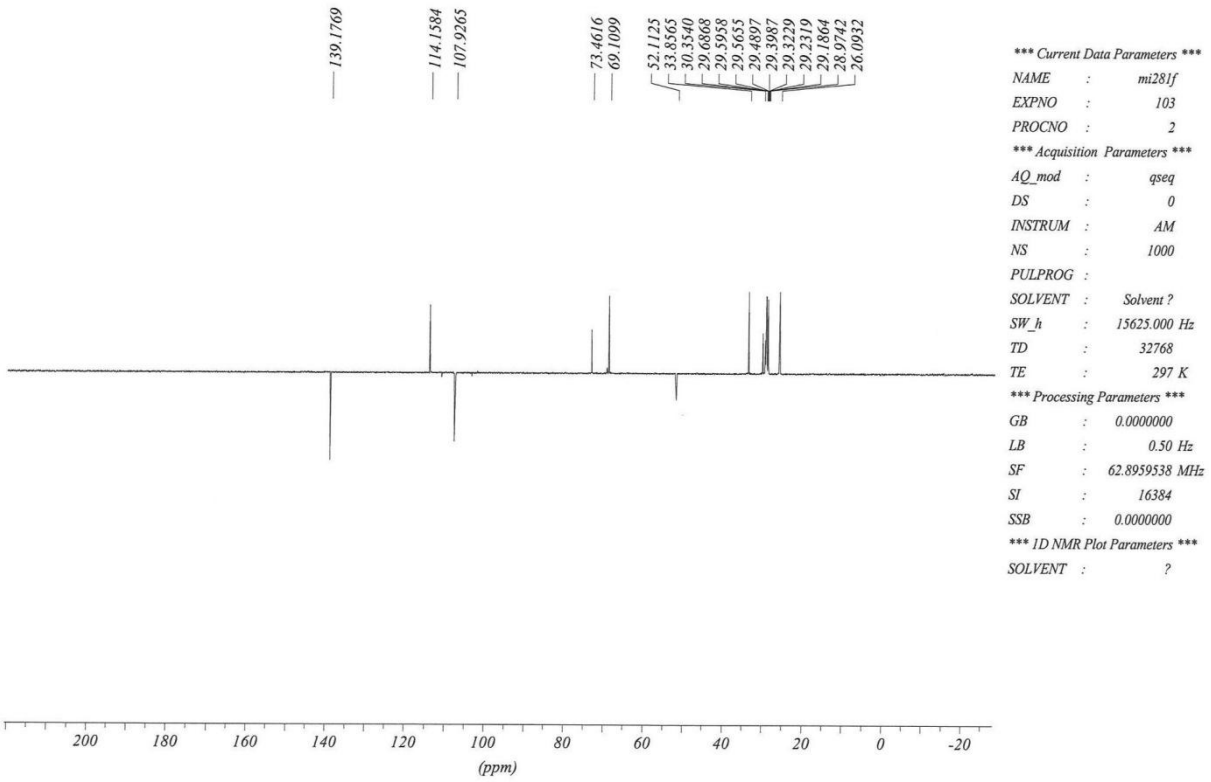
^{1}H NMR spectrum



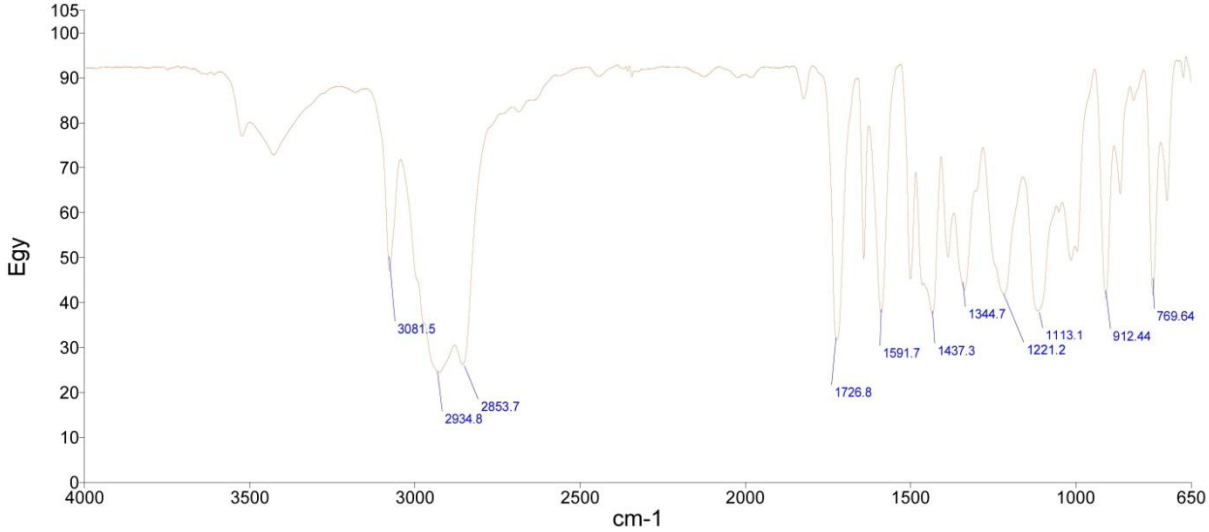
^{13}C NMR spectrum



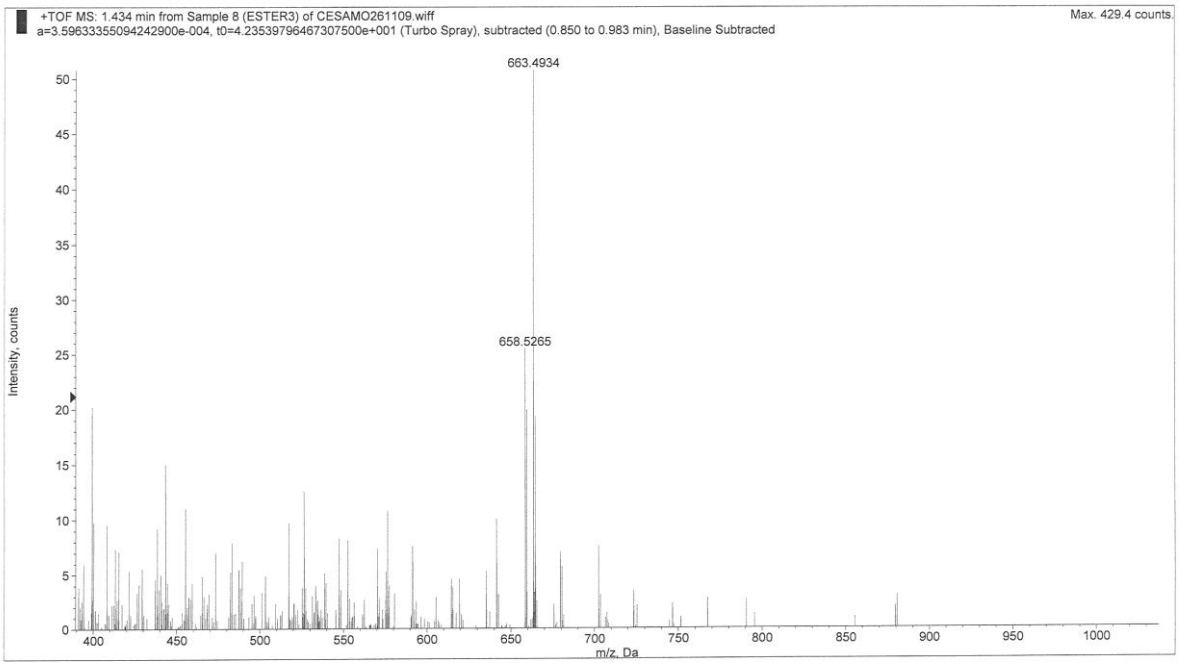
DEPT-135 NMR spectrum



IR spectrum



Mass spectrum (1/2)



Elemental composition calculator

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Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: -0.5000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAMO261109.wiff

	Elements	Min Number	Max Number
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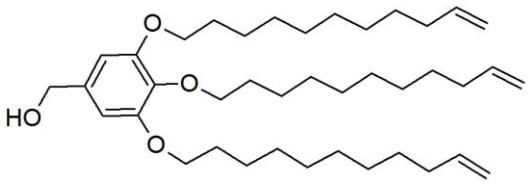
2	Br	0	0
3	C	0	500
4	Cl	0	0
5	Cu	0	0
6	Fe	0	0
7	H	0	1000
8	K	0	0
9	N	0	0
10	Na	1	1

	Elements	Min Number	Max Number
11	O	0	5
12	P	0	0
13	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C41 H68 O5 Na	663.4958	-2.4970	-3.7634	7.5

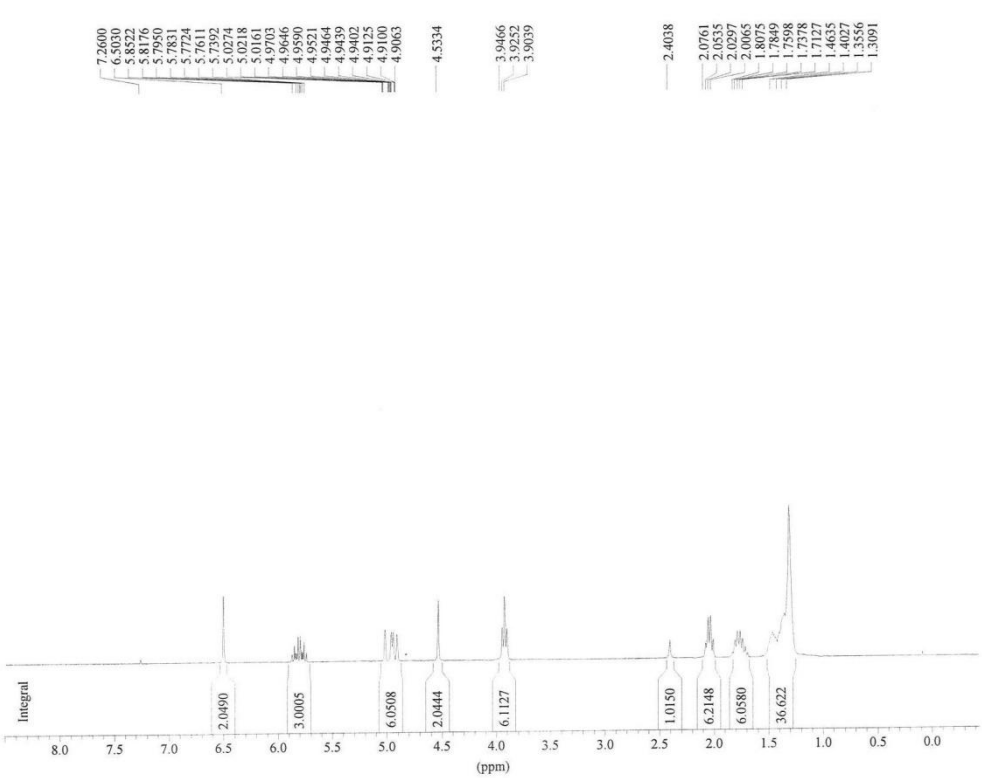
Synthesis of the [3,4,5-tris(10-undecen-1-yloxy)phenyl]methanol 6



To a solution of methyl 3,4,5-tris(10-undecen-1-yloxy)benzoate **5** (3g, 4.68mmol, 1eq) in distillated THF at -20°C, was added dropwise a suspension of $LiAlH_4$ (0.9g, 23.7mmol, 5eq) in distillated THF. The reaction mixture was stirred 1h at 0°C and then 5h at room temperature. The medium was then cooled to 0°C and a saturated solution of NH_4Cl was added carefully. The aqueous layer was extracted two times with diethyl ether. The organic layer was dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a colorless oil (2.85g, 4.65mmol) in 99% yield.

^{1}H NMR ($CDCl_3$ 300MHz): 6.53 ppm (s, H_{Ar}, 2H); 5.80 ppm (m, -C*H*=CH_2, 3H); 5.03 to 4.90 ppm (m, -CH=CH_2, 6H); 4.56 ppm (s, -CH_2-OH, 2H); 3.94 ppm (m, meta and para -O-CH_2-, 6H); 2.04 ppm (m, -CH_2-CH=CH_2, 6H); 1.77 ppm (m, -O-CH_2-CH_2-, 6H); 1.50 to 1.25 ppm (m, -CH_2-, 36H)
JMOD NMR ($CDCl_3$ 50.3MHz): 152.95 ppm (meta C_{ar}-O); 138.98 ppm (-*C*H=CH_2); 136.94 ppm (para C_{ar}-O) ; 136.38 ppm (C_{ar}-CH_2-OH); 114.10 ppm (-CH=*C*H_2); 104.89 ppm (C_{ar}-H); 73.31 ppm (para -O-*C*H_2-); 68.84 ppm (meta -O-*C*H_2-); 65.09 ppm (C_{ar}-*C*H_2-OH); 33.77, 30.25, 29.65, 29.57, 29.51, 29.43, 29.38, 29.15, 29.11, 28.88 and 26.07 ppm (-*C*H_2-)
IR spectroscopy (cm^{-1}) : 3305.3 (O-H) ; 2931 (Car-H) ; 2853.7 (C-H)
HRMS: calculated for $[M+H]^+$, m/z = 613.5190 ; found m/z = 613.5206
$[M-OH]^+$ m/z = 595.5144 ; $[M+H]^+$ m/z = 613.5206 ; $[M+Na]^+$ m/z = 635.5043

^{1}H NMR spectrum

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SW_h      :   6172.840 Hz
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SOLVENT   :   ?
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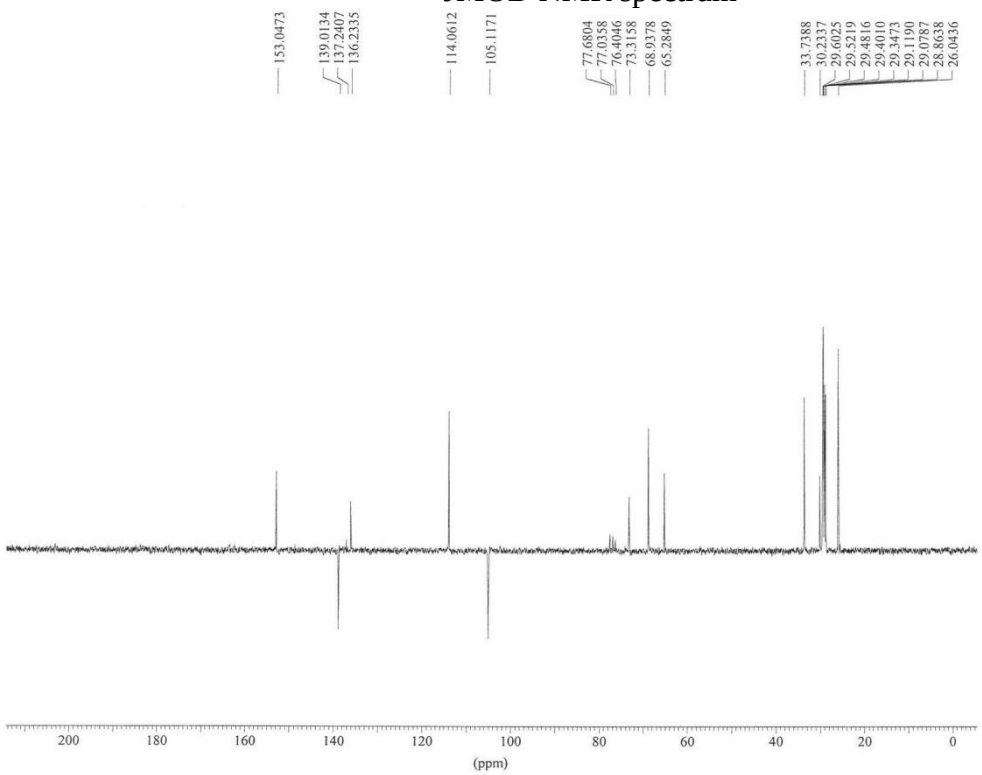
JMOD NMR spectrum

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PROBHD    :   5 mm Multinuclear
SOLVENT   :   CDCl3
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TI        :
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SOLVENT   :   ?
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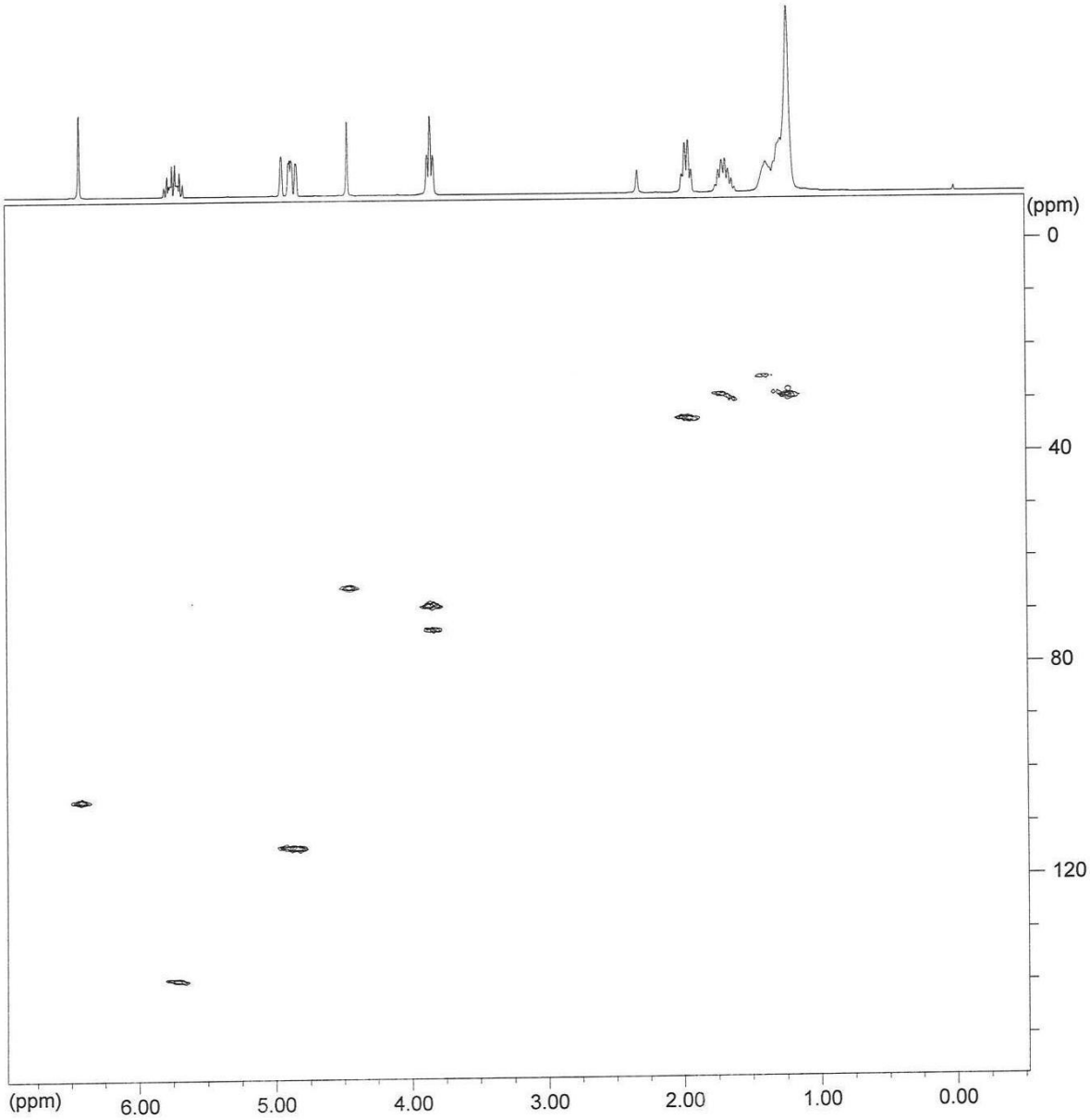
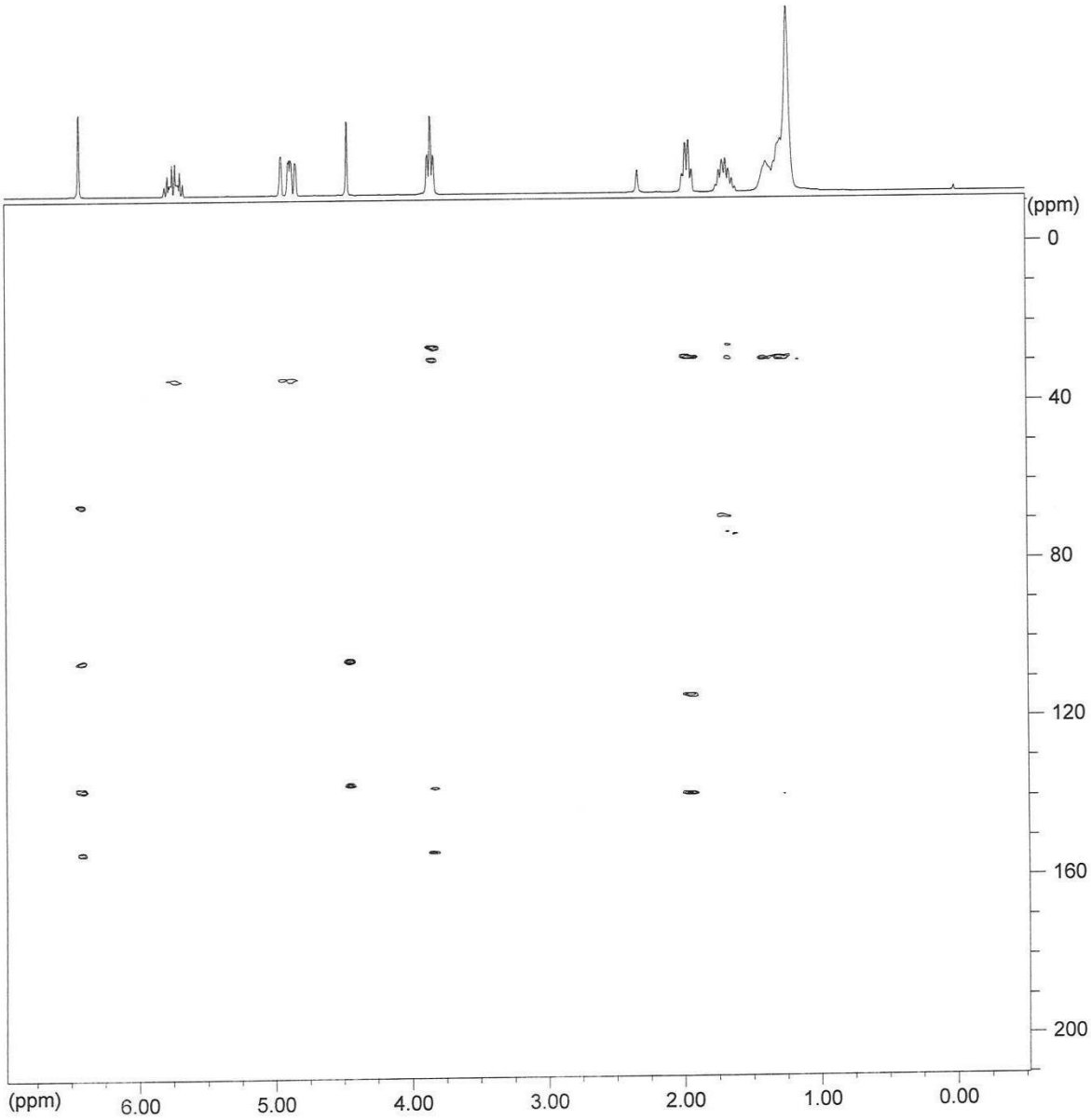
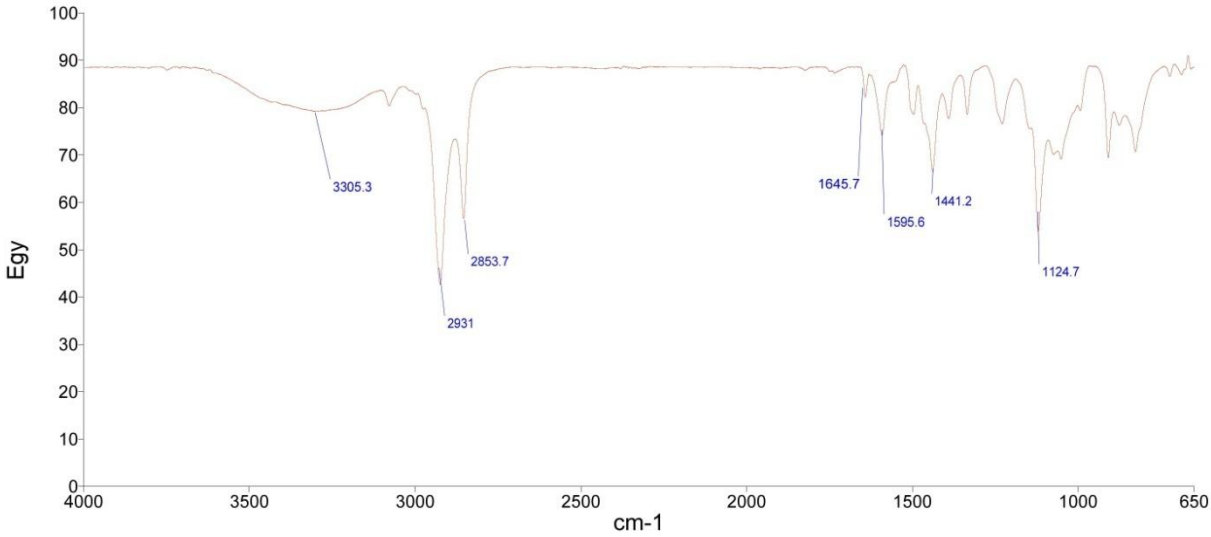
HMQC NMR spectrum



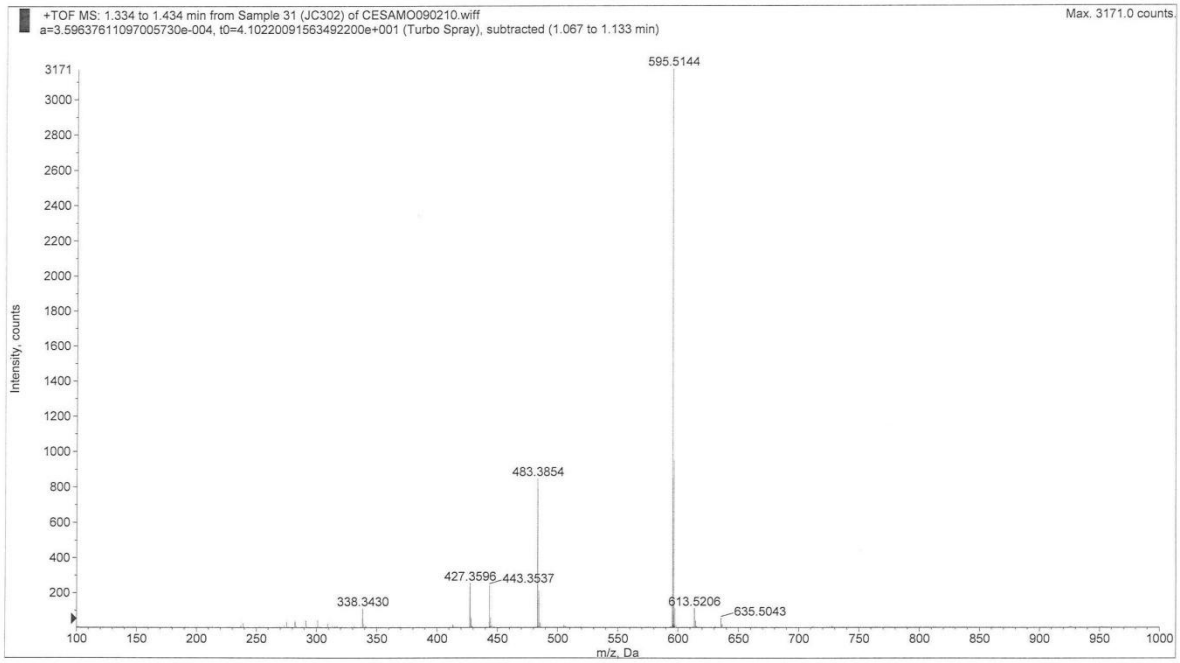
HMBC NMR spectrum



IR spectrum



Mass spectrum (1/2)



Elemental composition calculator

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Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: -0.5000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAM0090210.wiff

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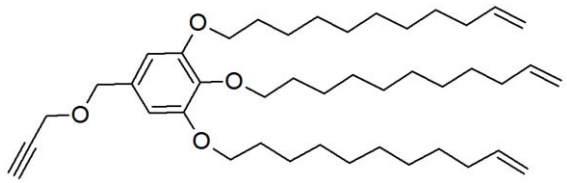
4	Cu	0	0
5	Fe	0	0
6	H	0	1000
7	I	0	0
8	K	0	0
9	N	0	1
10	Na	0	0

	Elements	Min Number	Max Number
11	O	2	4
12	S	0	0
13	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C40 H69 O4	613.5190	1.5622	2.5463	6.5

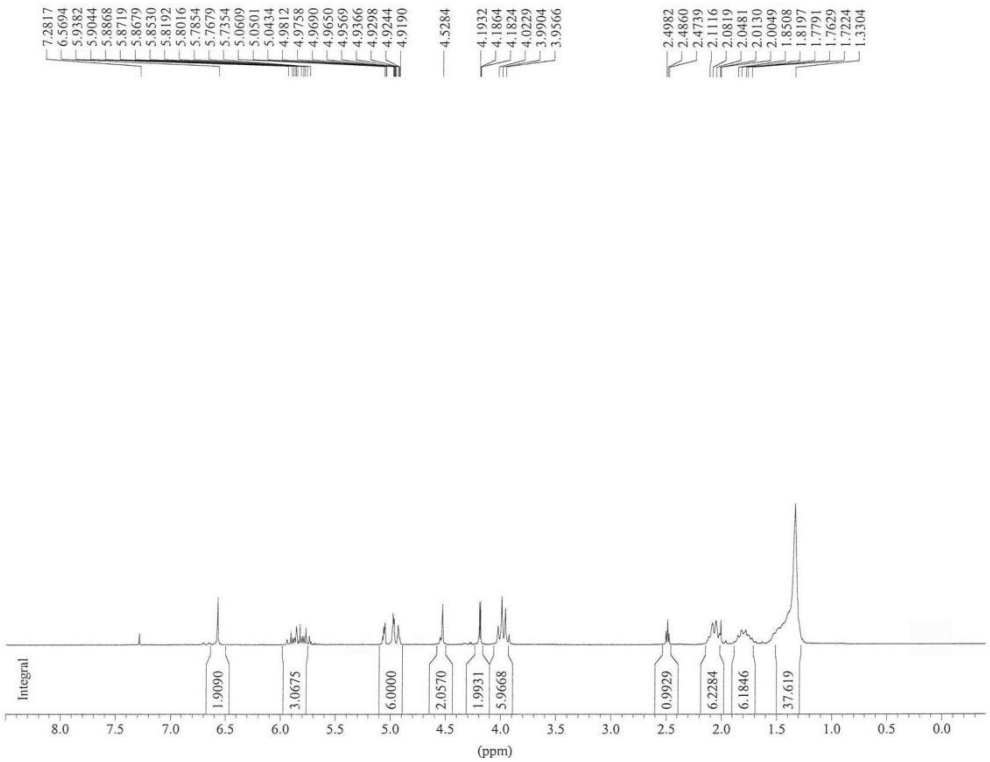
Synthesis of the 1,2,3-tris(10-undecen-1-yloxy)-5-[(2-propyn-1-yloxy)methyl]benzene 7



To a solution of [3,4,5-tris(10-undecen-1-yloxy)phenyl]methanol **6** (2.6g, 4.24mmol, 1eq) in 100mL of distillated THF, were added a 80% solution of propargyl bromide in xylene (1.9 mL, 17.0 mmol, 4eq) and NaH (0.50g, 20.8mmol, 5eq). The medium was stirred for 1h at room temperature and then under reflux for one night. The reaction mixture was allowed to cool down and water was added. THF and excess propargyl bromide was removed *in vacuo*. The medium was extracted two times with diethyl ether. The organic layer was dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane as eluent.
The desired product was obtained as a light red oil (2.4g, 3.7mmol) in 88% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 6.57 ppm (s, H_{Ar}, 2H); 5.83 ppm (m, -C*H*=CH_2, 3H); 5.07 to 4.90 ppm (m, -CH=CH_2, 6H); 4.53 ppm (s, C_{Ar}-CH_2-O-CH_2-C≡CH, 2H); 4.19 ppm (d, C_{Ar}-CH_2-O-CH_2-C≡CH, ^{4}J = 1.4Hz, 2H); 3.99 ppm (m, para and meta -O-CH_2-CH_2-, 6H); 2.49 ppm (t, C_{Ar}-CH_2-O-CH_2-C≡C*H*, ^{4}J = 2.4Hz, 1H); 2.08 ppm (m, -CH_2-CH=CH_2, 6H); 1.82 ppm (m, -O-CH_2-CH_2-, 6H); 1.50 to 1.25 ppm (m, -CH_2-, 36H)
JMOD NMR ($CDCl_3$ 50.3MHz): 153.10 ppm (meta C_{ar}-O); 139.10 ppm (-*C*H=CH_2); 137.81 ppm (para C_{ar}-O); 132.15 (C_{Ar}-CH_2-O-CH_2-C≡CH); 114.03 ppm (-CH=*C*H_2); 106.52 ppm (C_{ar}-H); 79.61 ppm (C_{Ar}-CH_2-O-CH_2-*C*≡CH); 74.50 ppm (C_{Ar}-CH_2-O-CH_2-*C*≡CH); 73.28 ppm (para -O-*C*H_2-CH_2-) ; 71.77 ppm (C_{ar}-*C*H_2-O-CH_2-C≡CH); 69.00 ppm (meta -O-*C*H_2-CH_2-); 56.90ppm (C_{Ar}-CH_2-O-*C*H_2-C≡CH); 33.73, 30.23, 29.59, 29.50, 29.37, 29.31, 29.11, 29.07, 28.86 and 26.00 ppm (-*C*H_2-)
IR spectroscopy (cm^{-1}) : 3307.4 (≡C-H) ; 2930.0 (Car-H); 2855.3 (C-H); 2121.2 (C≡C)
HRMS: calculated for $[M+Na]^+$, m/z = 673.5166 ; found m/z = 673.5191
$[M-OCH2C≡CH]^+$ m/z = 595.5113 ; $[M+H]^+$ m/z = 651.5360 ; $[M+Na]^+$ m/z = 673.5191

^{1}H NMR spectrum

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SOLVENT   :         CDCl3
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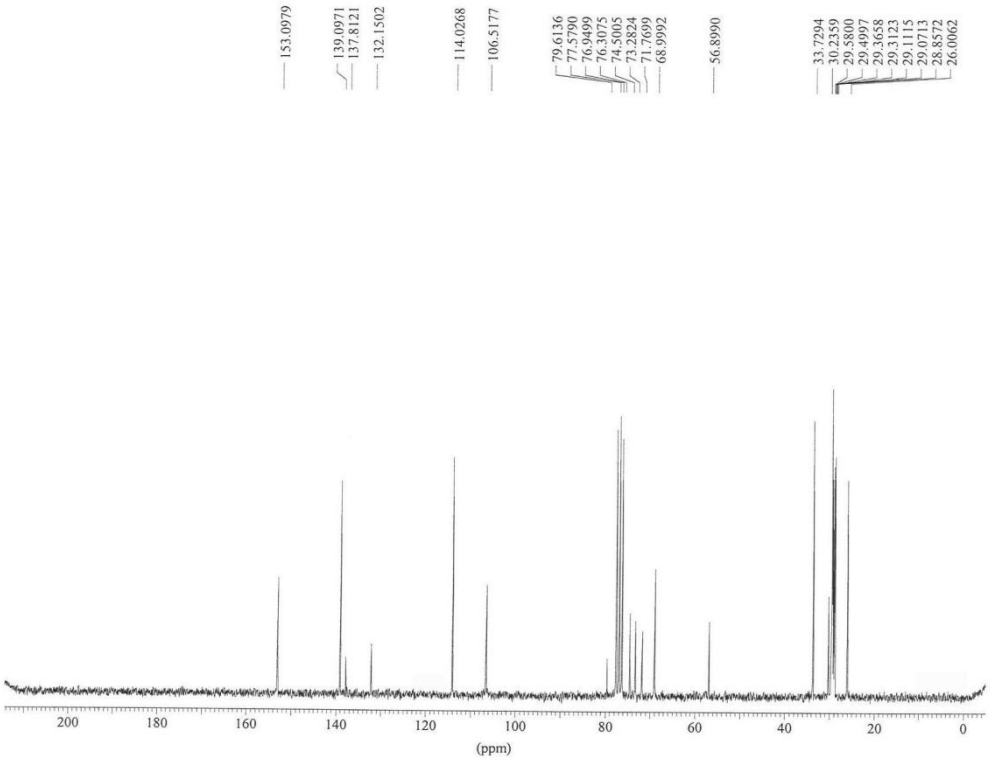
^{13}C NMR spectrum

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PROBHD    : 5 mm Multinuclear
SOLVENT   :         CDCl3
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NZP       :            0
OFFSET    :     214.335 ppm
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TI        :
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Start     :     214.33 ppm
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SR        :      27.22 Hz
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SOLVENT   :          ?
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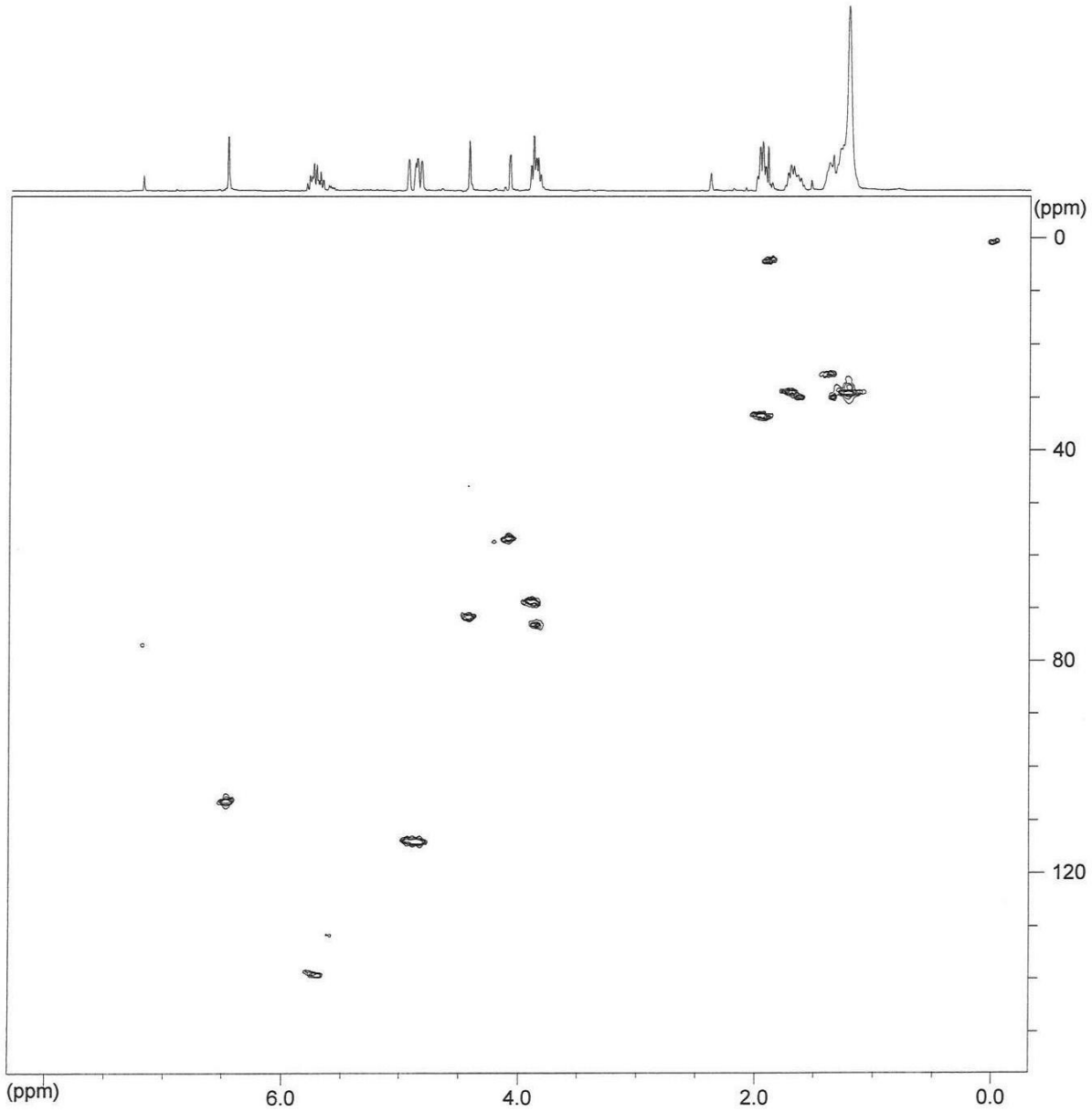
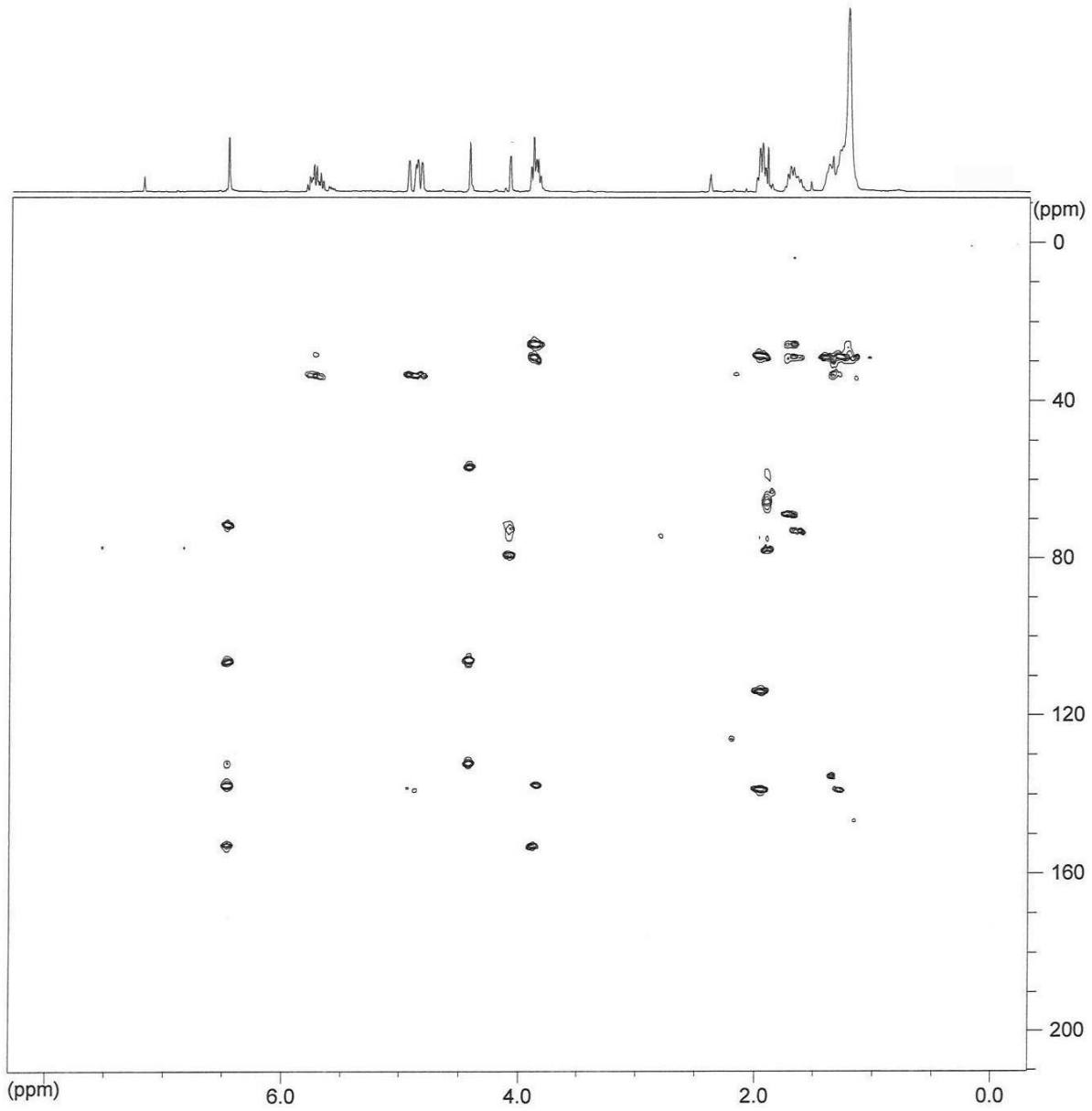
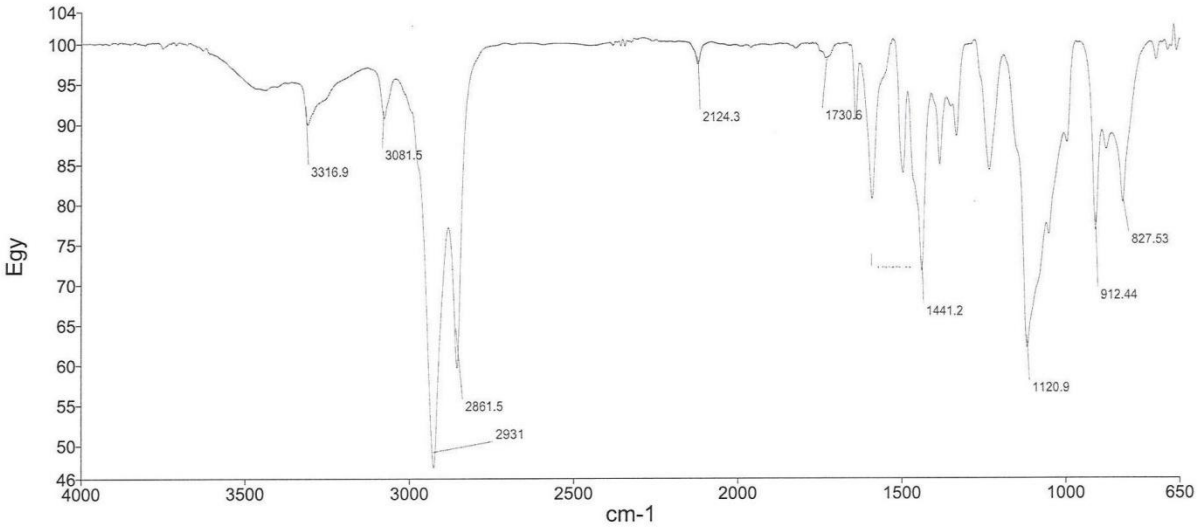
HMQC NMR spectrum



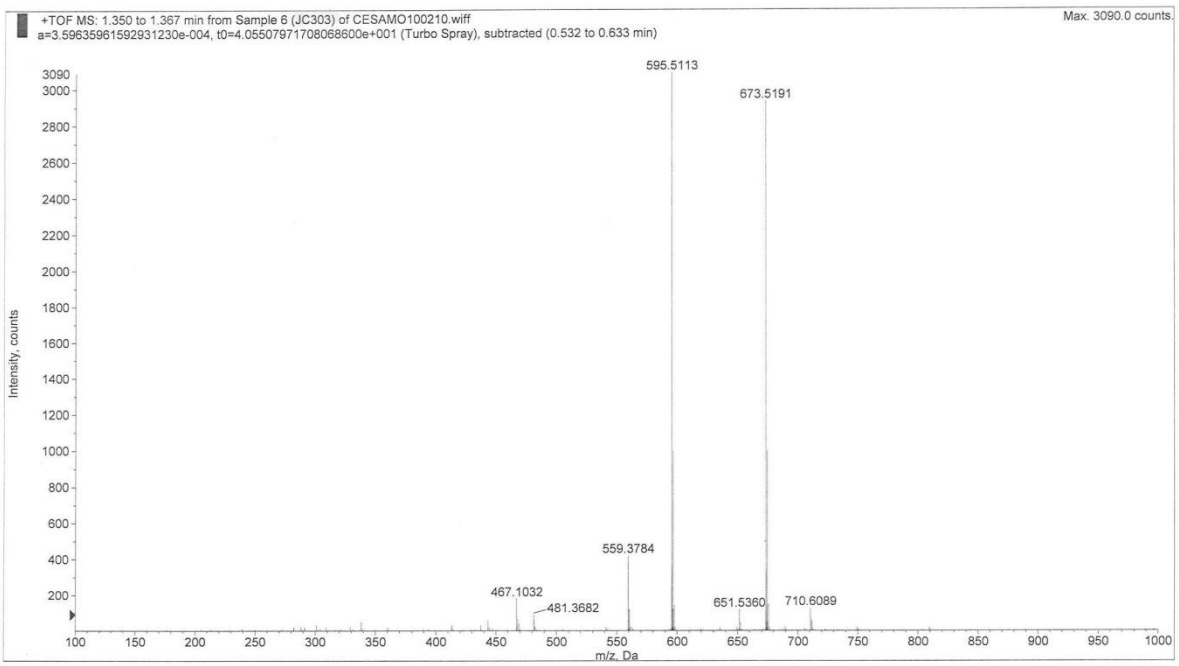
HMBC NMR spectrum



IR spectrum



Mass spectrum (1/2)



Elemental composition calculator

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Tolerance: +5.0000 ppm
Result type: Elemental
Max num of results: 100
Min DBE: -0.5000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAMO100210.wiff

	Elements	Min Number	Max Number
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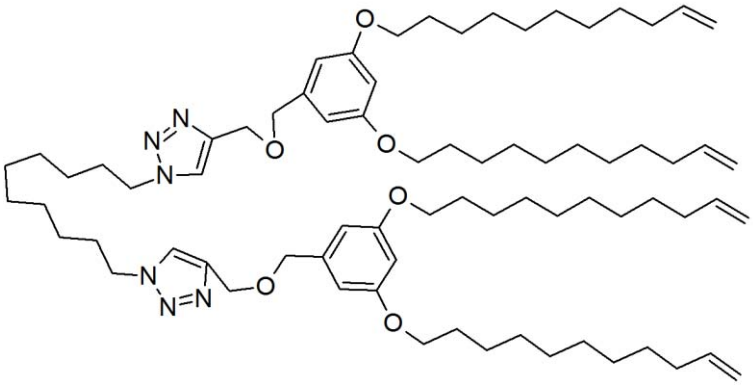
2	C	0	500
3	Cl	0	0
4	Cu	0	0
5	Fe	0	0
6	H	0	1000
7	I	0	0
8	K	0	0
9	N	0	0
10	Na	1	1
11	O	4	4
12	S	0	0
13	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C43 H70 O4 Na	673.5166	2.4675	3.6636	8.5

Synthesis of the G_1-tetra alkene dendrimer 8



1,10-diazidodecane **1** (0.19g, 0.85mmol, 1eq) and 1,3-bis(10-undecen-1-yloxy)-5-[(2-propyn-1-yloxy)methyl]benzene **4** (1.64g, 3.40mmol, 4eq) were dissolved in 20mL of dichloromethane. A solution of $CuSO_4.5H_2O$ (1.70g, 6.80mmol ,8eq) in 10mL of water was then added. The reaction mixture was energically stirred. An aqueous solution of sodium ascorbate (2.69g, 13.6mmol, 16eq) was then added dropwise. The medium was stirred at room temperature for one night. Dichloromethane was removed *in vacuo*. The aqueous layer was extracted two times with diethyl ether and the organic layer were mixed. The organic layer was then washed with an ammonia solution until the aqueous layer was colorless. The organic layer was then washed with water to neutrality. The organic layer was dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a yellow powder (0.99g, 0.83mmol) in 98% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.53 ppm (s, $H_{triazole}$, 2H); 6.50 ppm (d, H_{Ar}, ^4J = 1.9Hz, 4H); 6.38 ppm (t, H_{Ar}, ^4J = 1.9Hz, 2H); 5.80 ppm (m, -C*H*=CH_2, 4H); 5.04 to 4.90 ppm (m, -CH=CH_2, 8H); 4.67 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.52 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.32 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.92 ppm (t, -O-CH_2-CH_2-, ^3J = 6.5Hz, 8H); 2.06 ppm (m, -CH_2-CH=CH_2, 8H); 1.88ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.79 ppm (m, -O-CH_2-CH_2-, 8H); 1.50 to 1.25 ppm (m, -CH_2-, 60H)
^{13}C NMR ($CDCl_3$ 75.5MHz): 160.14 ppm (C_{ar}-O); 144.80 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.81 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 138.82 ppm (-*C*H=CH_2); 122.07 ($C_{triazole}$-H) ; 113.90 ppm (-CH=*C*H_2); 105.78 and 100.34 ppm (C_{ar}-H); 72.26 ppm (C_{Ar}-*C*H_2-O-CH_2-$C_{triazole}$); 67.69 ppm (-O-*C*H_2-CH_2-); 63.44 ppm (C_{Ar}-CH_2-O-*C*H_2-$C_{triazole}$); 49.96 ppm (-*C*H_2-$N_{triazole}$); 33.54, 29.99, 29.26, 29.16, 29.11, 29.02, 28.91, 28.86, 28.65, 28.61, 26.14 and 25.79 ppm (-*C*H_2-)
IR spectroscopy (cm-1) : 3143.2 ; 3081.5 ; 2934.8 (Car-H) ; 2857.6 (C-H) ; 1603.3 ; 1460.5 ; 1171 ; 1059.1
HRMS: calculated for $[M+Na]^+$, m/z = 1211.9161 ; found m/z = 1211.9216
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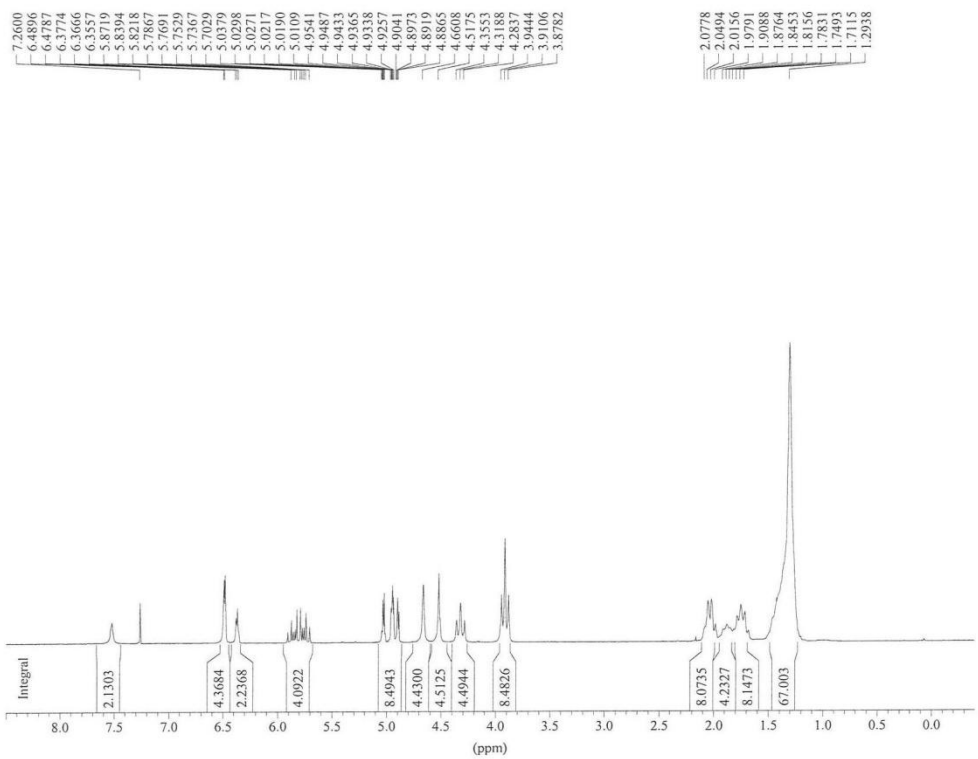
^{1}H NMR spectrum

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PROBHD    :  5 mm Multinuclear
SOLVENT   :  CDCl3
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SOLVENT   :  ?
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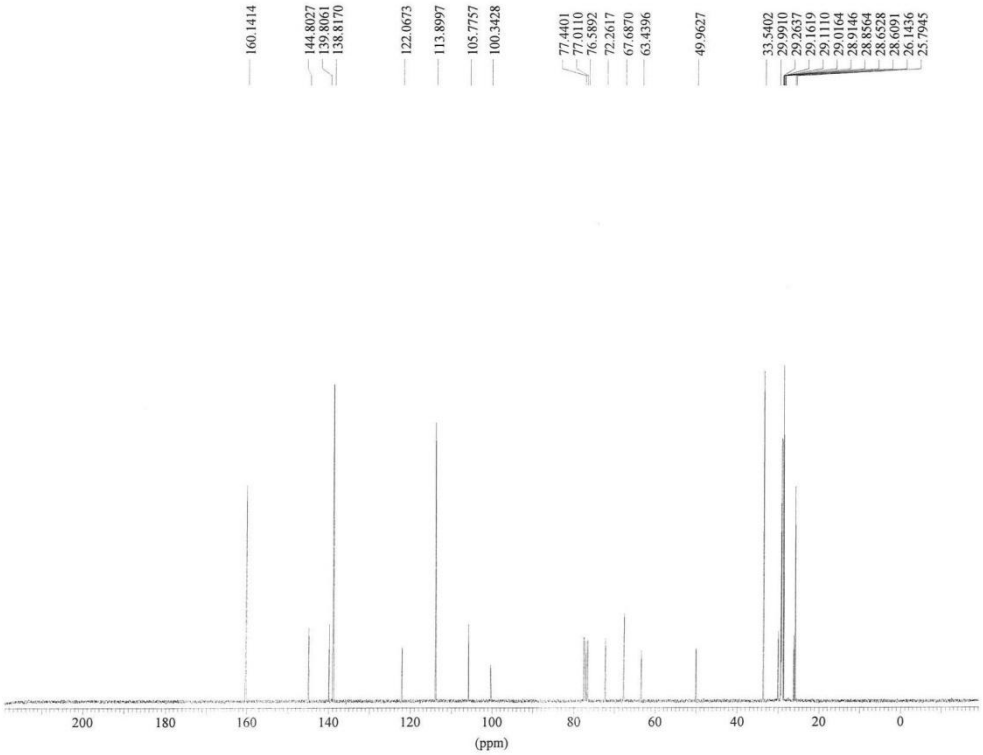
^{13}C NMR spectrum

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SI        :  32768
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SOLVENT   :  ?
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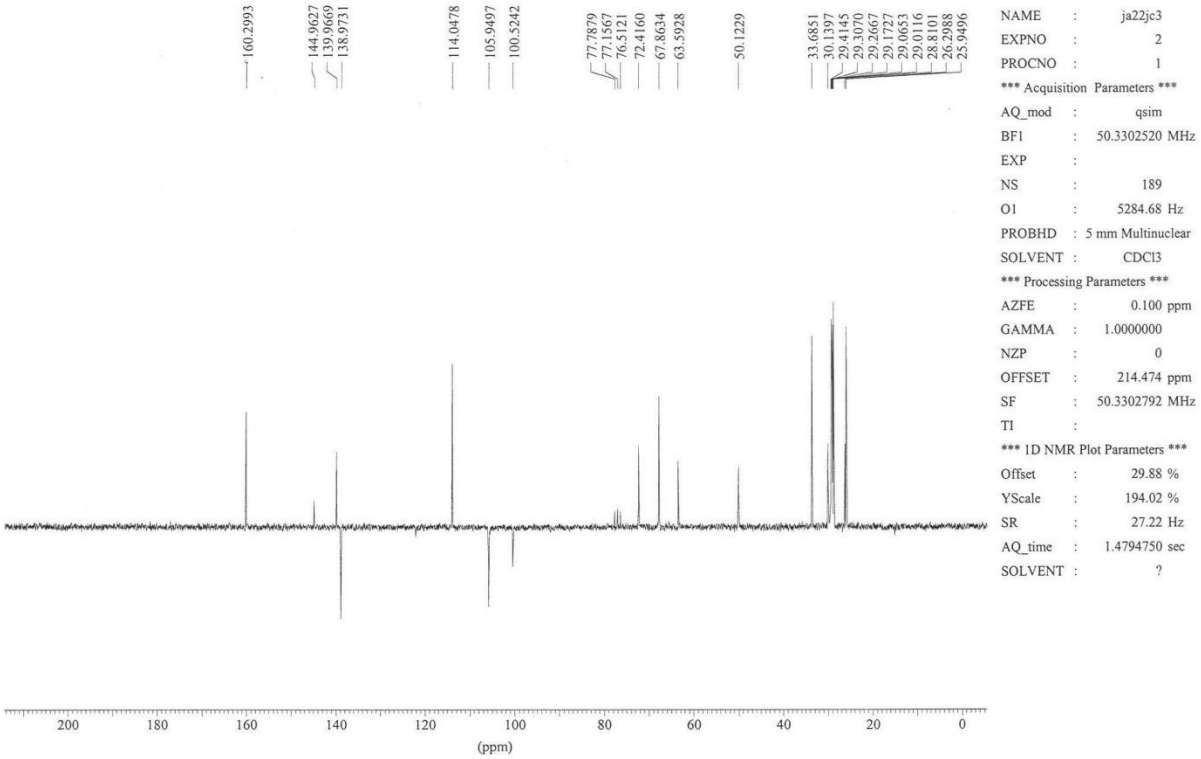
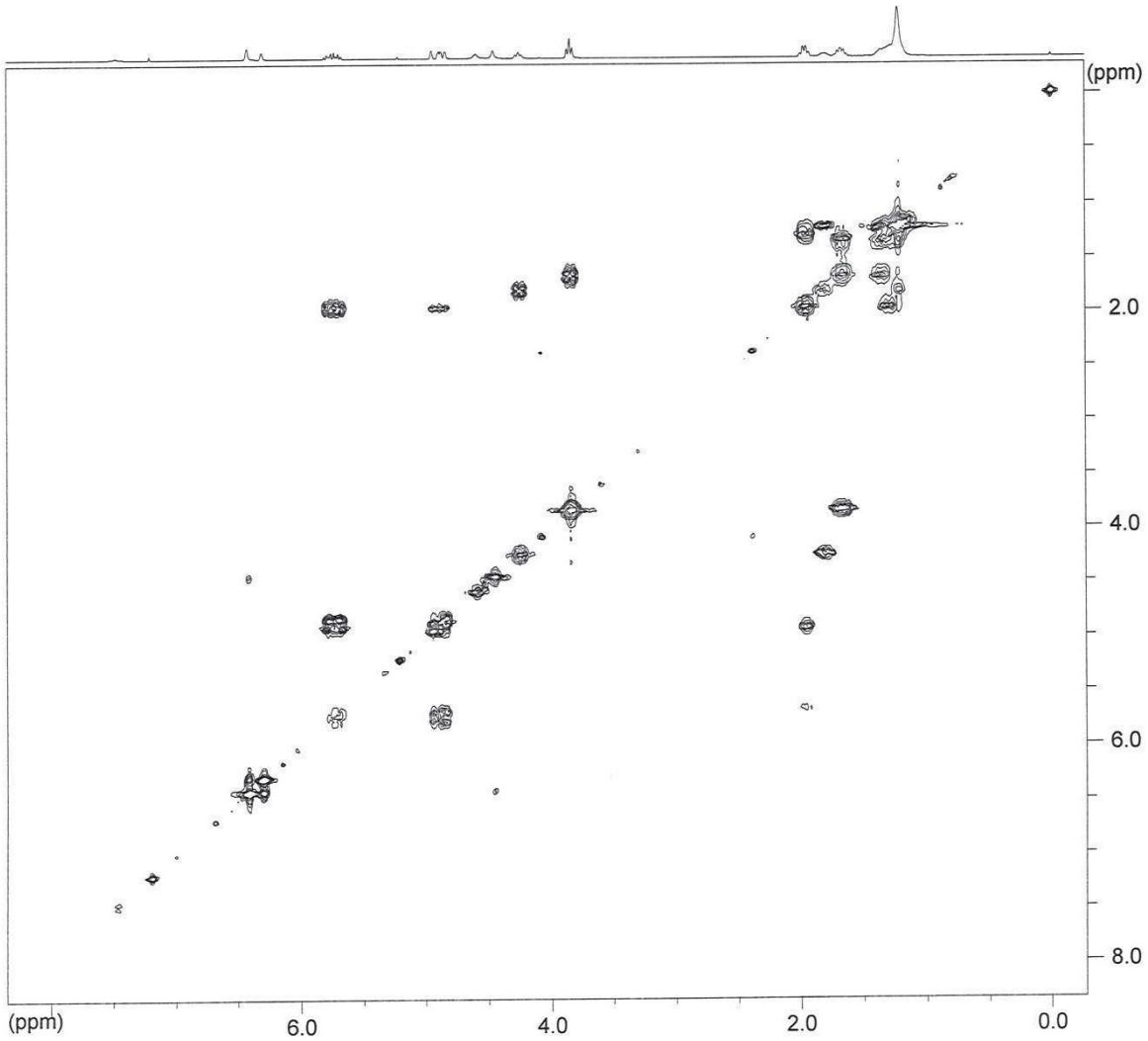
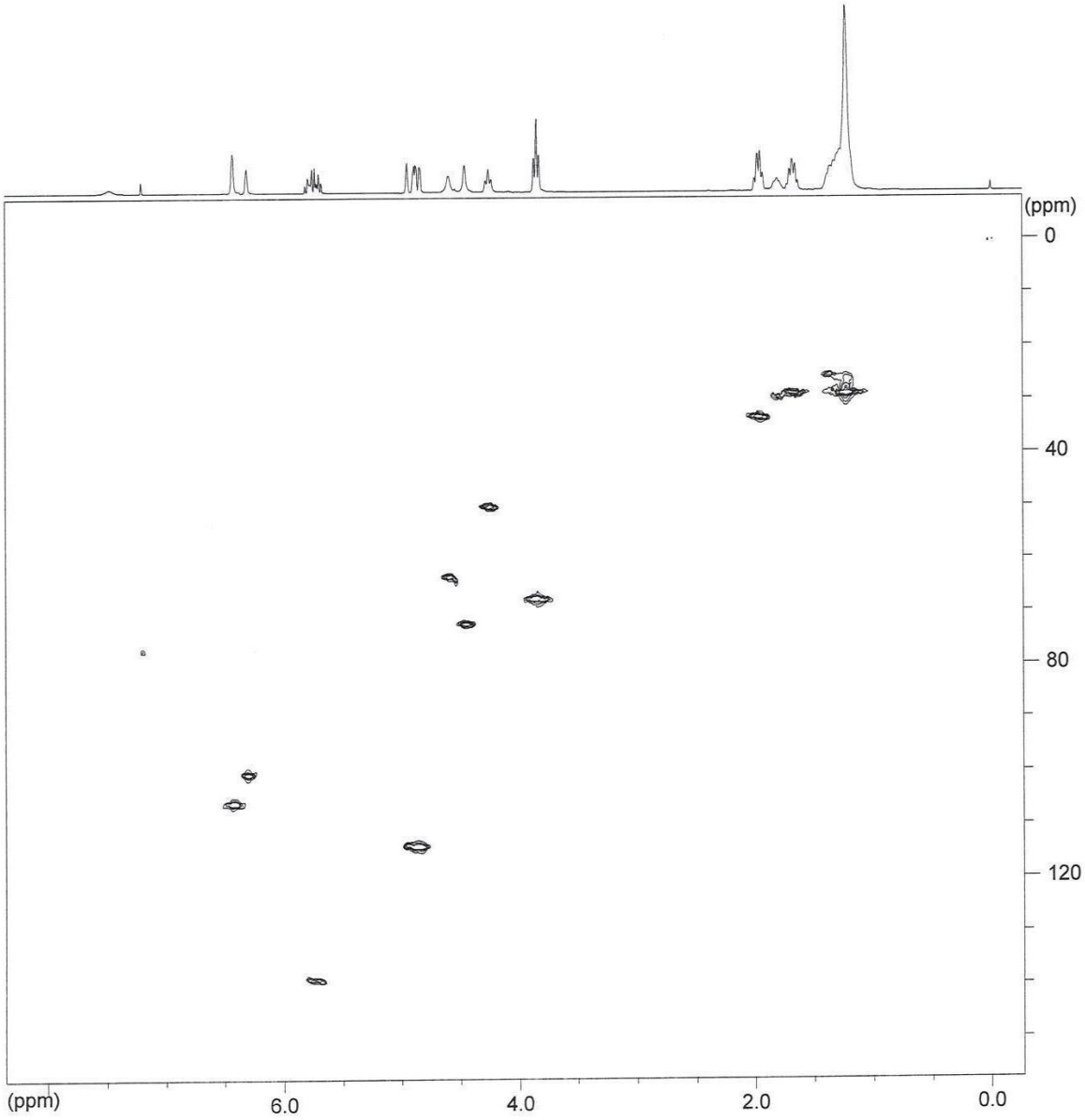
JMOD NMR spectrum



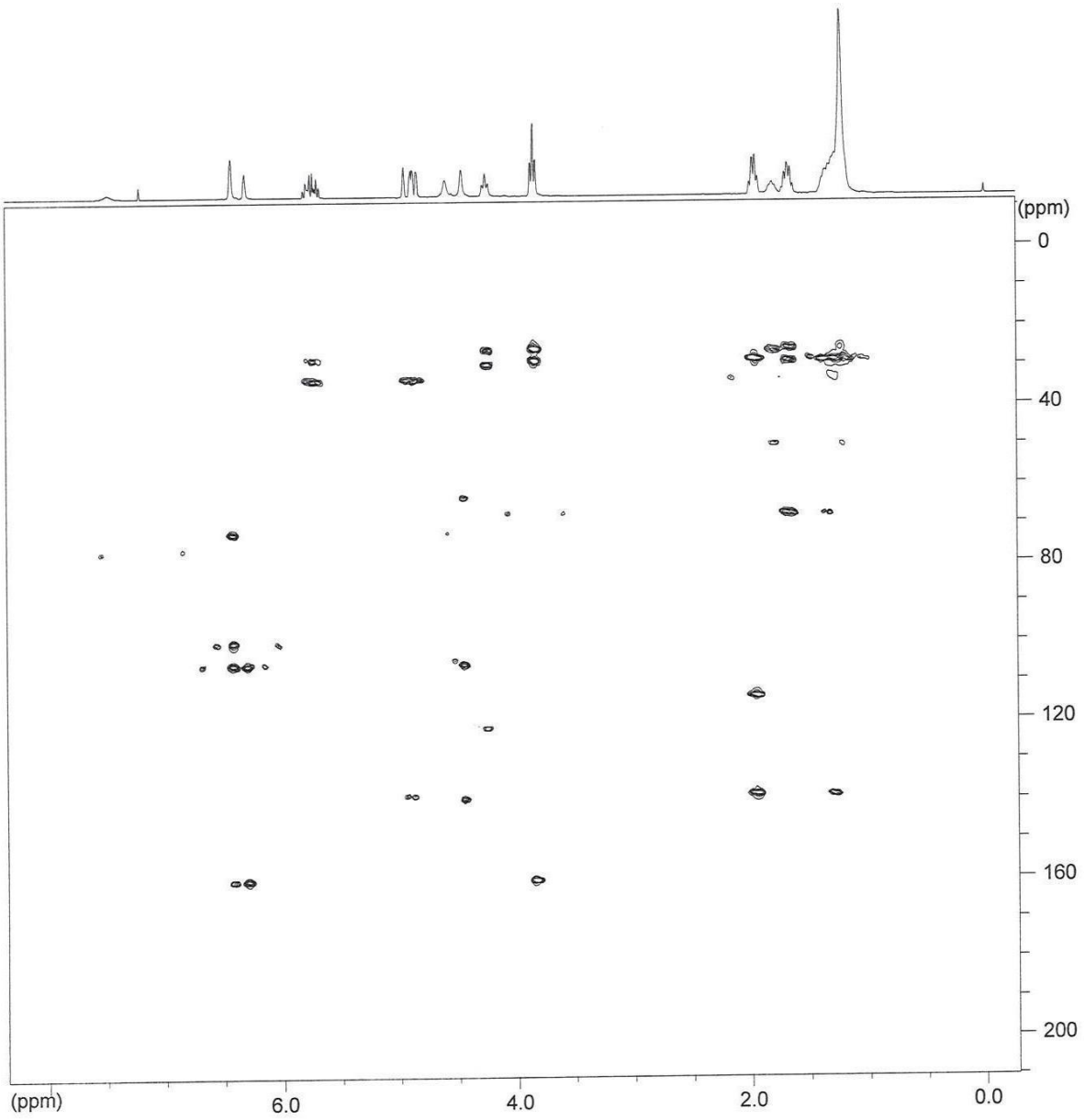
COSY NMR spectrum



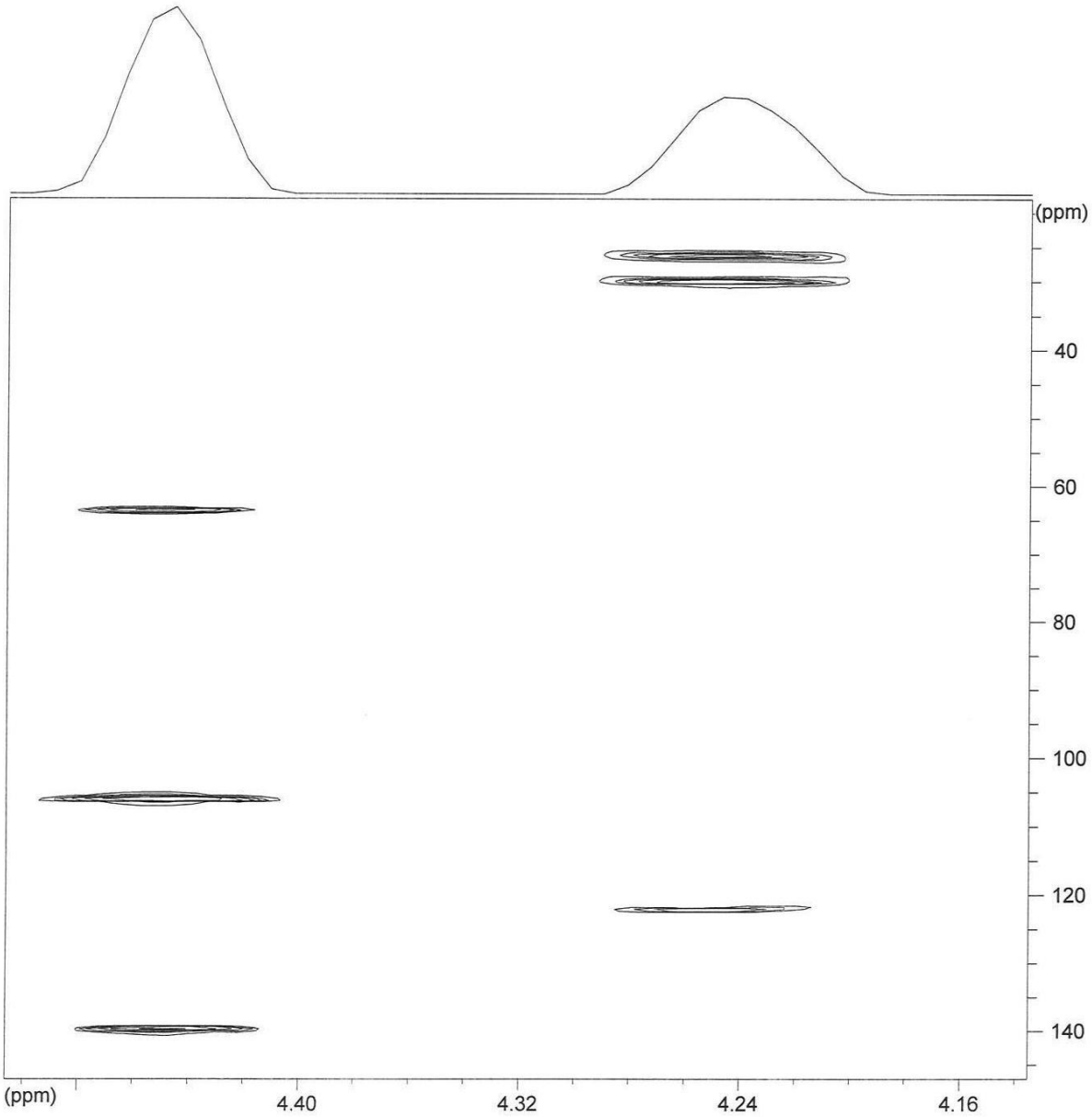
HMQC NMR spectrum



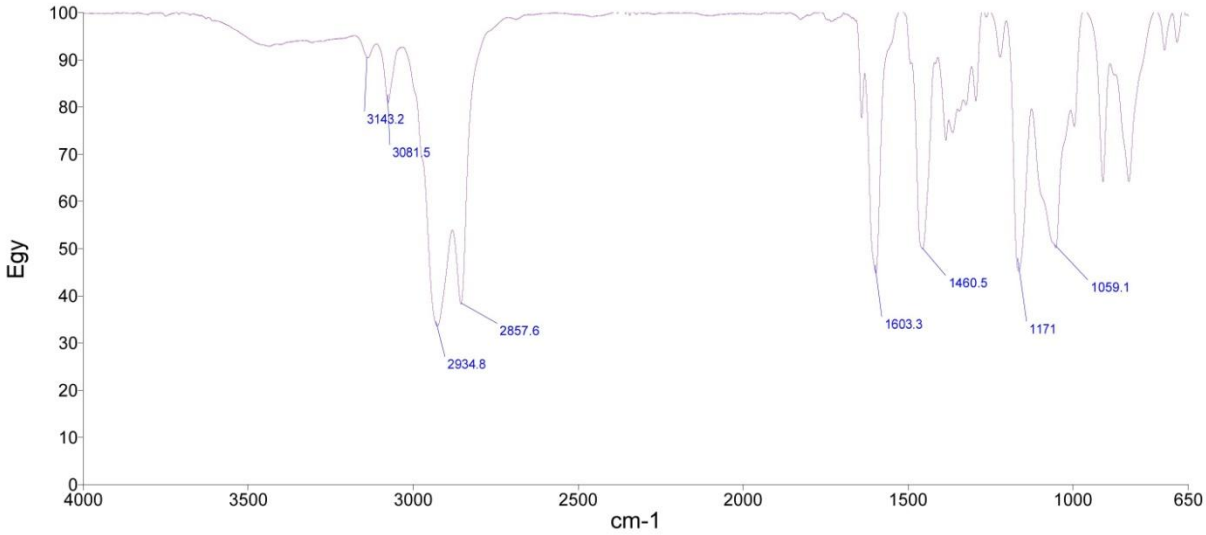
HMBC NMR spectrum



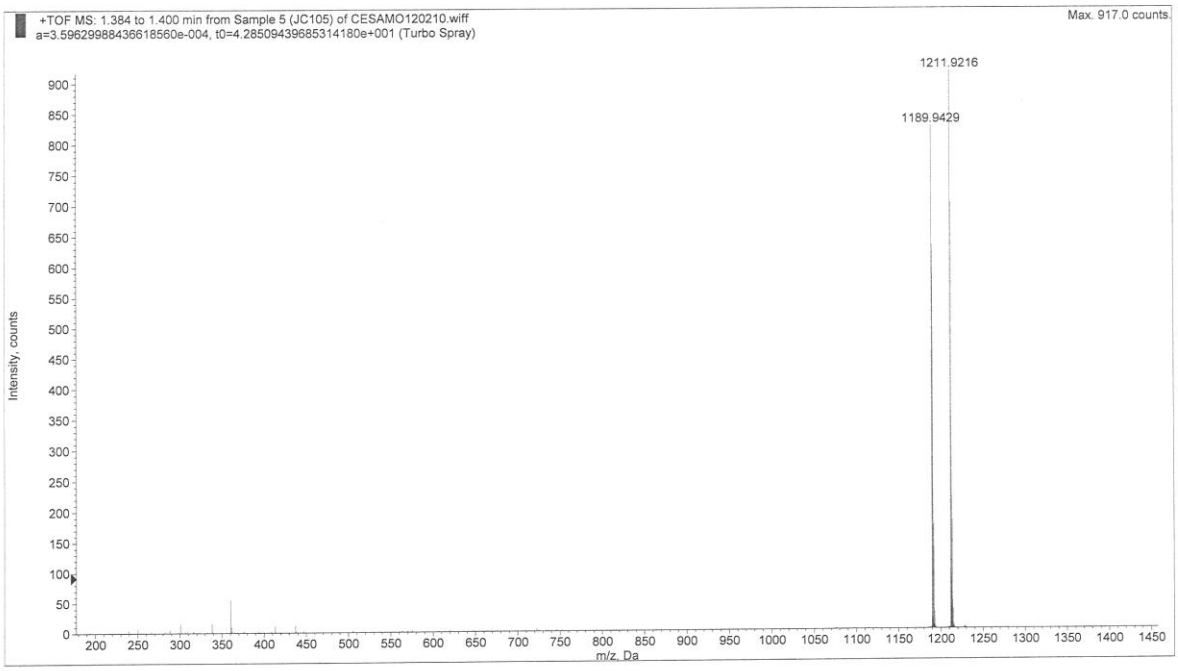
HMBC NMR spectrum (zoom)



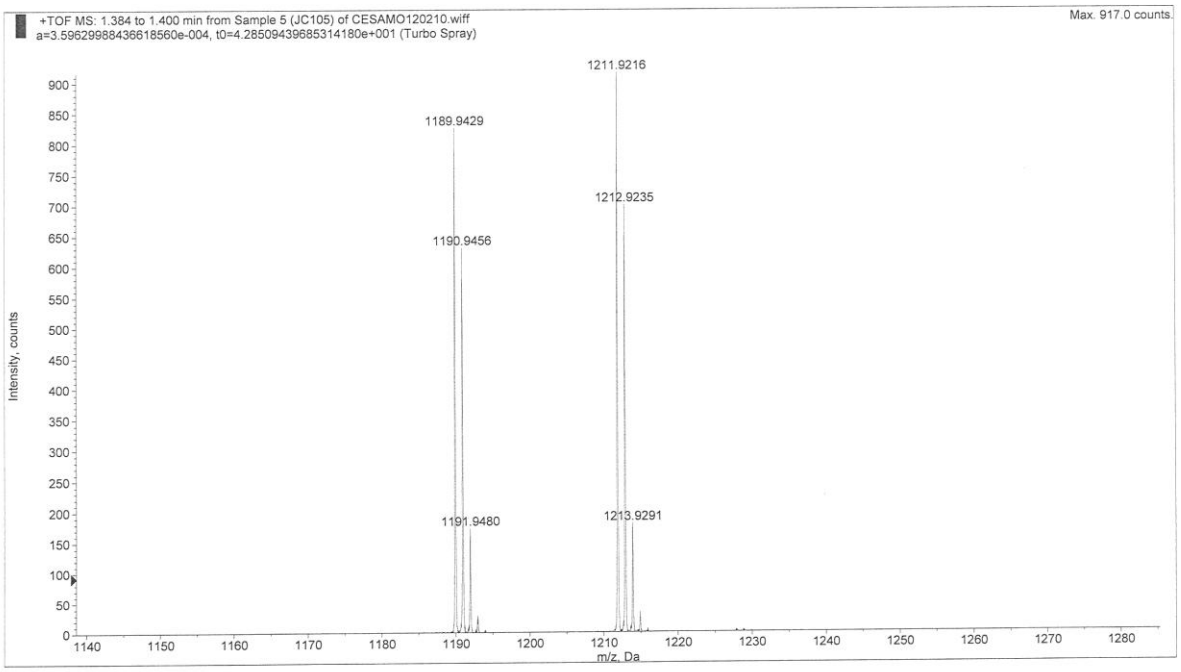
IR spectrum



Mass spectrum (1/3)



Mass spectrum (2/3)



Elemental composition calculator

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Result type: Elemental
Max num of results: 100
Min DBE: -0.5000 Max DBE: +100.0000
Electron state: OddAndEven
Num of charges: 1
Add water: N/A
Add proton: N/A
File Name: CESAMO120210.wiff

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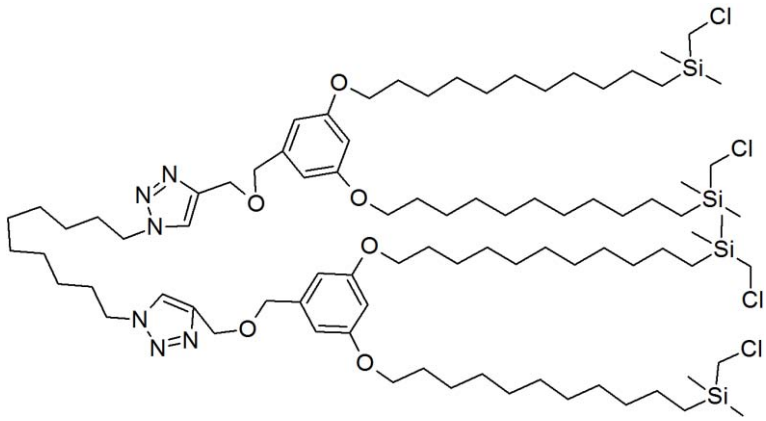
2	C	0	500
3	Cl	0	0
4	Cu	0	0
5	Fe	0	0
6	H	0	1000
7	I	0	0
8	K	0	0
9	N	6	6
10	Na	1	1
11	O	0	6
12	S	0	0
13	Si	0	0

	Formula	Calculated m/z (Da)	mDa Error	PPM Error	DBE
1	C74 H120 N6 O6 Na	1211.9161	5.4421	4.4905	17.5

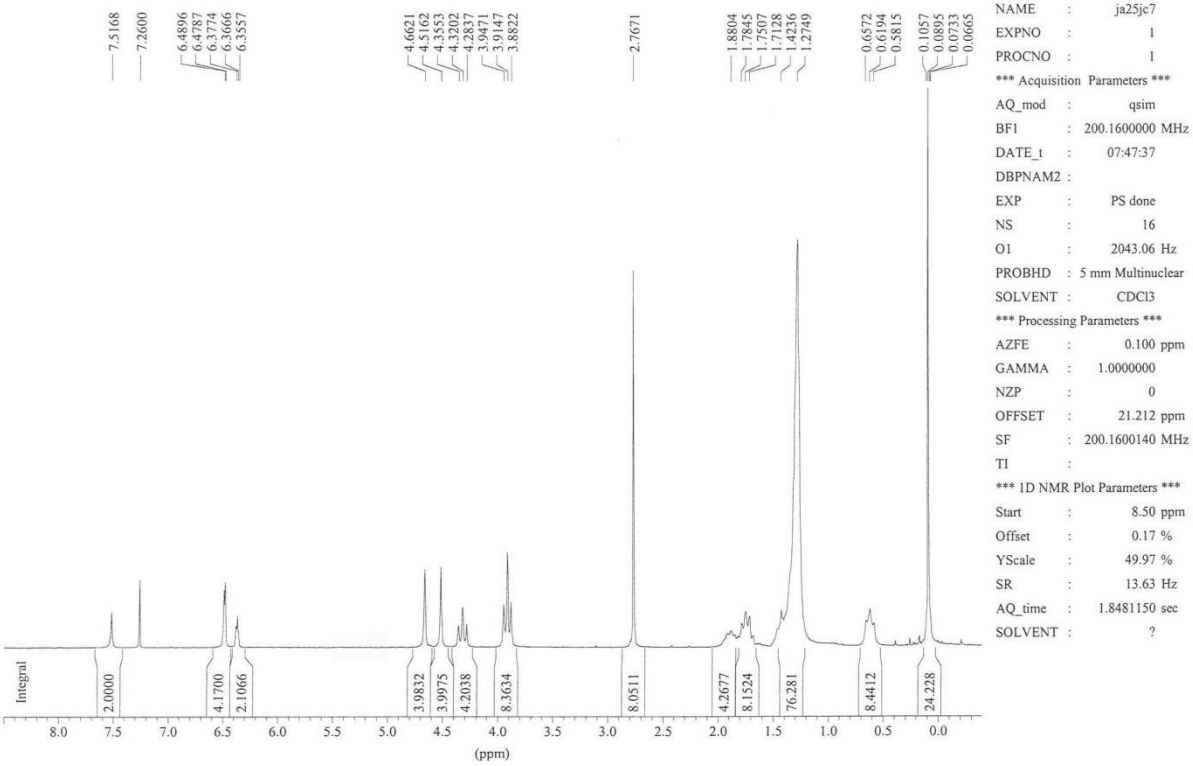
Synthesis of G_1-tetra chloro dendrimer 9



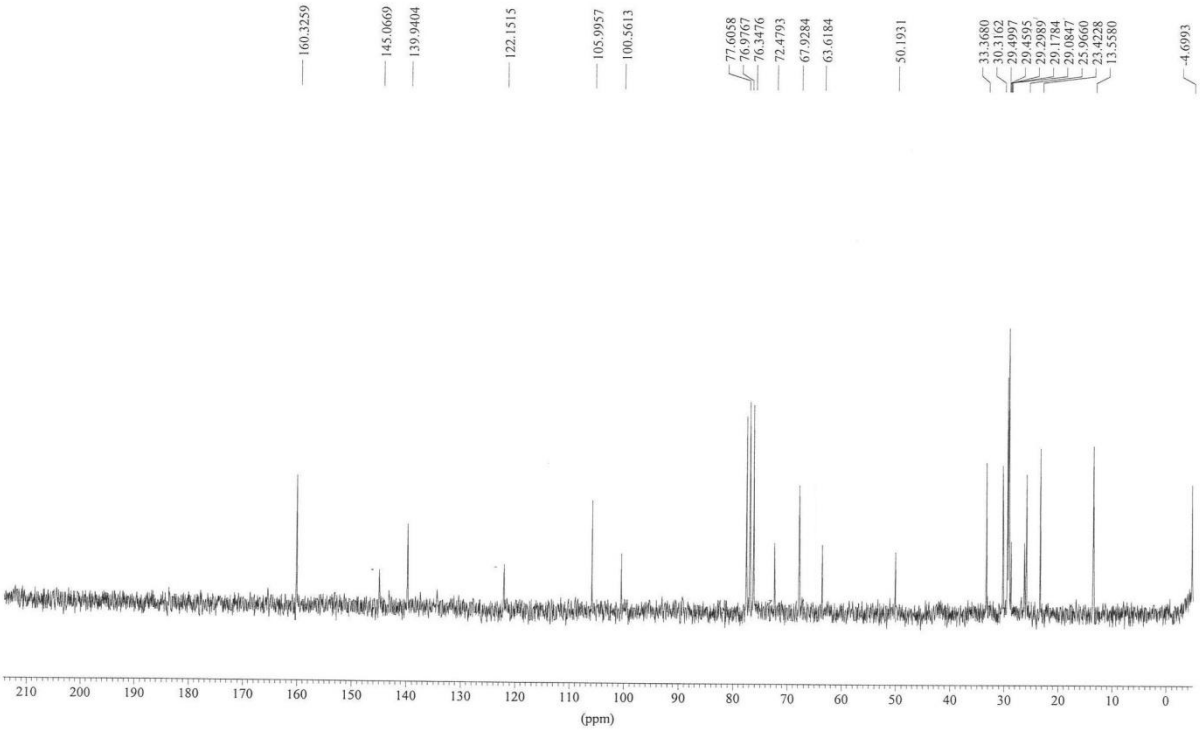
Dry G1-tetra alkene dendrimer **8** (0.75g, 0.63mmol, 1eq) was dissolved in 30mL distillated diethyl ether. In a glove box, chloromethyldimethylsilane (0.6mL, 5.07mmol, 8eq) and then Karstedt catalyst (10 drops) were added. The medium was stirred at room temperature for one night. The solvant and the excess silane were removed *in vacuo*. Dichloromethane was added and the medium was stirred in contact with the air. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a yellow waxy product (0.89g, 0.55mmol) in 87% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.52 ppm (s, $H_{triazole}$, 2H); 6.48 ppm (d, H_{Ar}, ^4J = 2.2Hz, 4H); 6.37 ppm (t, H_{Ar}, ^4J = 2.2Hz, 2H); 4.66 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.52 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.32 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.91 ppm (t, -O-CH_2-CH_2-, ^3J = 6.5Hz, 8H); 2.77 ppm (s, Si-CH_2-Cl, 8H); 1.88 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.75 ppm (m, -O-CH_2-CH_2-, 8H); 1.50 to 1.25 ppm (m, -CH_2-, 76H) ; 0.62 ppm (t, -CH_2-CH_2-Si, ^3J = 7.6Hz, 8H) ; 0.07 ppm (s, Si-CH_3, 24H)
JMOD NMR ($CDCl_3$ 50.3MHz): 160.34 ppm (C_{ar}-O); 145.07 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.94 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.15 ppm ($C_{triazole}$-H) ; 106.02 and 100.59 ppm (C_{ar}-H); 72.51 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 67.96 ppm (-O-CH_2-CH_2-); 63.62 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 50.24 ppm (-CH_2-$N_{triazole}$); 33.38 ppm (-CH_2-) ; 30.37 ppm (-Si-CH_2-Cl) ; 30.18, 29.52, 29.45, 29.32, 29.20, 29.11, 28.80, 26.35, 25.98 and 23.44 ppm (-CH_2-) ; 13.57 (-CH_2-CH_2-Si) ; -4.67 ppm (Si-CH_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 4.02 ppm
Maldi-Tof mass spectrometry $[M+H]^+$ m/z = 1622.66 ; $[M+Na]^+$ m/z = 1645.63

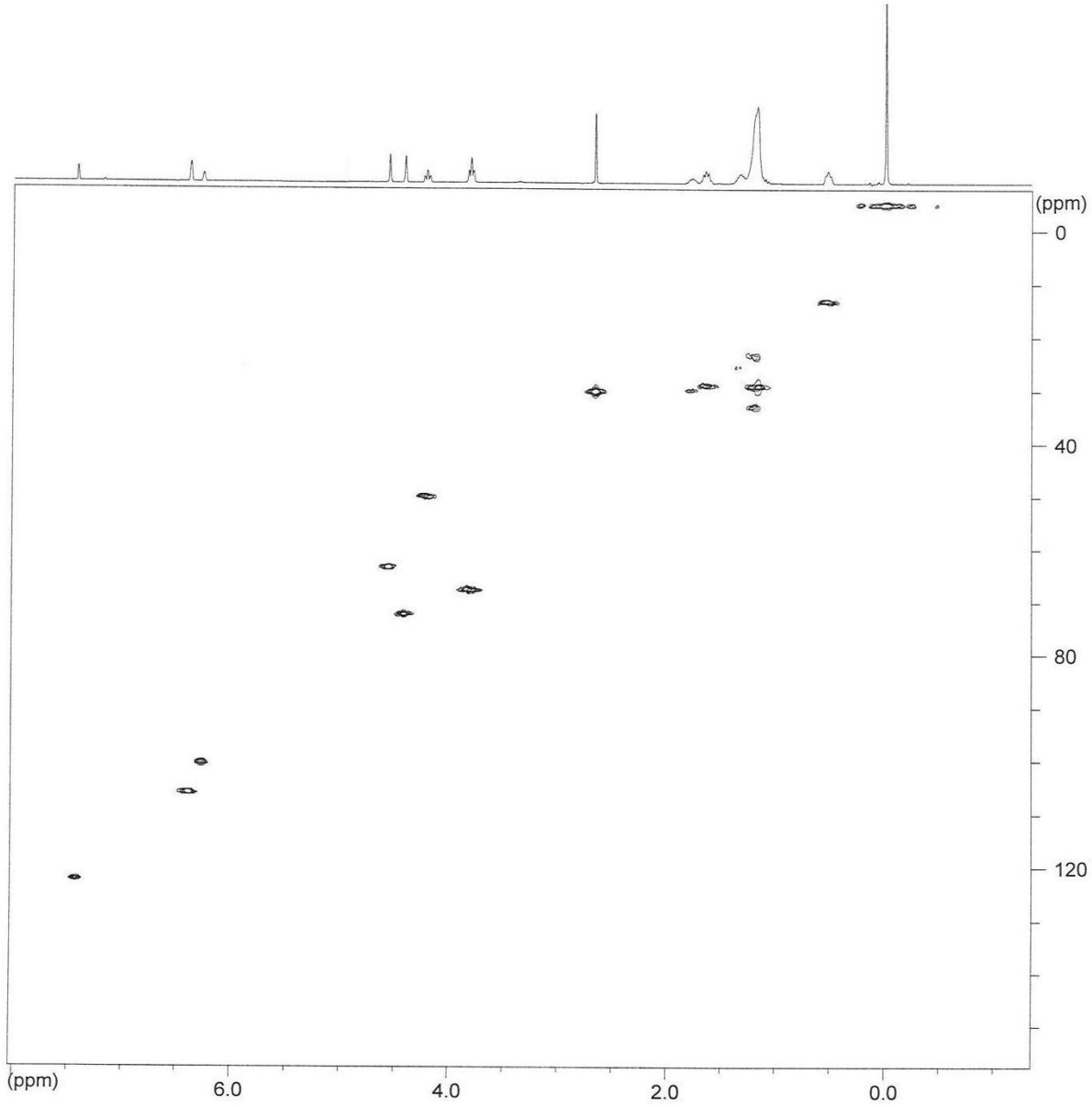
^{1}H NMR spectrum



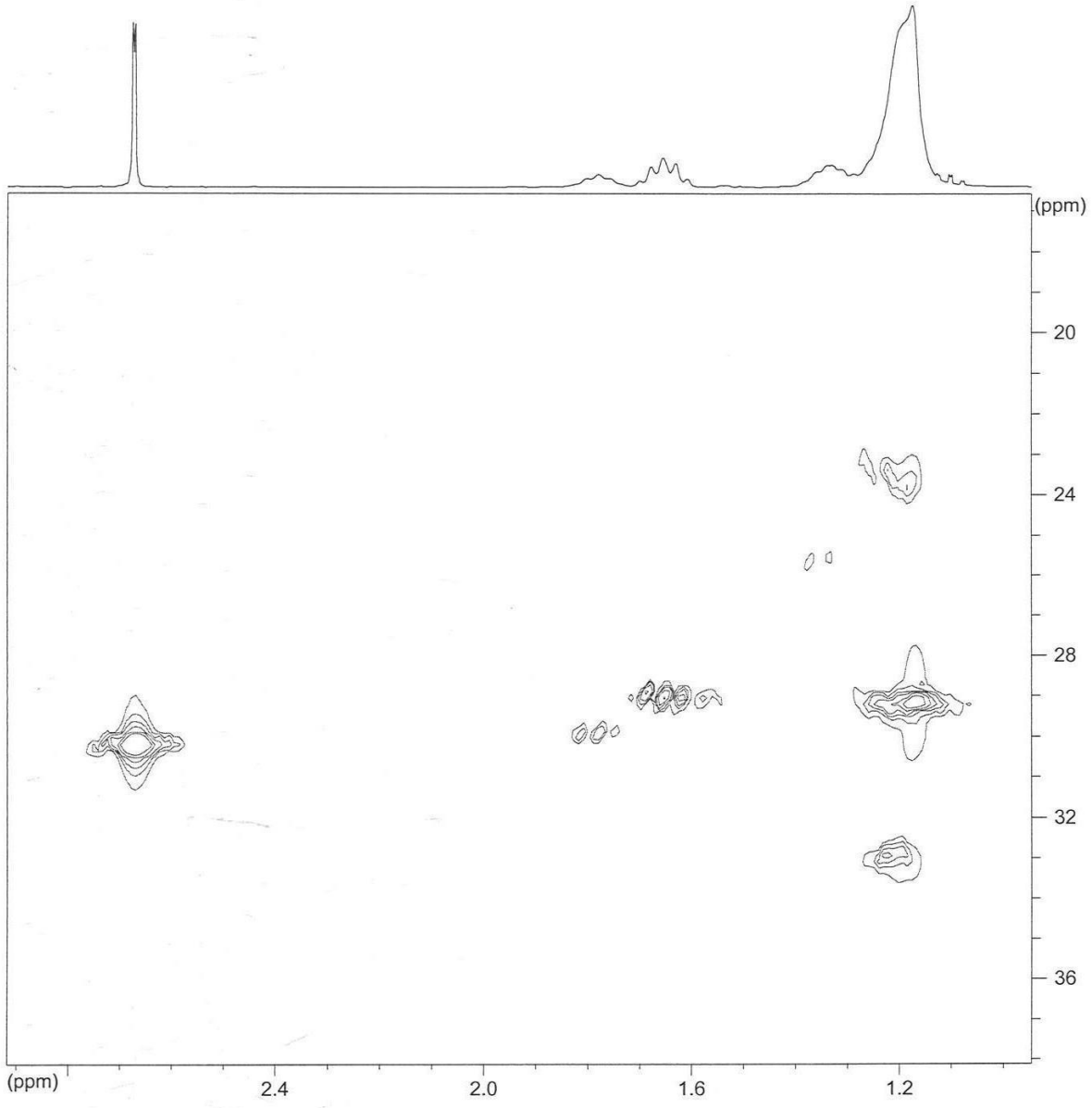
^{13}C NMR spectrum



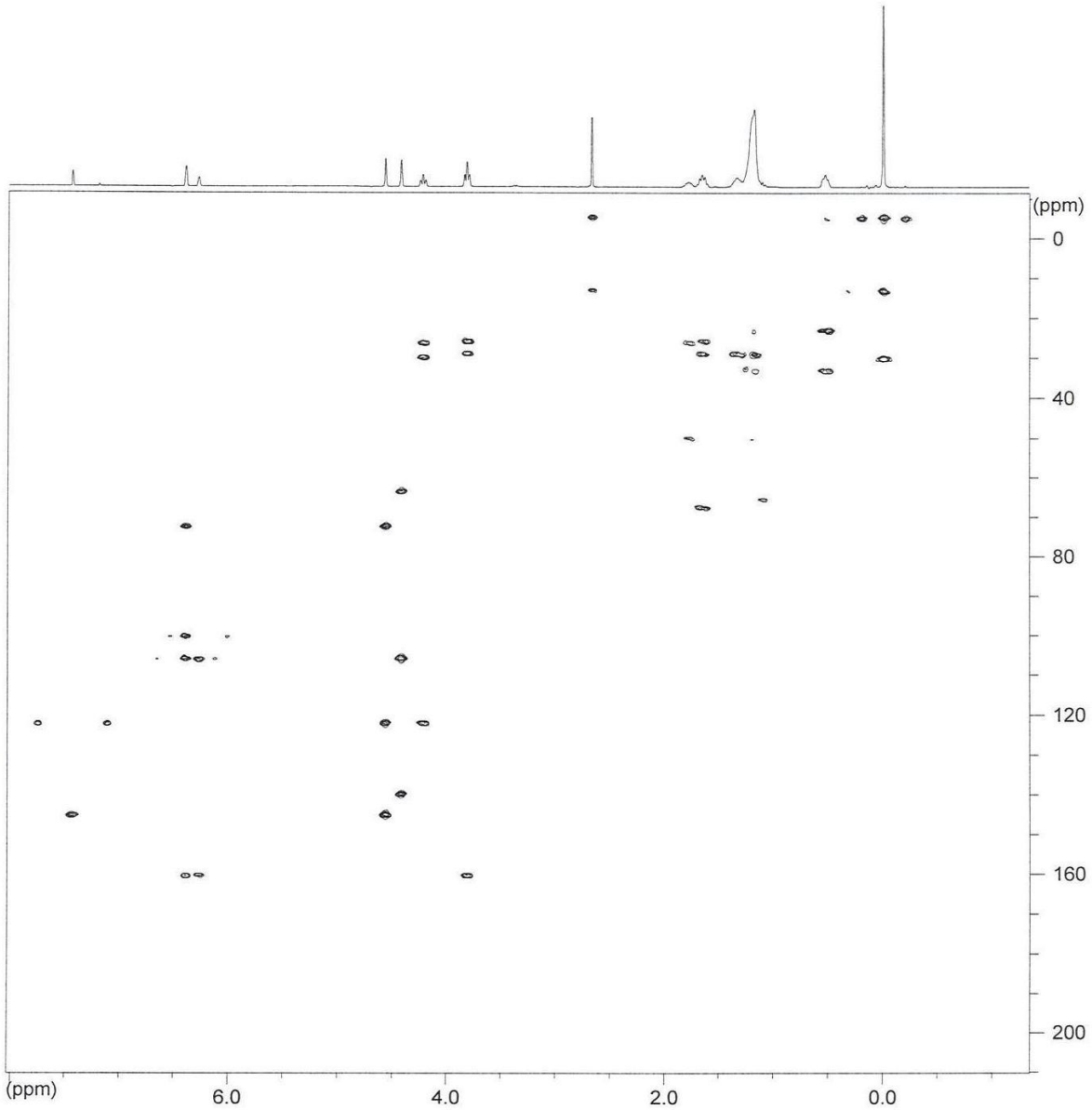
HMQC NMR spectrum



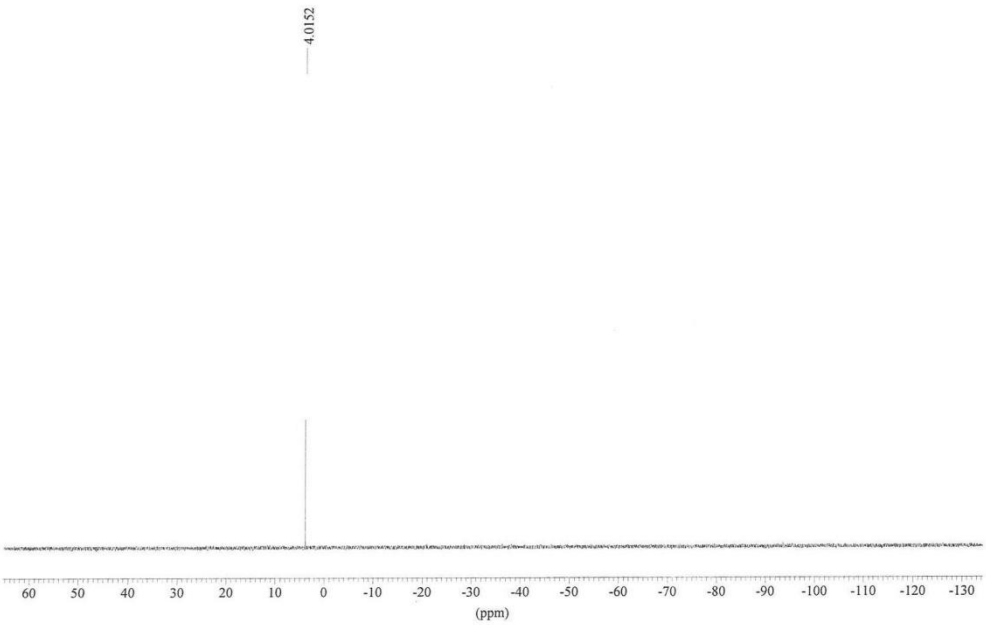
HMQC NMR spectrum (zoom)



HMBC NMR spectrum



^{29}Si NMR spectrum



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SI	:	32768
WDW	:	EM
*** 1D NMR Plot Parameters ***		
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Hz_cm	:	572.34
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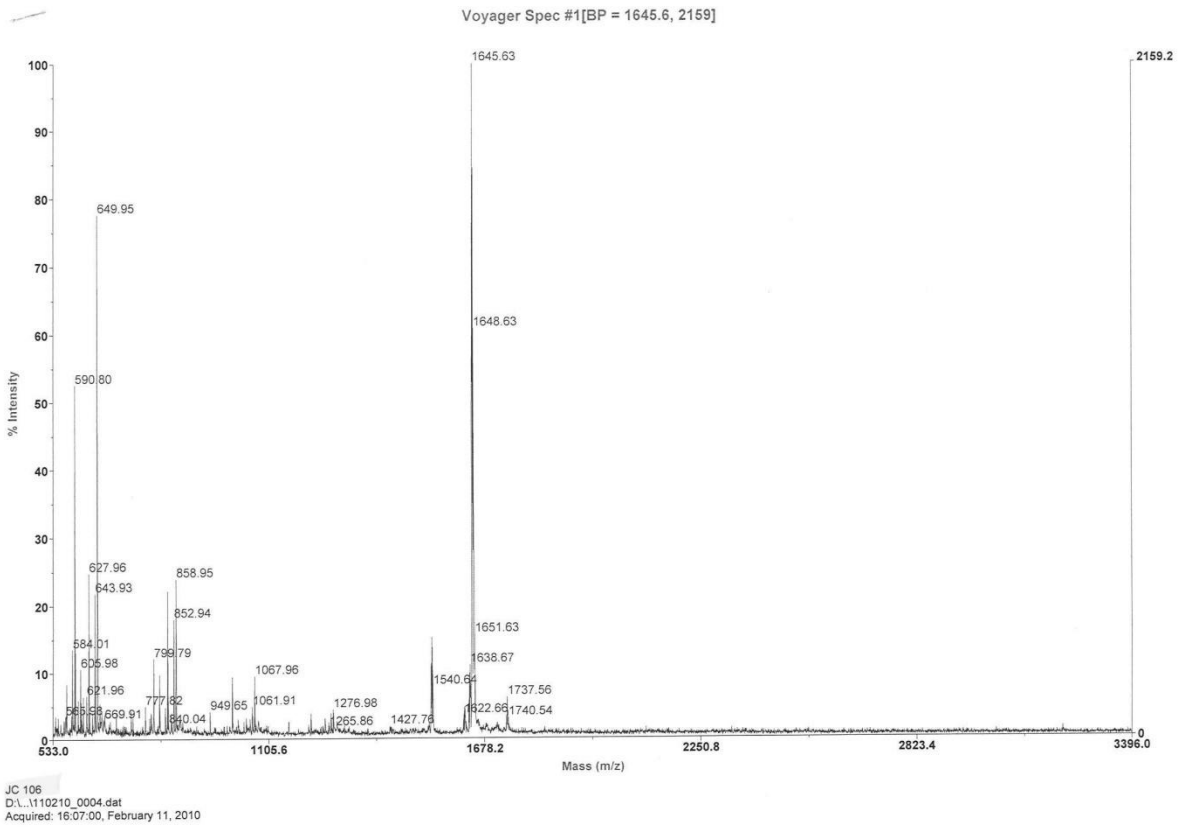
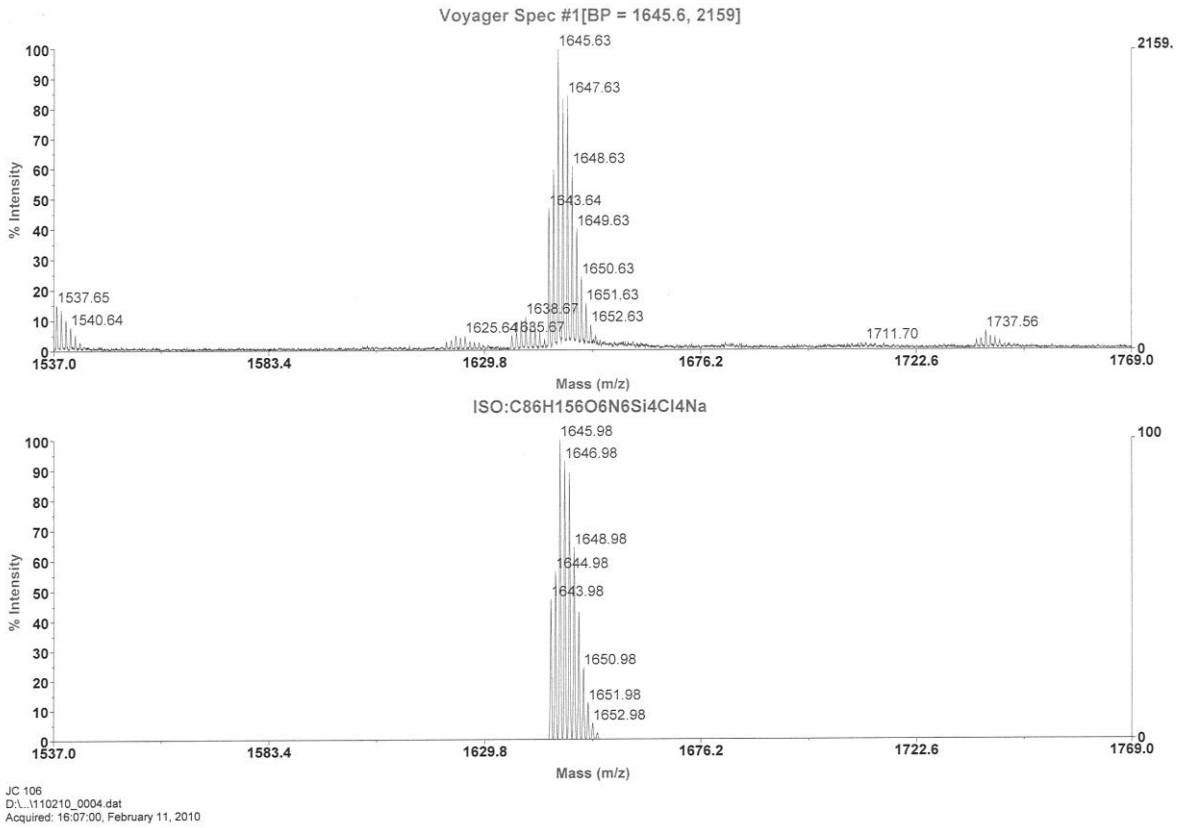
VENT	:	?

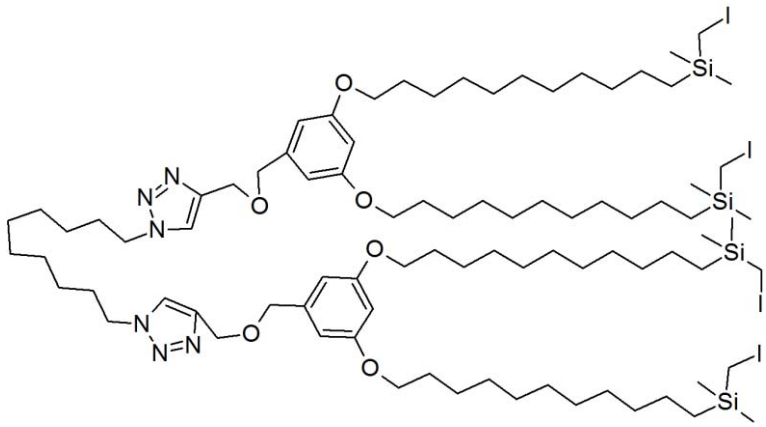
MALDI-TOF Mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



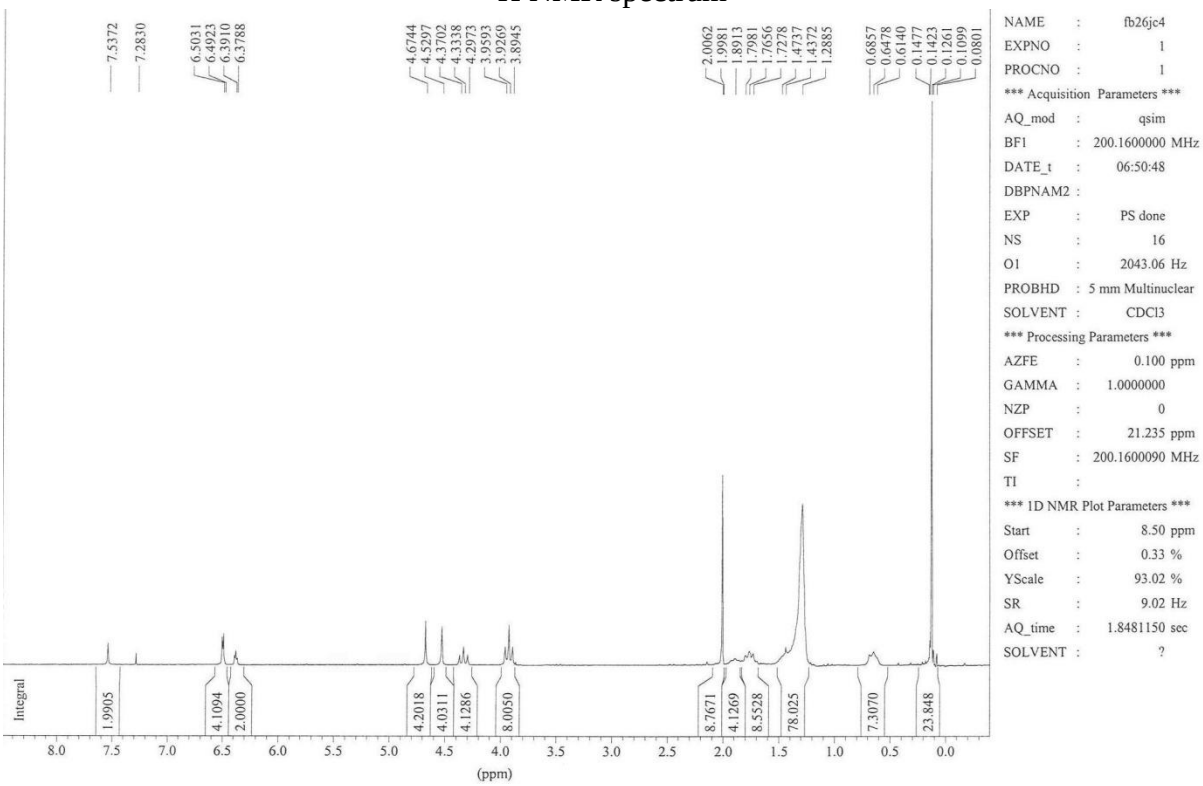
Synthesis of G_1-tetra iodo dendrimer 10



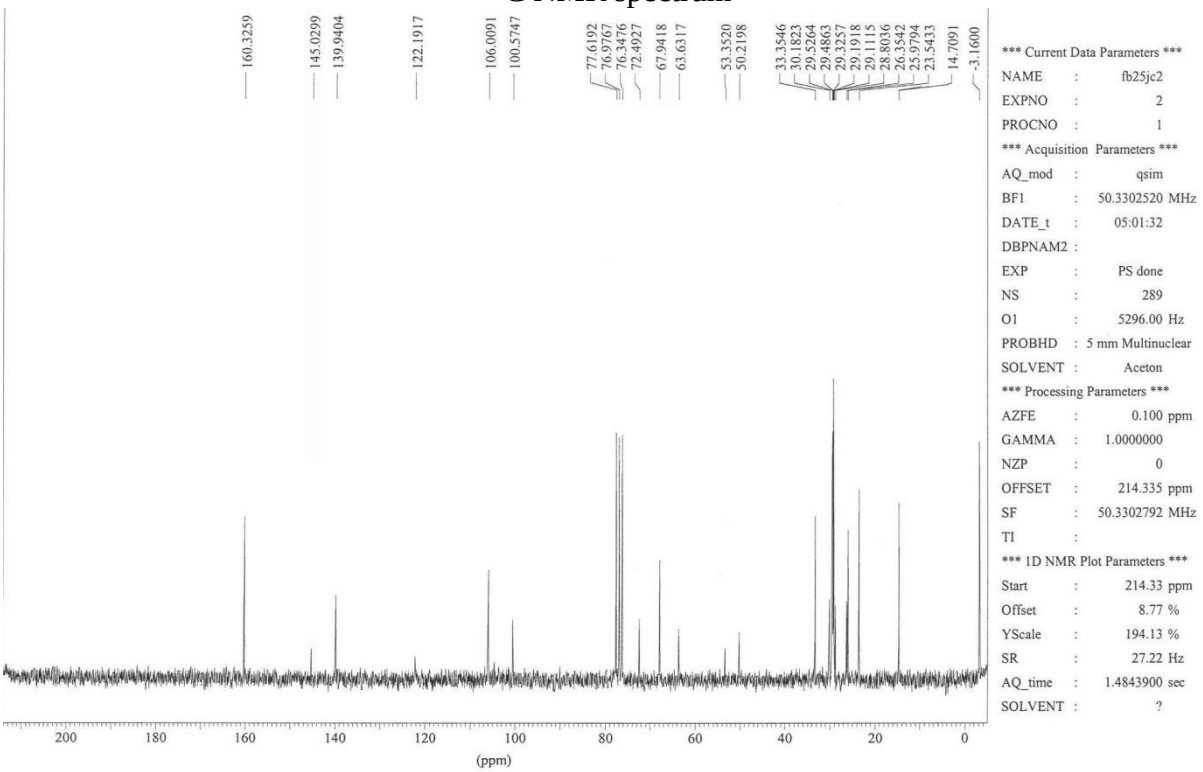
To a solution of G_1-tetra chloro dendrimer **9** (0.65g, 0.40mmol, 1eq) in 50mL butanone was added NaI (0.48g, 3.20mmol, 8eq). The medium was stirred under reflux for 5h. Solvent was removed *in vacuo*. Dichloromethane was added. The medium was filtered. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a yellow waxy product (0.81g, mmol) in 98% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.51 ppm (s, $H_{triazole}$, 2H); 6.47 ppm (d, H_{Ar}, ^4J = 2.2Hz, 4H); 6.37 ppm (t, H_{Ar}, ^4J = 2.3Hz, 2H); 4.64 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.50 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.30 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.90 ppm (t, -O-CH_2-CH_2-, ^3J = 6.5Hz, 8H); 1.98 ppm (s, Si-CH_2-I, 8H); 1.86 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.74 ppm (m, -O-CH_2-CH_2-, 8H); 1.50 to 1.25 ppm (m, -CH_2-, 76H) ; 0.62 ppm (t, -CH_2-CH_2-Si, ^3J = 7.6Hz, 8H) ; 0.10 ppm (s, Si-CH_3, 24H)
JMOD NMR ($CDCl_3$ 50.3MHz): 160.31 ppm (C_{ar}-O); 145.03 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.94 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.19 ppm ($C_{triazole}$-H) ; 106.00 and 100.56 ppm (C_{ar}-H); 72.48 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 67.93 ppm (-O-CH_2-CH_2-); 63.62 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 50.20 ppm (-CH_2-$N_{triazole}$); 33.35, 30.18, 29.52, 29.48, 29.45, 29.32, 29.20, 29.11, 28.80, 26.34, 25.98 and 23.55 ppm (-CH_2-); 14.71 (-CH_2-CH_2-Si) ; -3.13 ppm (Si-CH_3); -13.05ppm (Si-CH_2-I)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 5.12 ppm
Maldi-Tof mass spectrometry $[M+H]^+$ m/z = 1989.24 ; $[M+Na]^+$ m/z = 2011.23

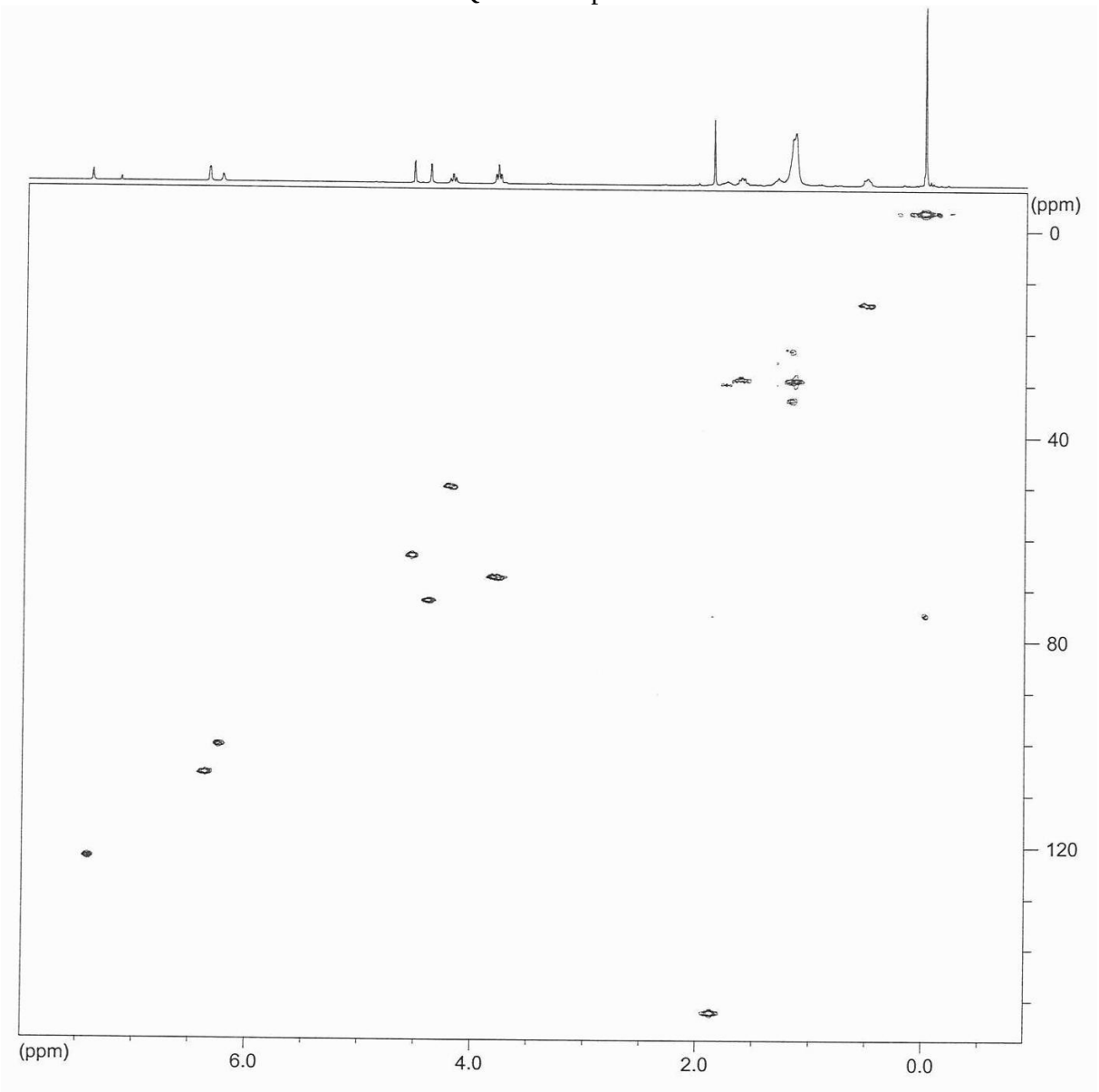
^{1}H NMR spectrum



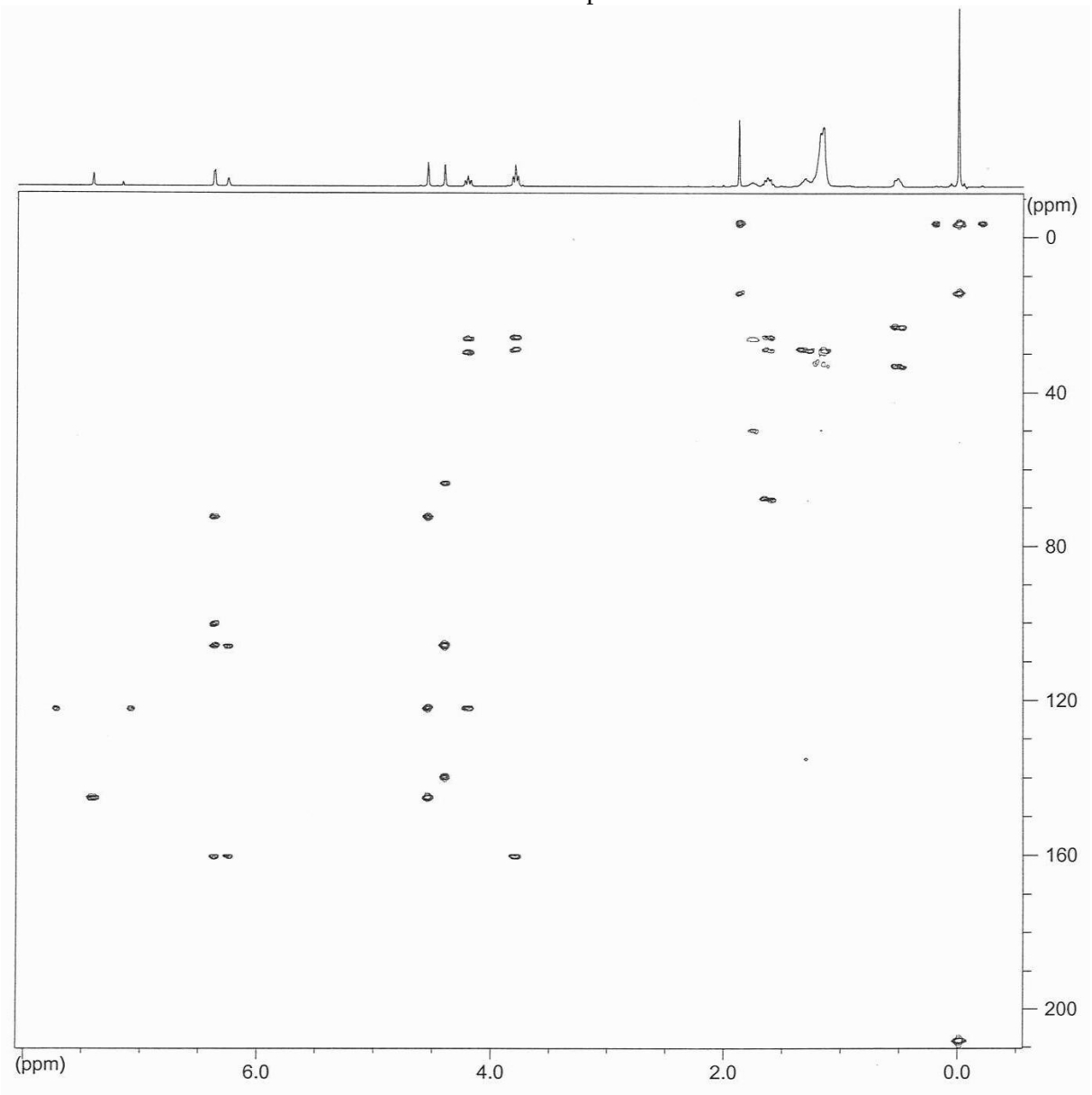
^{13}C NMR spectrum



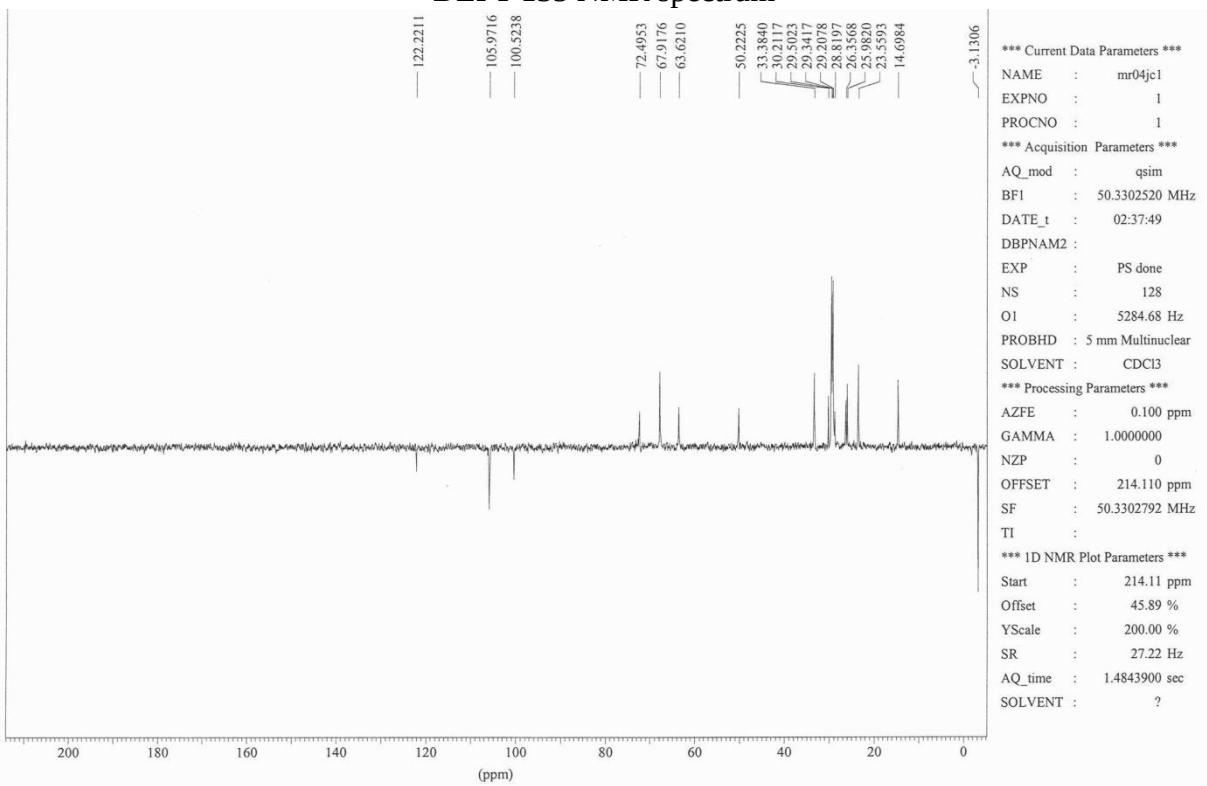
HMQC NMR spectrum



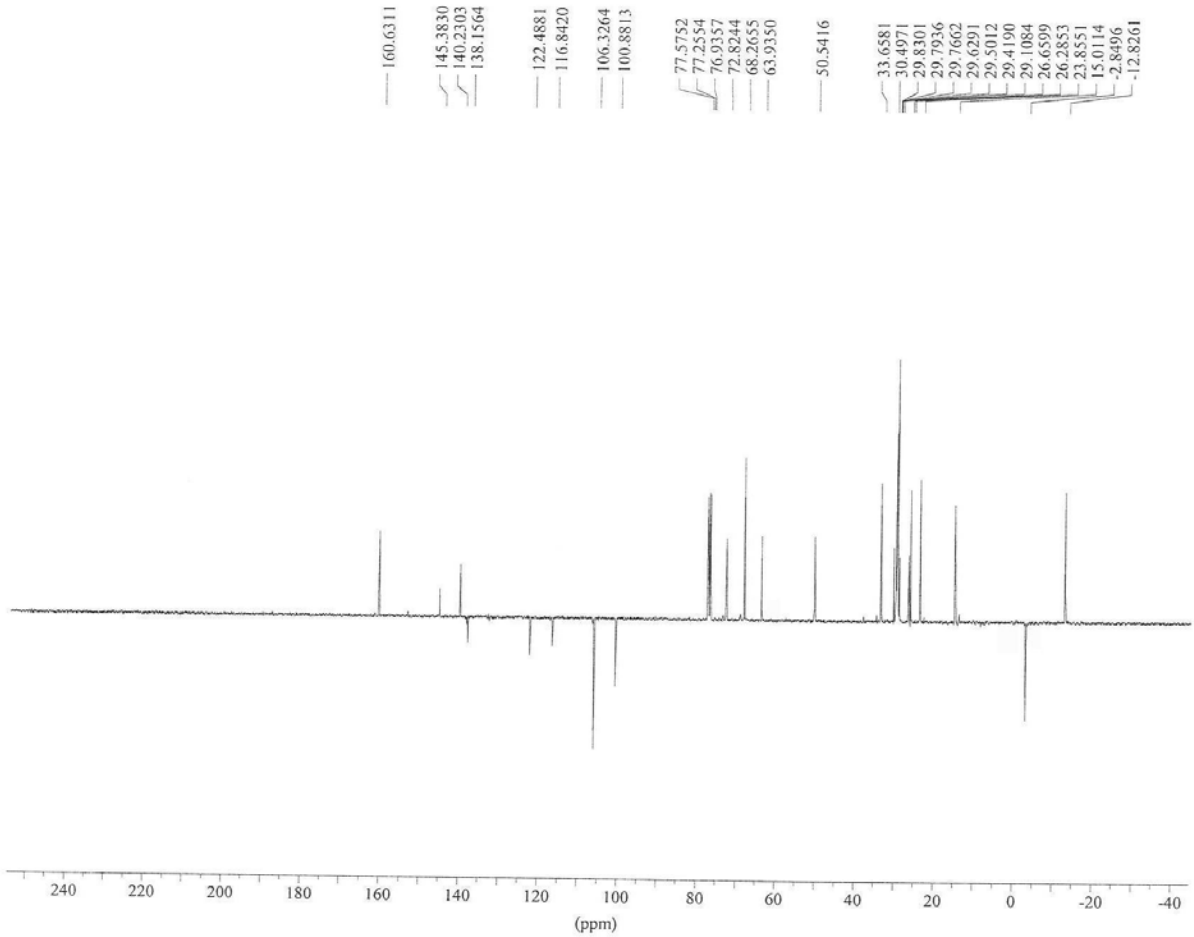
HMBC NMR spectrum



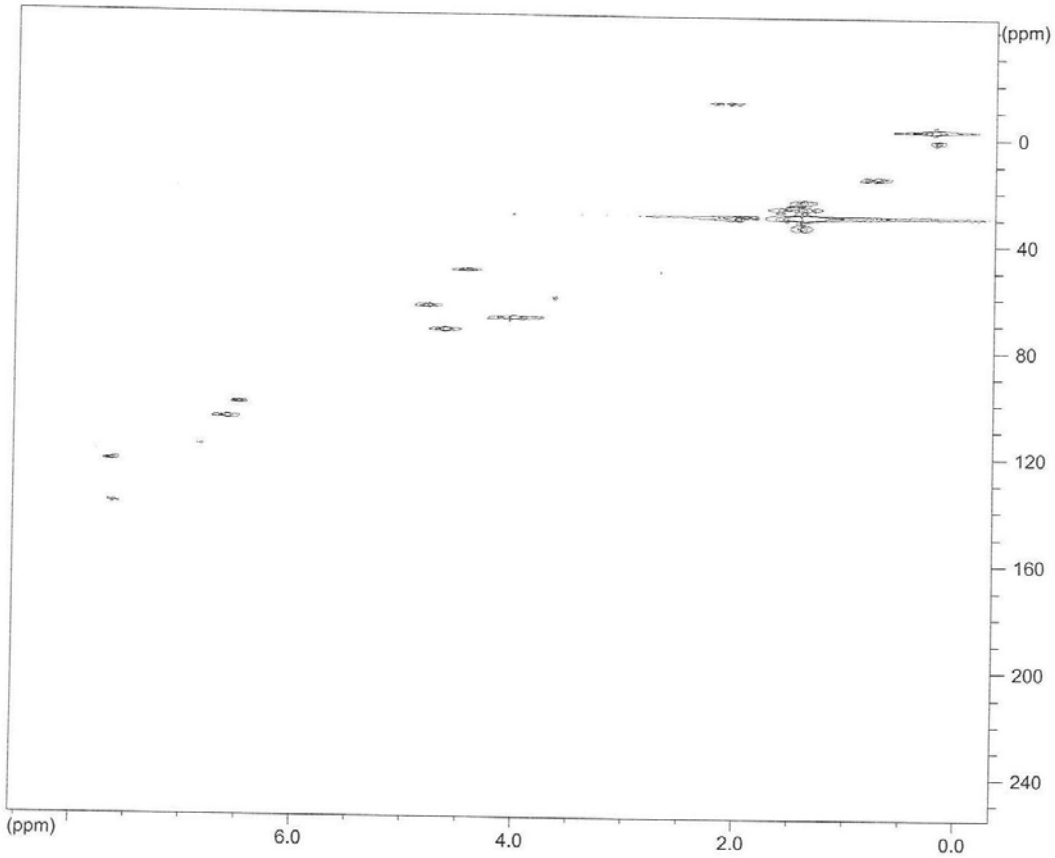
DEPT-135 NMR spectrum

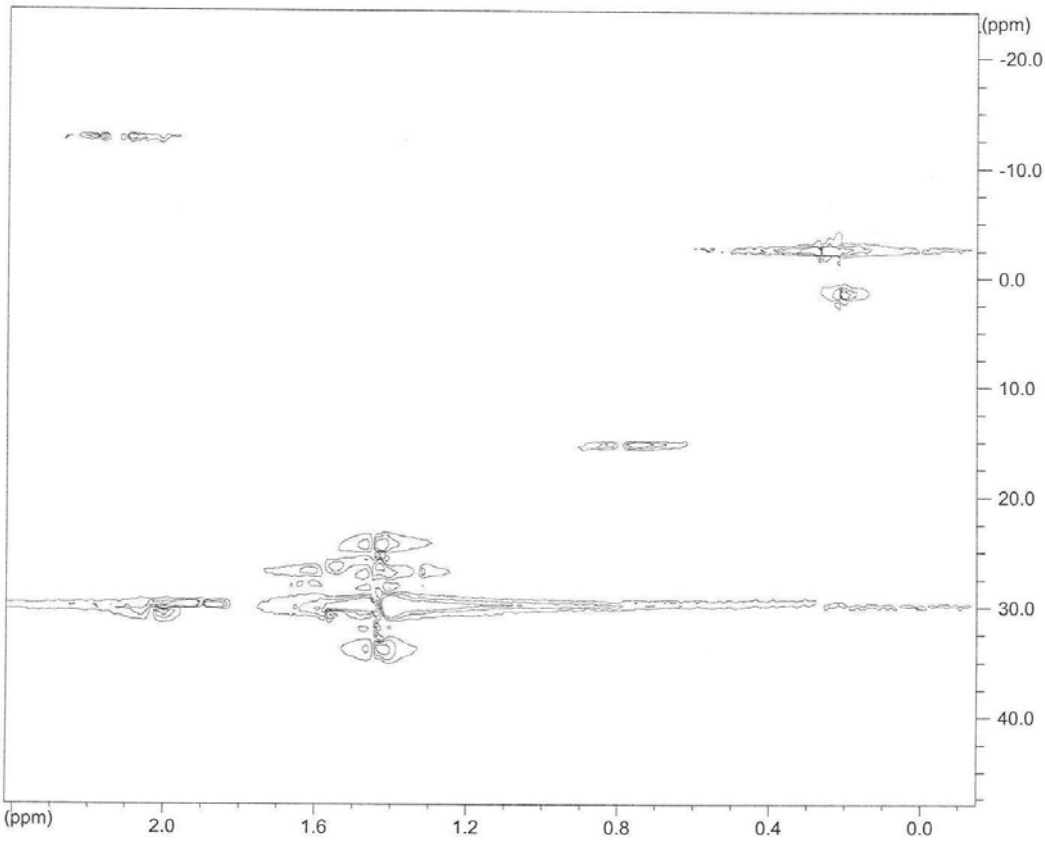


JMOD NMR spectrum (enlarged spectral window)

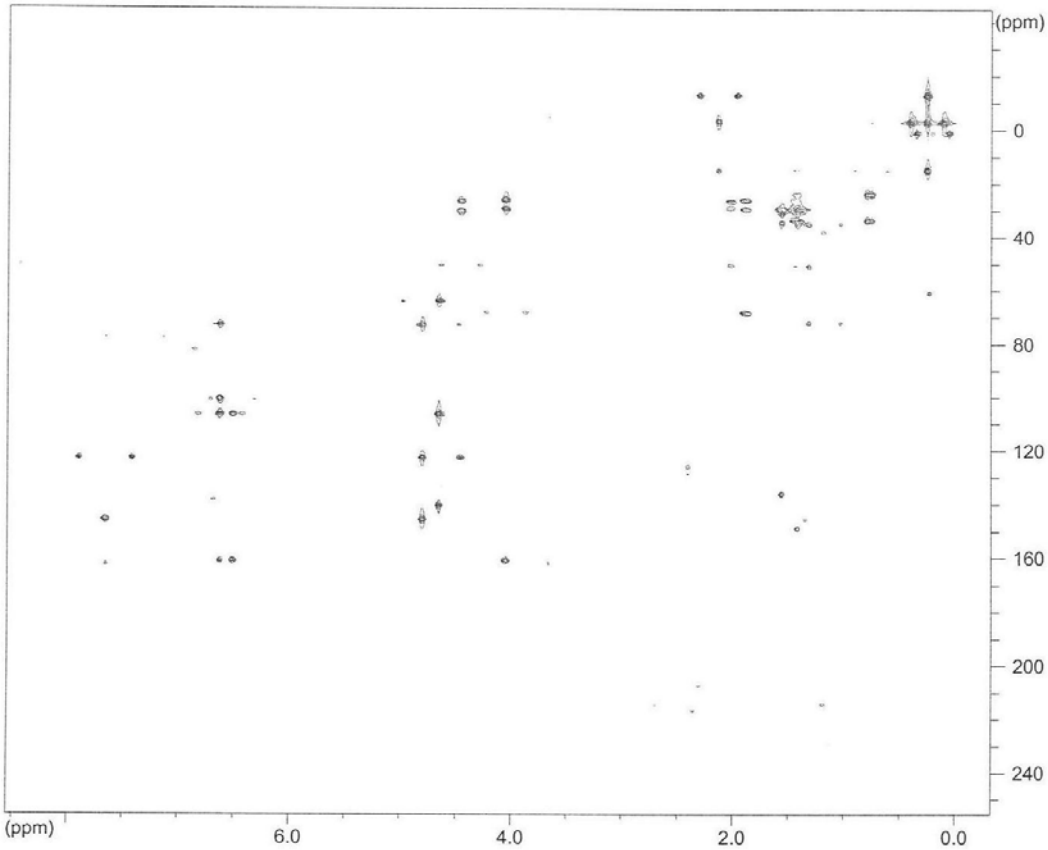


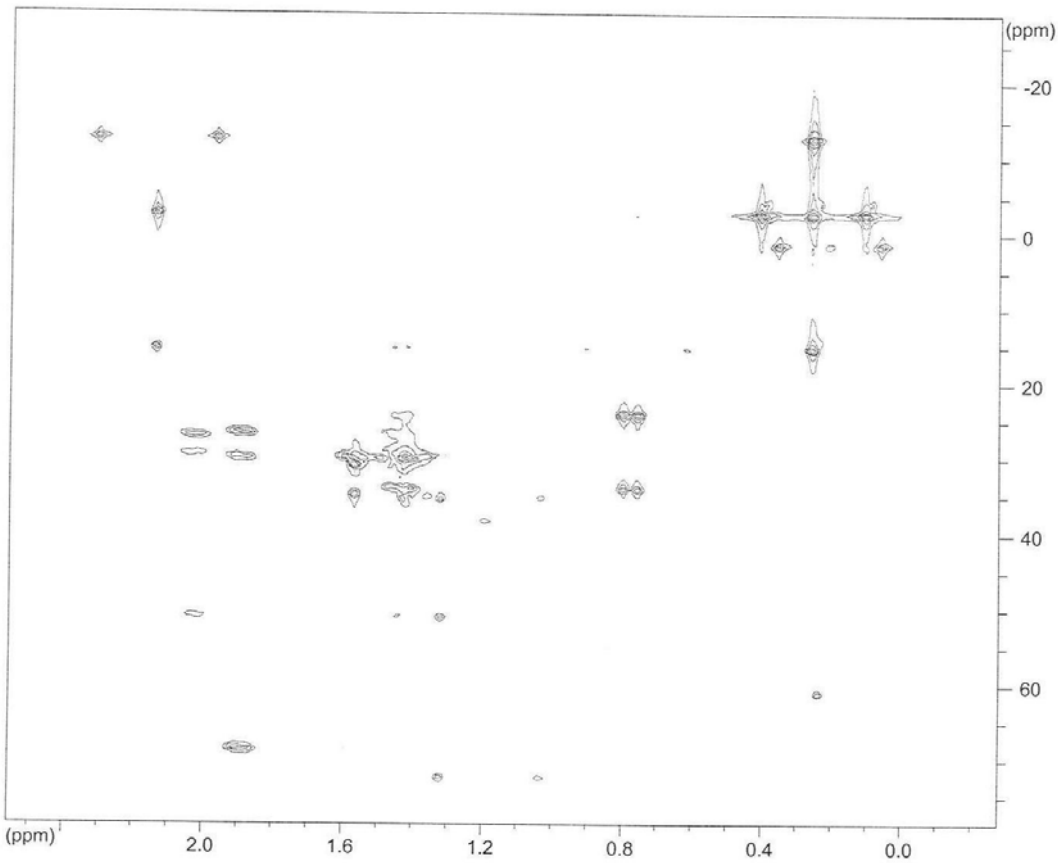
HSQC NMR spectrum (enlarged spectral window)



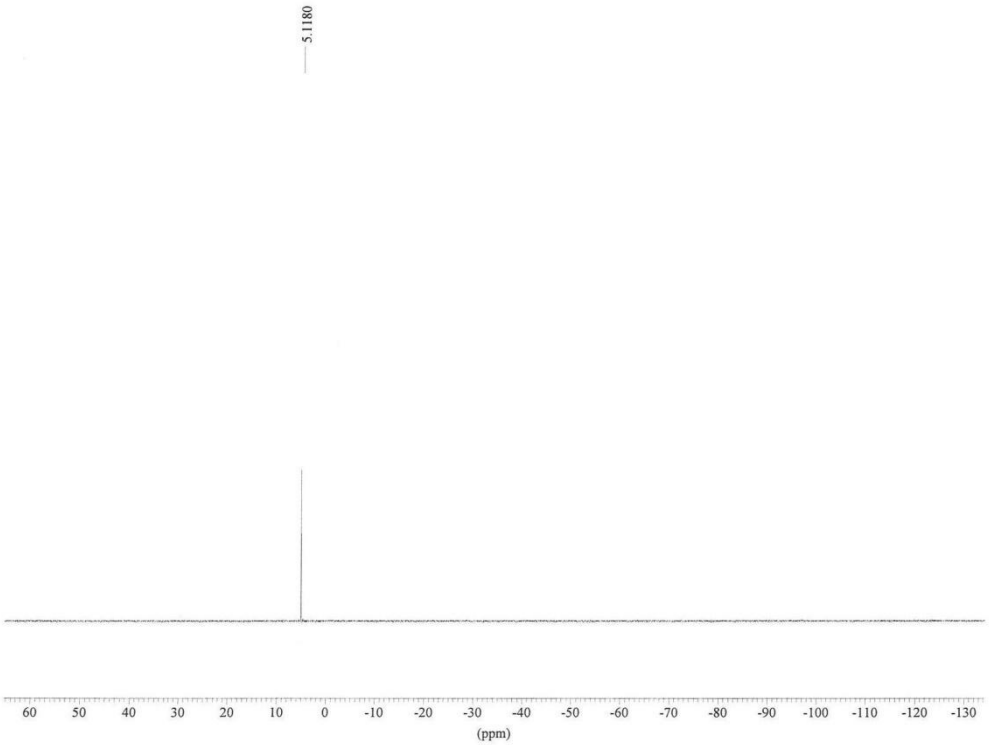


HMBC NMR spectrum (enlarged spectral window)





^{29}Si NMR spectrum



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SW_h	:	11904.762 Hz
*** Processing Parameters ***		
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SI	:	32768
WDW	:	EM
*** 1D NMR Plot Parameters ***		
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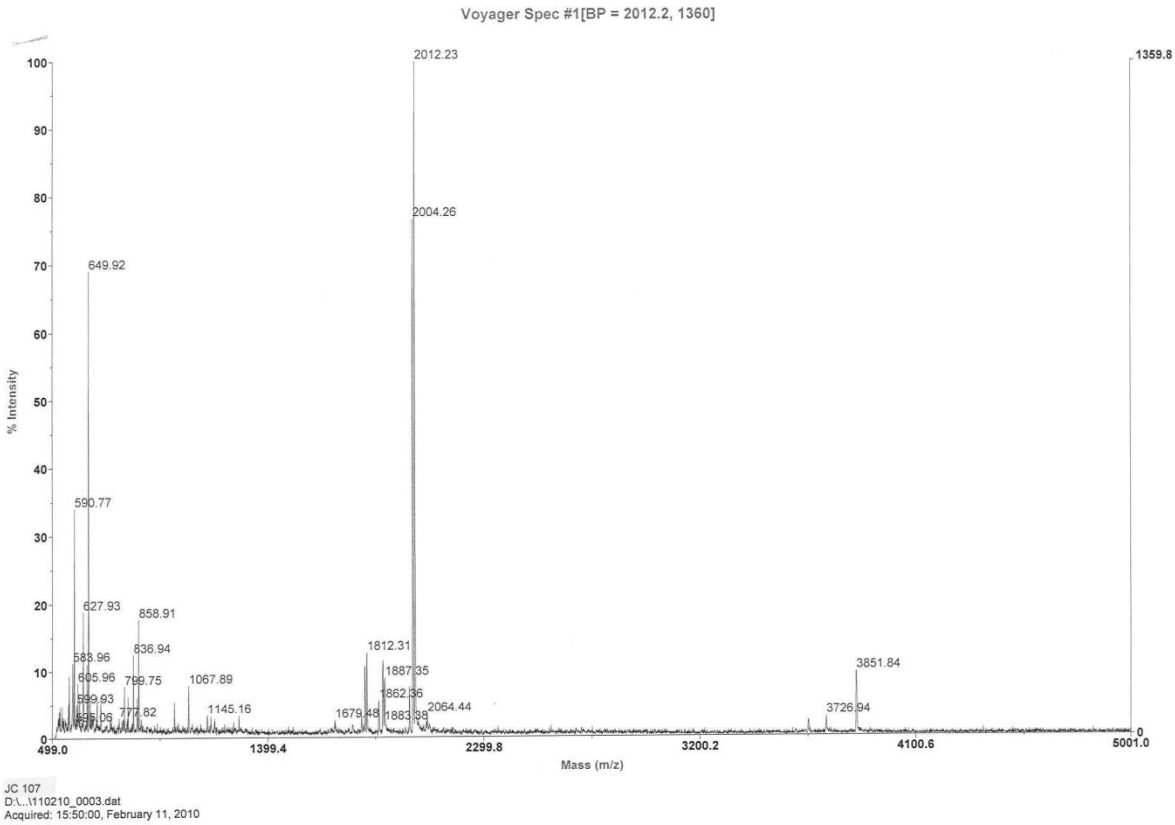
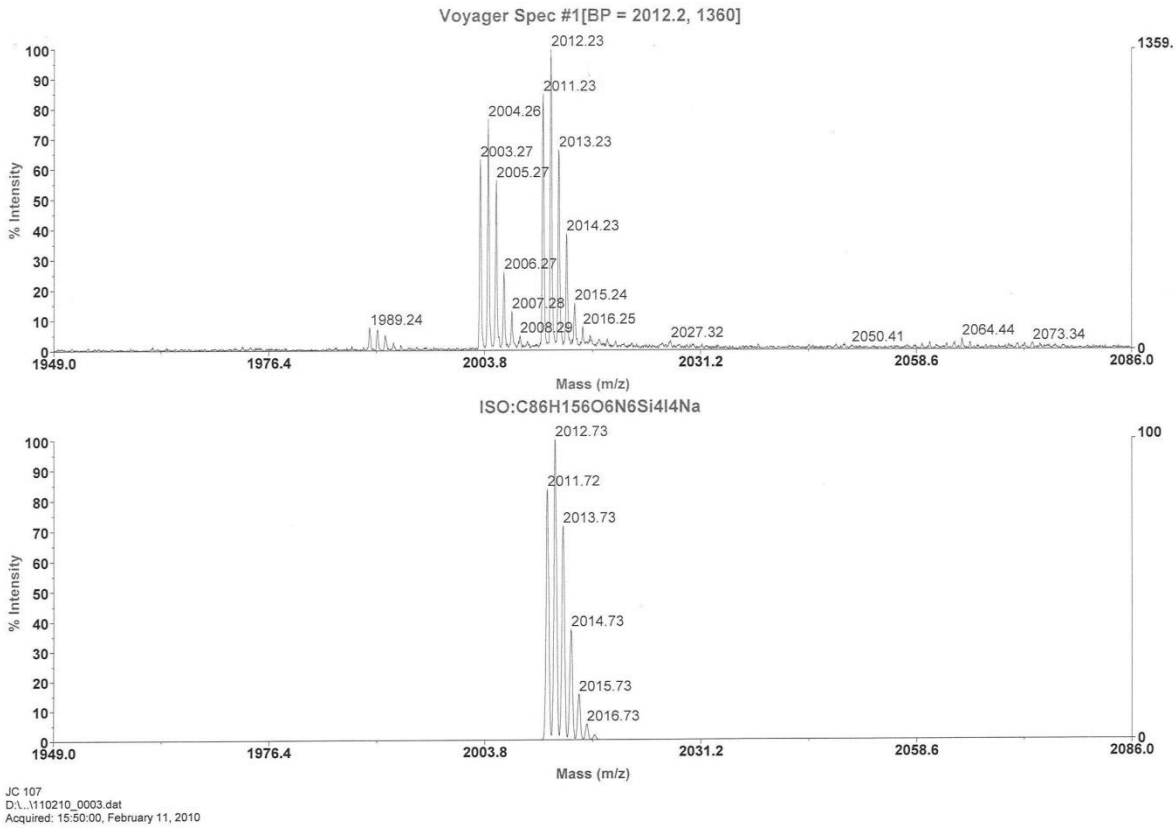
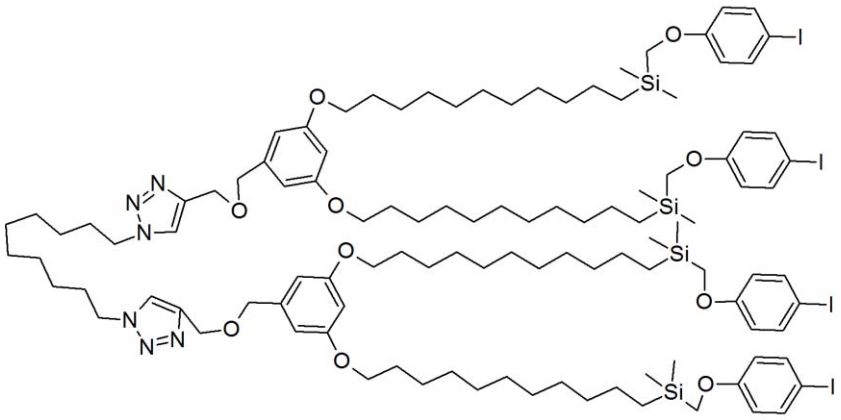
MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



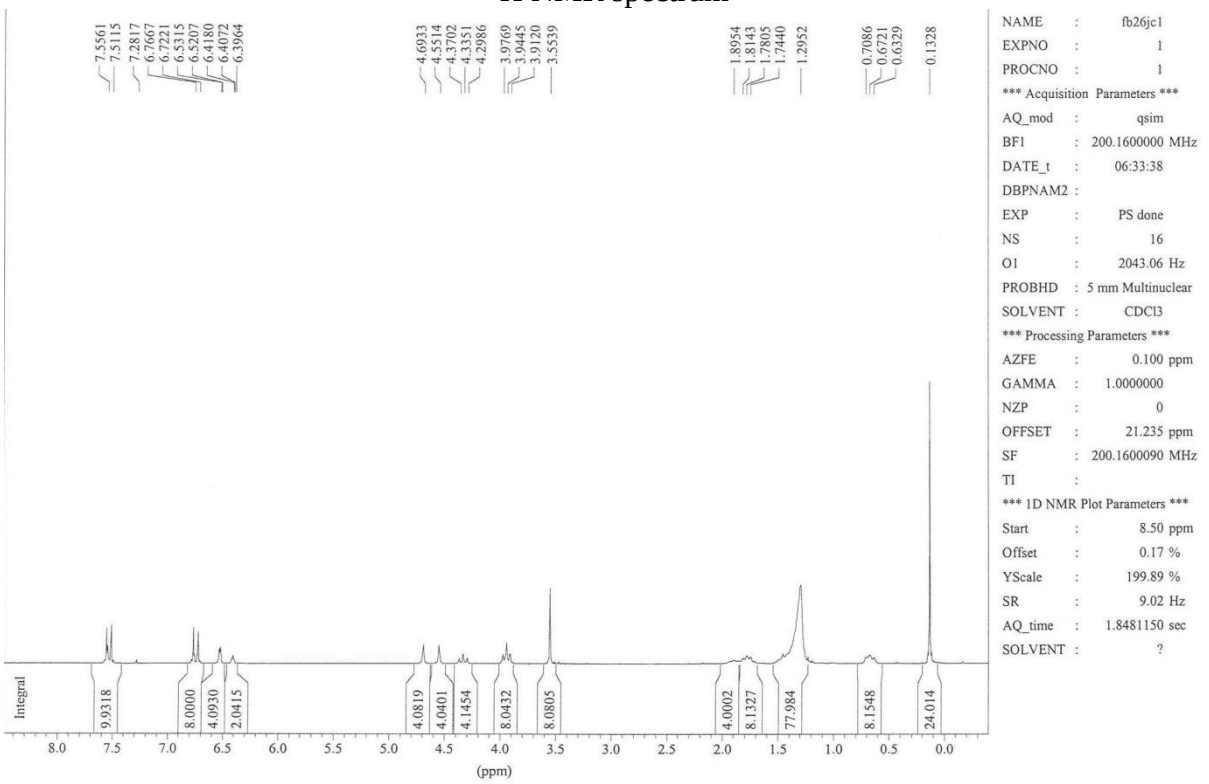
Synthesis of G_1-tetra iodophenyl dendrimer 11



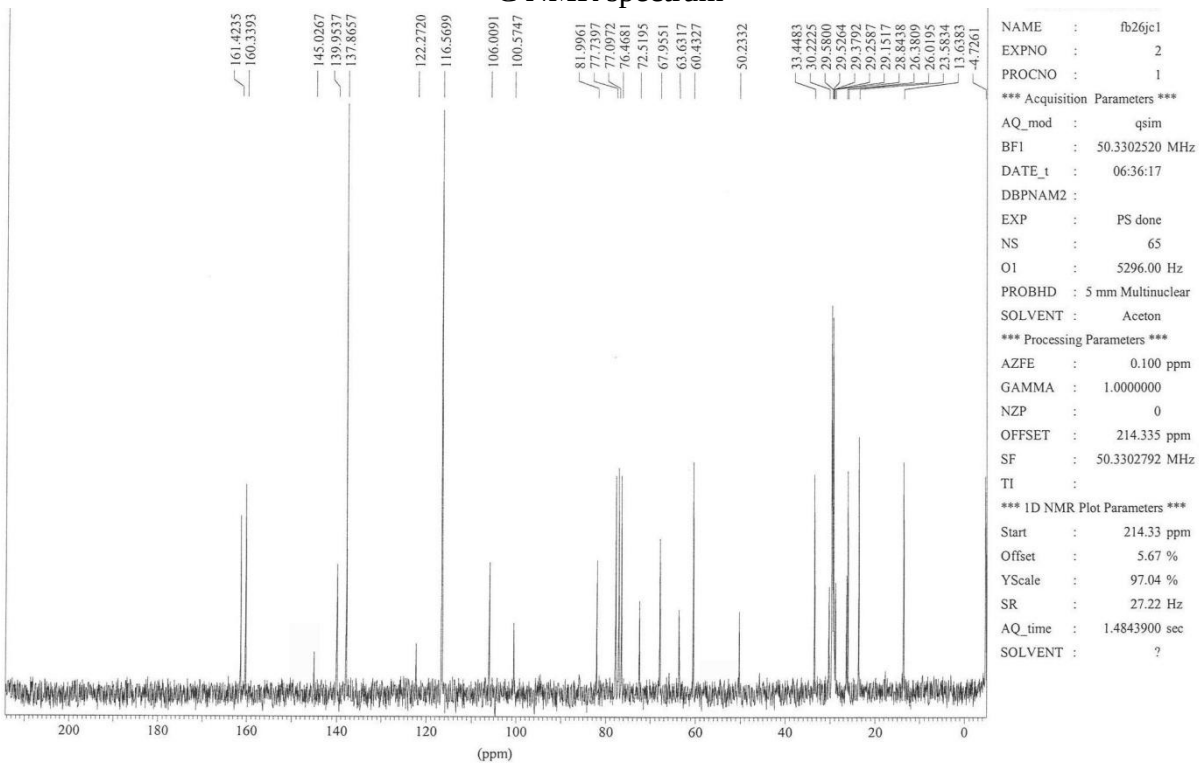
To a solution of G1-tetra iodo dendrimer **10** (1.3g, 0.65mmol, 1eq) in 20mL of anhydrous DMF was added p-iodophenol (1.15g, 5.23mmol, 8eq) and K_2CO_3 (1.8g, 13.0mmol, 20eq). The mixture was stirred at 70°C for one night. The mixture was authorized to cool down to room temperature and diethyl ether and water were added. The organic layer was washed two times with water, dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluents.
The desired product was obtained as a light brown oil (1.38g, 0.54mmol) in 83% yield

^{1}H NMR ($CDCl_3$ 200MHz): 7.51 ppm (m, $H_{triazole}$ + H_{Ar}, 10H); 6.72 ppm (d, H_{Ar}, ^3J = 9.2Hz , 8H) ; 6.50 ppm (d, H_{Ar}, ^4J = 2.2Hz, 4H); 6.38 ppm (t, H_{Ar}, ^4J = 2.2Hz, 2H); 4.67 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.53 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.32 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.93 ppm (t, -O-CH_2-CH_2-, ^3J = 6.5Hz, 8H); 3.54 ppm (s, Si-CH_2-O, 8H); 1.86 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, -O-CH_2-CH_2-, 8H); 1.50 to 1.25 ppm (m, -CH_2-, 76H) ; 0.65 ppm (t, -CH_2-CH_2-Si, ^3J = 7.7Hz, 8H) ; 0.11 ppm (s, Si-CH_3, 24H)
JMOD NMR ($CDCl_3$ 50.3MHz): 161.44 and 160.31 ppm (C_{ar}-O); 145.07 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.97 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 137.87 ppm (C_{ar}-H); 122.27 ppm ($C_{triazole}$-H) ; 116.57, 106.03 and 100.62 ppm (C_{ar}-H); 81.96 ppm (C_{ar}-I) ; 72.52 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 67.97 ppm (-O-CH_2-CH_2-); 63.65 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 60.46 ppm (Si-CH_2-O-) ; 50.23 ppm (-CH_2-$N_{triazole}$); 33.42, 30.19, 29.56, 29.51, 29.35, 29.24, 29.13, 28.82, 26.37, 26.00 and 23.56 ppm (-CH_2-) ; 13.63 (-CH_2-CH_2-Si) ; -4.76 ppm (Si-CH_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 0.94 ppm
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 2379.7

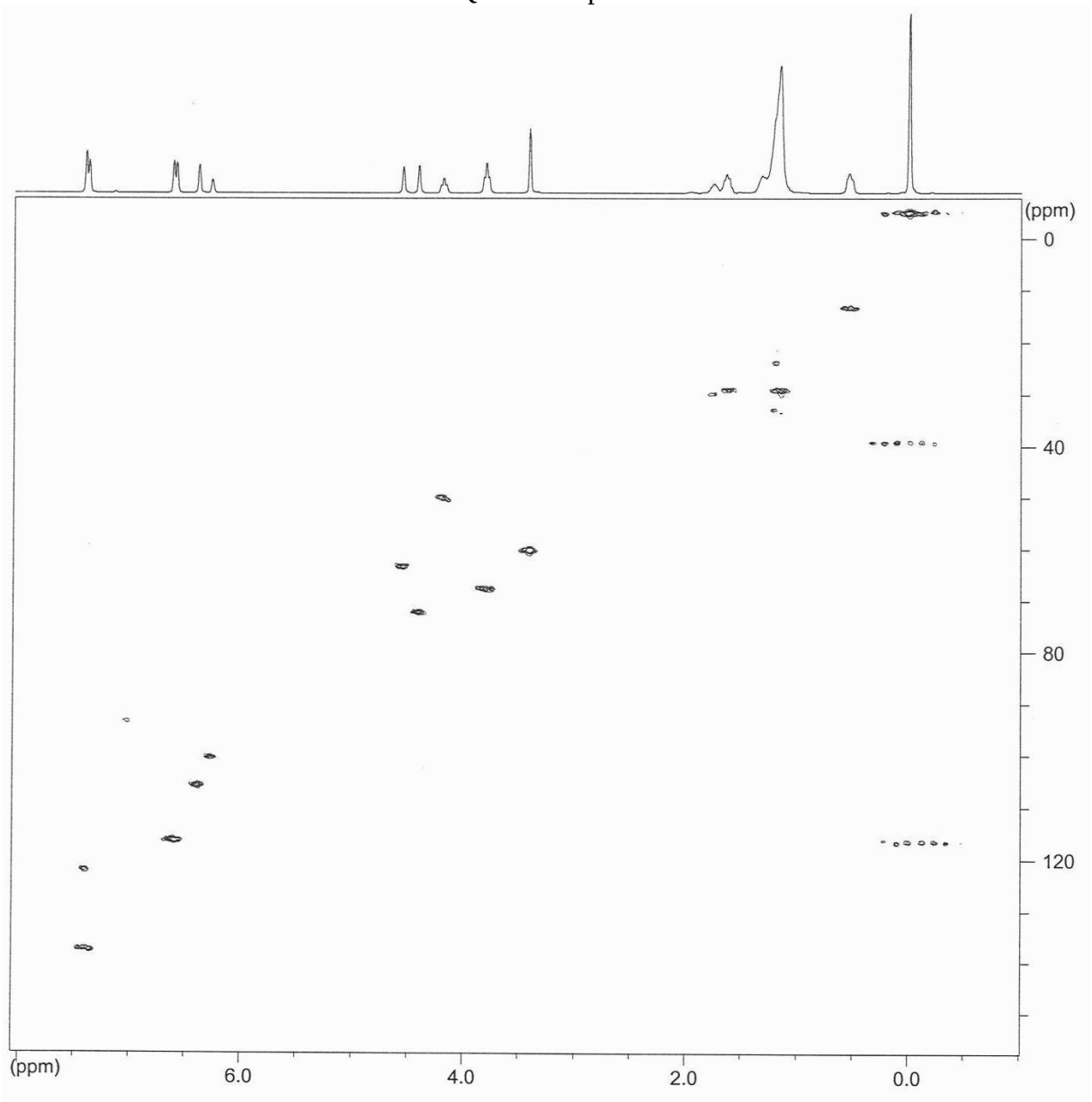
^{1}H NMR spectrum



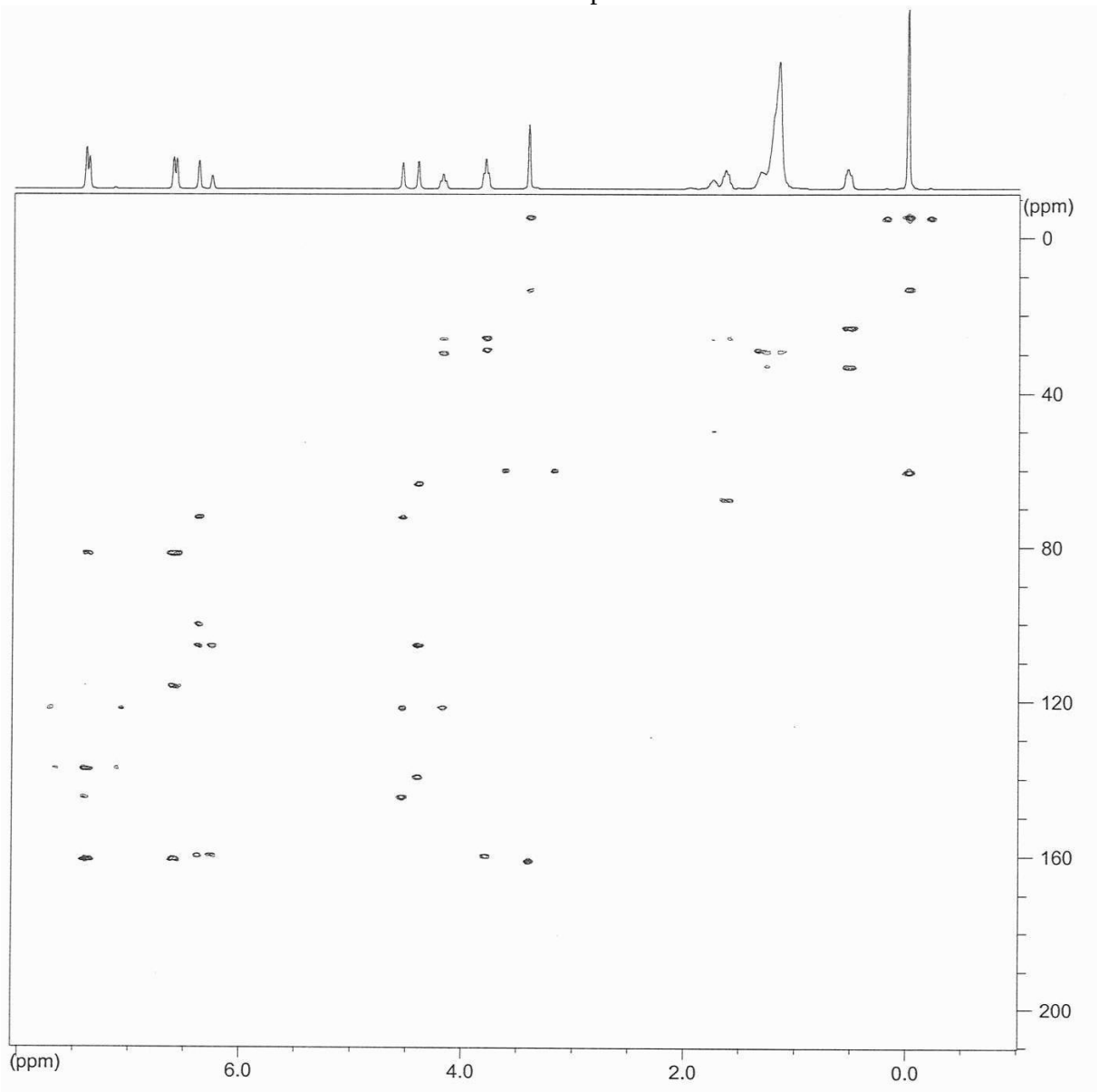
^{13}C NMR spectrum



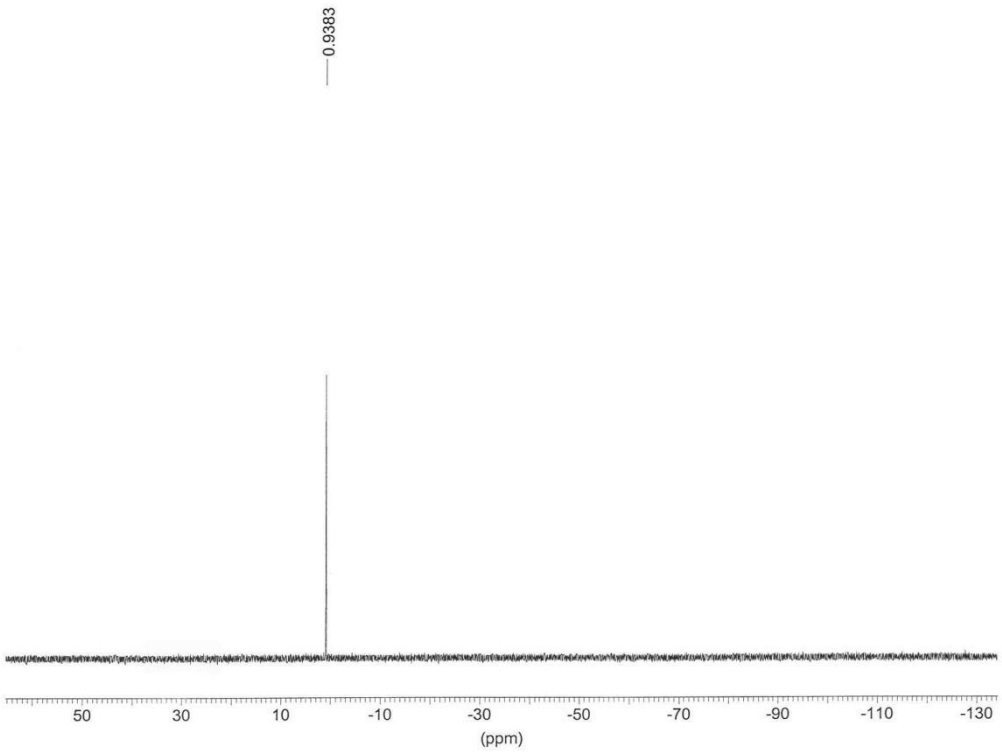
HMQC NMR spectrum



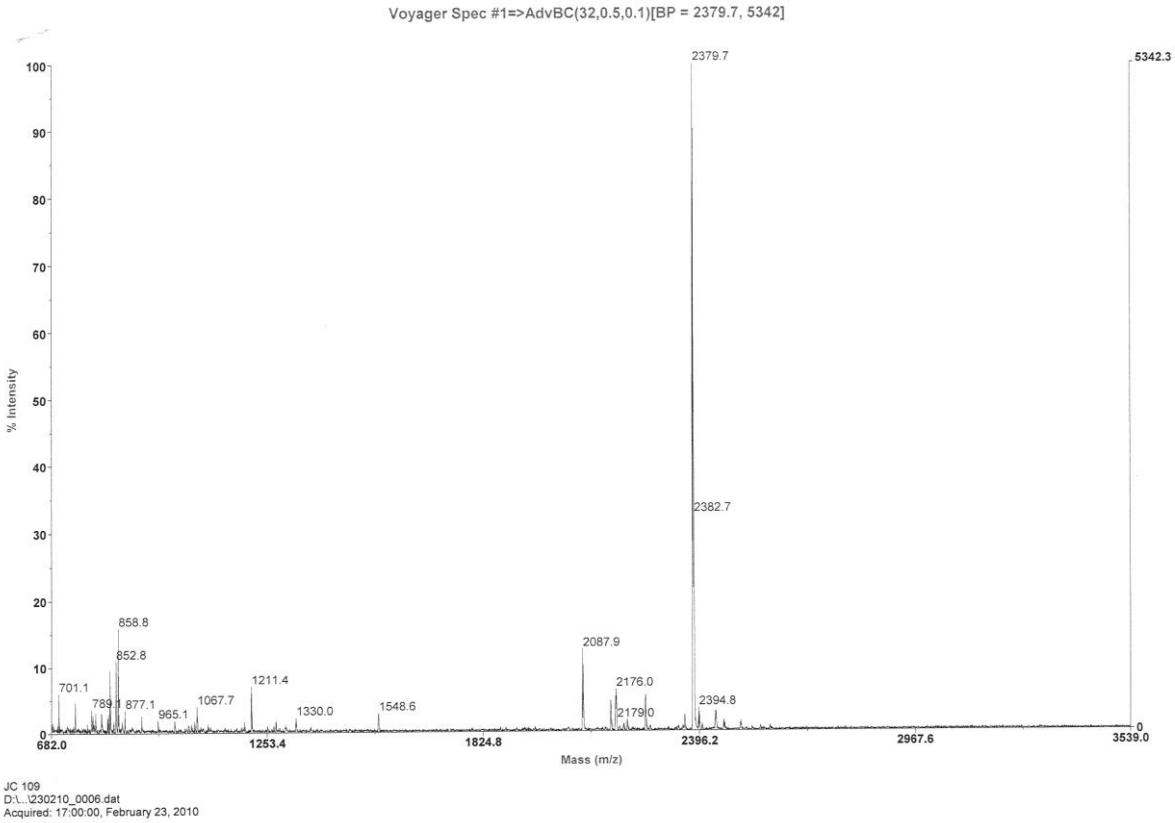
HMBC NMR spectrum



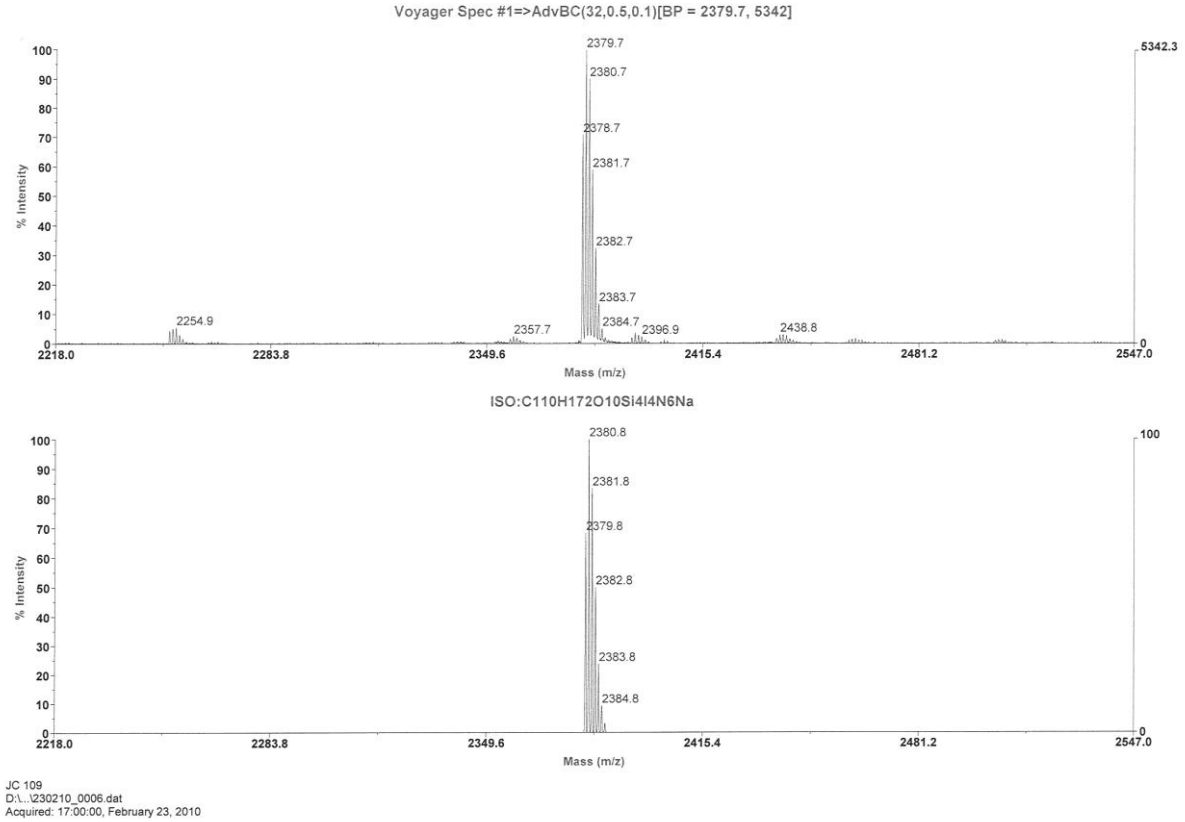
^{29}Si NMR spectrum



MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



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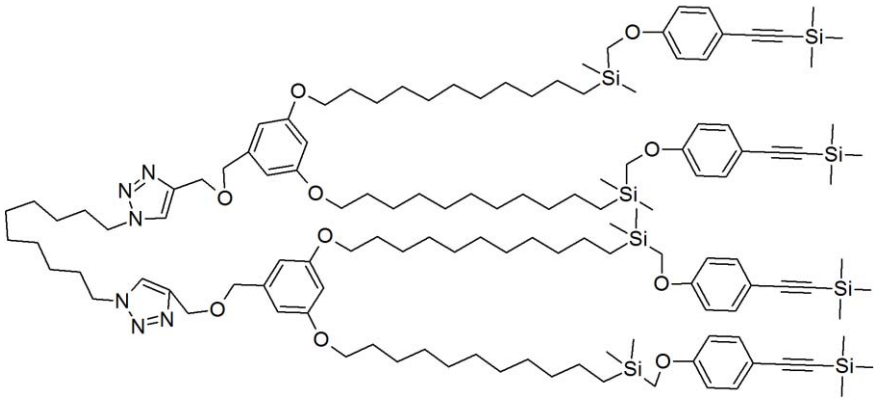
Acquired: 17:00:00, February 23, 2010

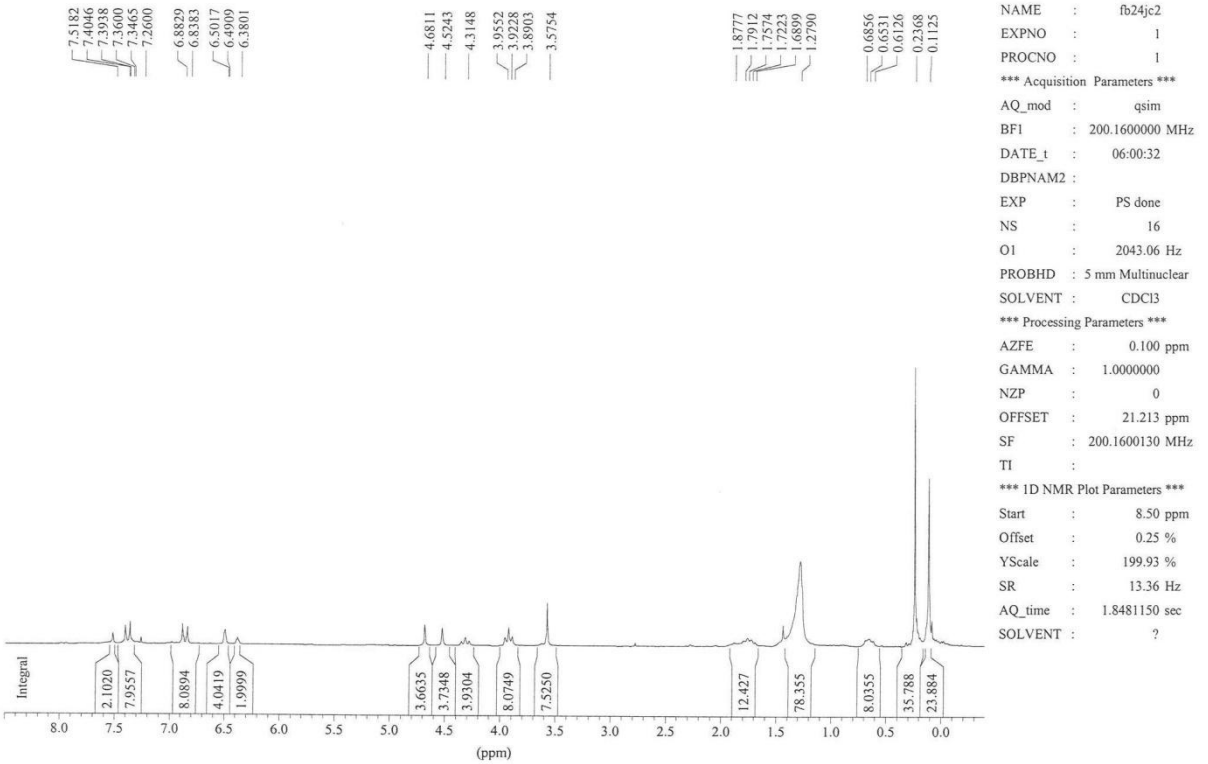
Synthesis of G_1-tetra trimethylsilyl dendrimer 12



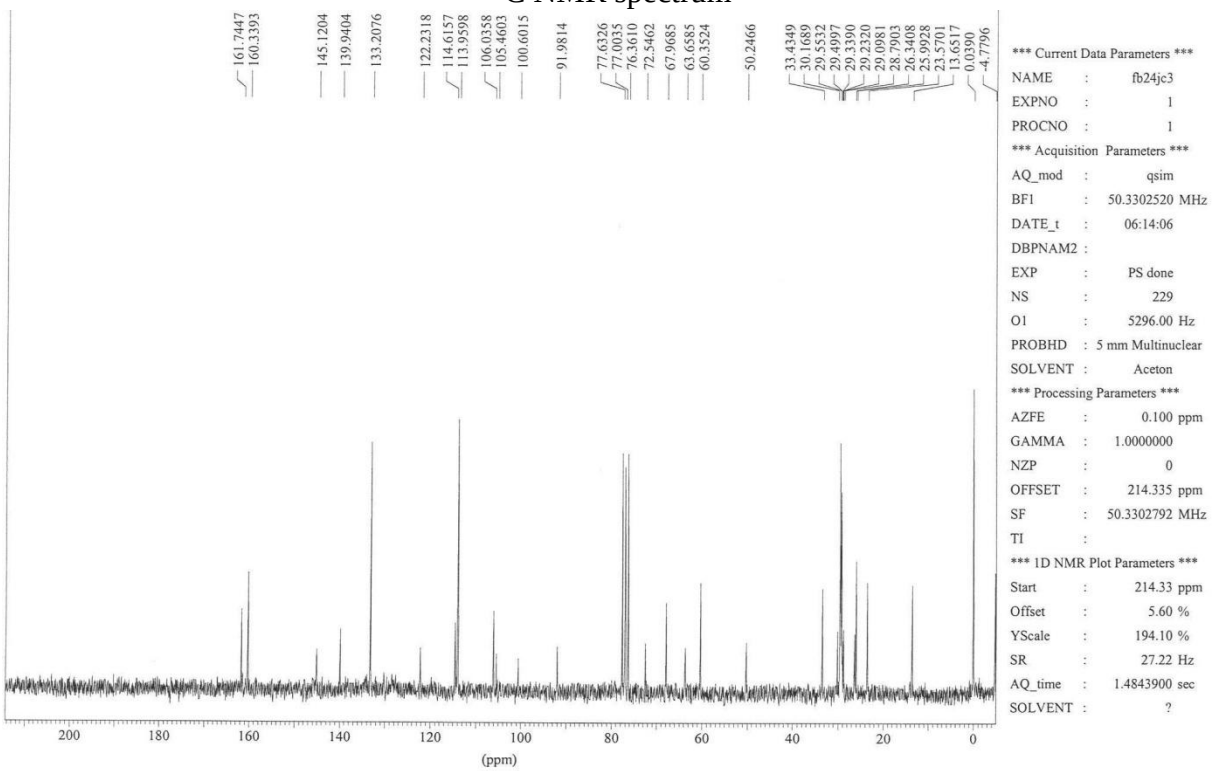
G1-tetra iodophenyl dendrimer **11** (0.75g, 0.32mmol, 1eq), $PdCl_2(PPh_3)_2$ (45mg, 0.06mmol, 0.2eq), CuI (45mg, 0.23mmol, 0.72eq) and then distillated triethylamine (30mL) were added into a schlenk flask. The reaction mixture was stirred for 10 minutes at 50°C and then trimethylsilylacetylene (0.4mL, 2.5mmol, 8eq) was added dropwise. The reaction mixture was stirred for one night at 65°C. Solvent was removed *in vacuo*. Diehtyl ether and water were added. The organic layer was washed three times with water, dried over anhydrous sodium sulfate, filtered and then evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a slightly yellow oil (0.65g, 0.33mmol) in 91% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.52 ppm (s, $H_{triazole}$, 2H); 7.38 ppm (d, H_{ar}, ^3J = 8,9Hz , 8H); 6.86 ppm (d, H_{Ar}, ^3J = 8,9Hz , 8H) ; 6.50 ppm (d, H_{Ar}, ^4J = 2.2Hz, 4H); 6.38 ppm (t, H_{Ar}, ^4J = 2.2Hz, 2H); 4.68 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.52 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.31 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.92 ppm (t, -O-CH_2-CH_2-, ^3J = 6.5Hz, 8H); 3.58 ppm (s, Si-CH_2-O, 8H); 1.86 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, -O-CH_2-CH_2-, 8H); 1.50 to 1.25 ppm (m, -CH_2-, 76H) ; 0.65 ppm (t, -CH_2-CH_2-Si, ^3J = 7.7Hz, 8H) ; 0,24 ppm (s, external Si-CH_3, 36H); 0.11 ppm (s, internal Si-CH_3, 24H)
^{13}C NMR ($CDCl_3$ 50.3MHz): 161.74 and 160.34 ppm (C_{ar}-O); 145.12 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.94 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 133.21 ppm (C_{ar}-H); 122.23 ppm ($C_{triazole}$-H) ; 114.62 (C_{ar}-C≡C-); 113.96 and 106.04 ppm (C_{ar}-H); 105.46 ppm (C_{ar}-*C*≡C);100.60 ppm (C_{ar}-H); 91.98 ppm (C_{ar}-C≡*C*); 72.55 ppm (C_{Ar}-*C*H_2-O-CH_2-$C_{triazole}$); 67.97 ppm (-O-*C*H_2-CH_2-); 63.66 ppm (C_{Ar}-CH_2-O-*C*H_2-$C_{triazole}$); 60.35 ppm (Si-*C*H_2-O-) ; 50.25 ppm (-*C*H_2-$N_{triazole}$); 33.43, 30.17, 29.55, 29.50, 29.34, 29.23, 29.10, 28.79, 26.34, 25.99 and 23.57 ppm (-*C*H_2-) ; 13.65 (-CH_2-*C*H_2-Si) ; 0,04 ppm (external Si-*C*H_3); -4.76 ppm (internal Si-*C*H_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : two peaks at 0.98 and -17.96 ppm
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 2262.2

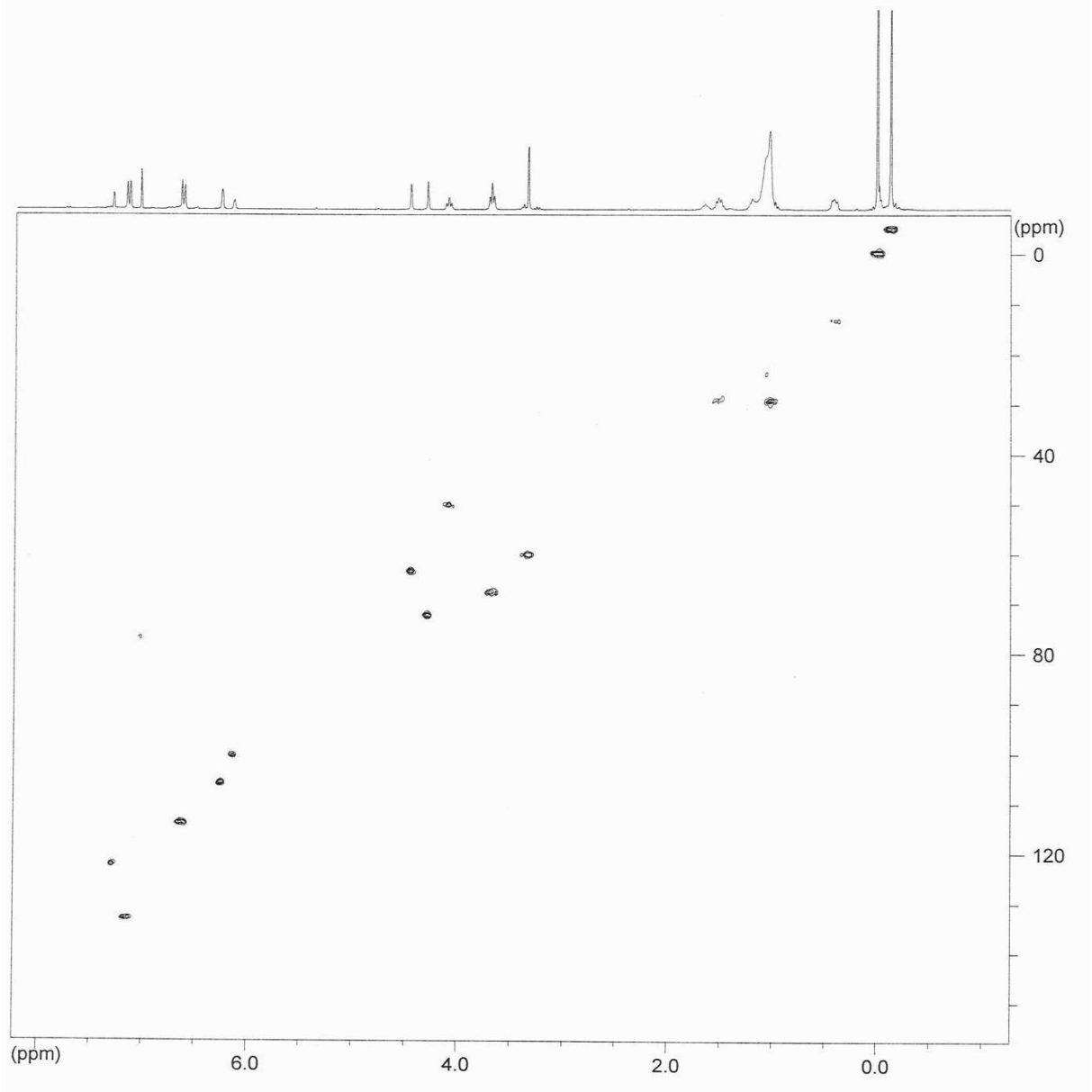
^{1}H NMR spectrum



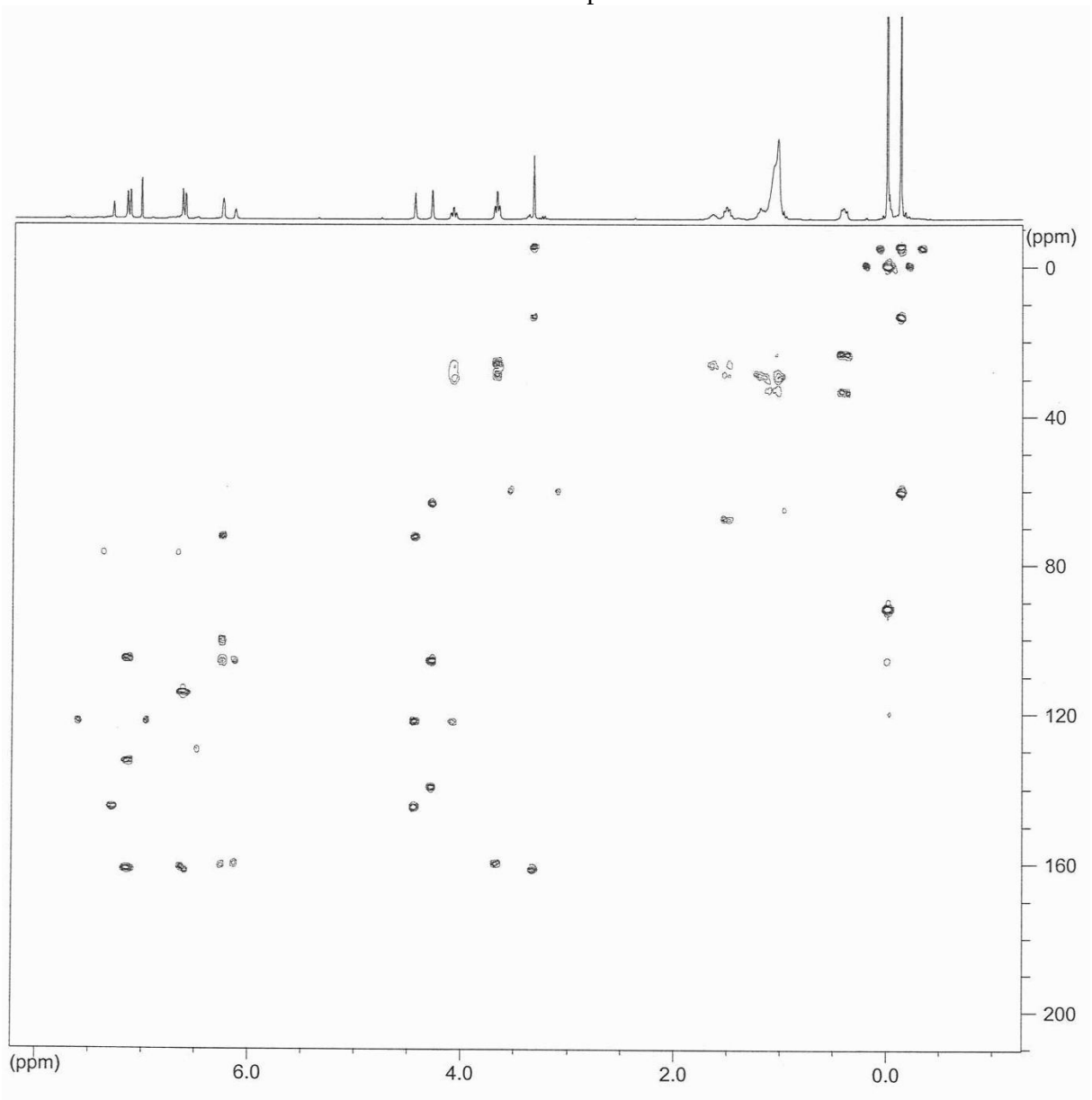
^{13}C NMR spectrum



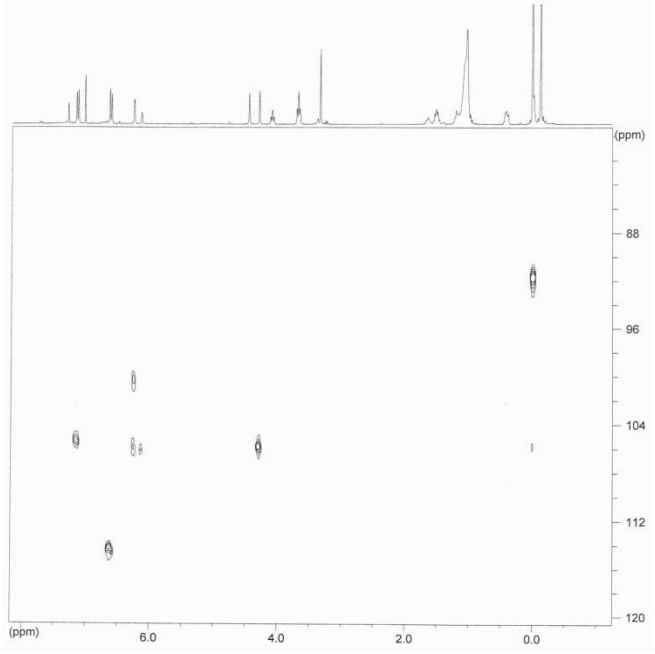
HMQC NMR spectrum

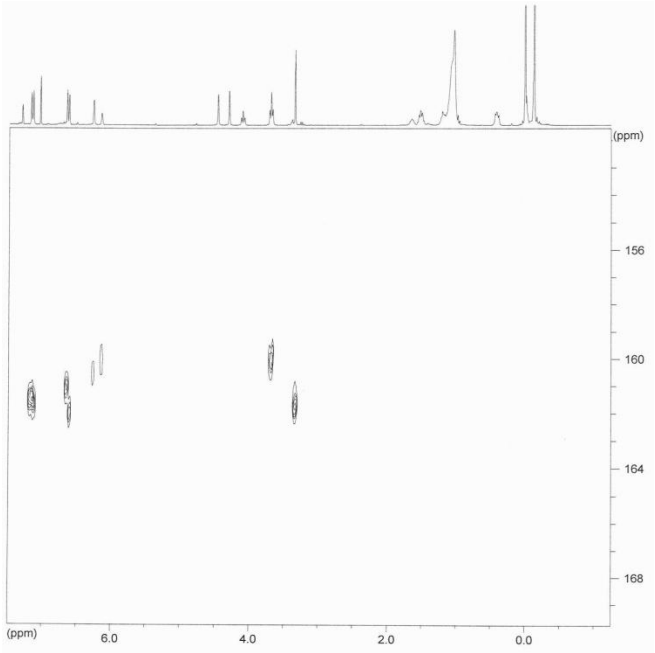


HMBC NMR spectrum

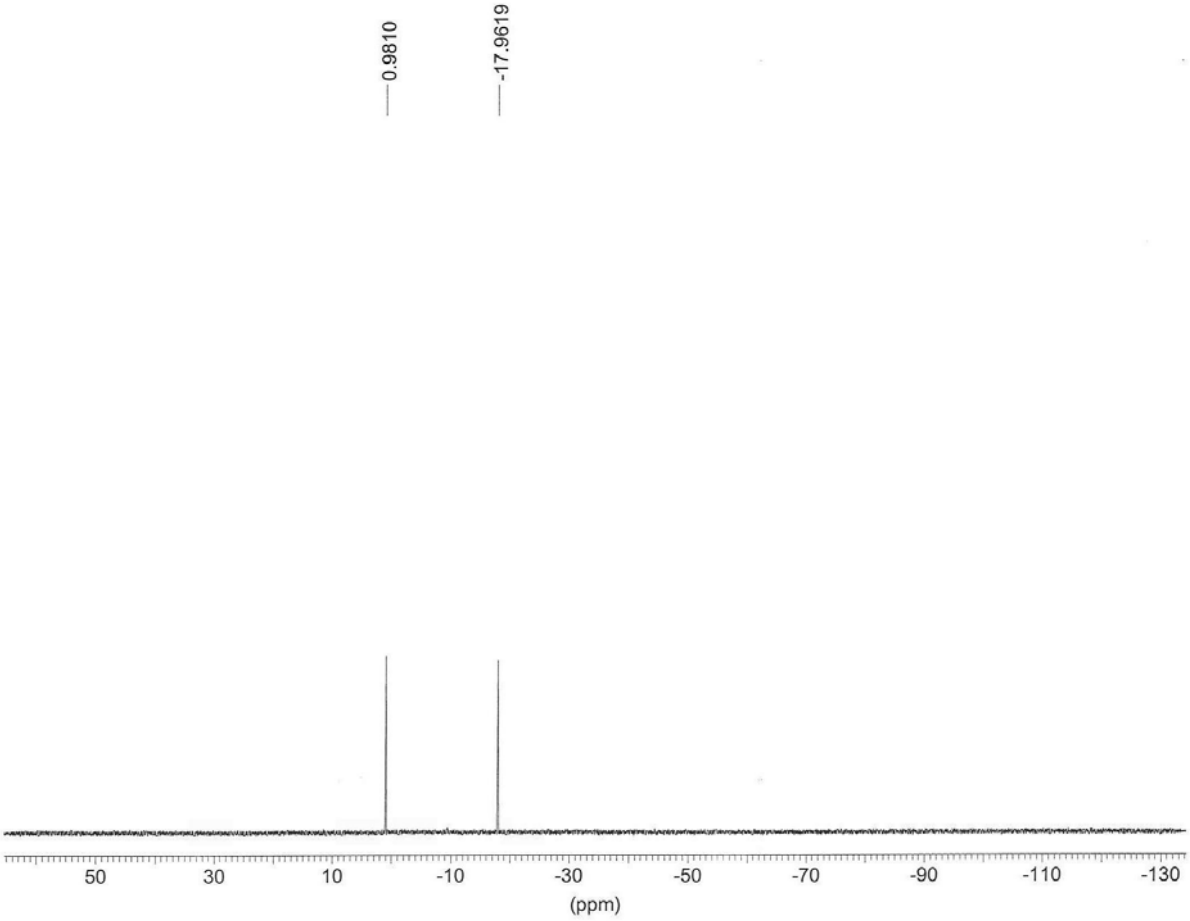


HMBC NMR spectrum (zoom)

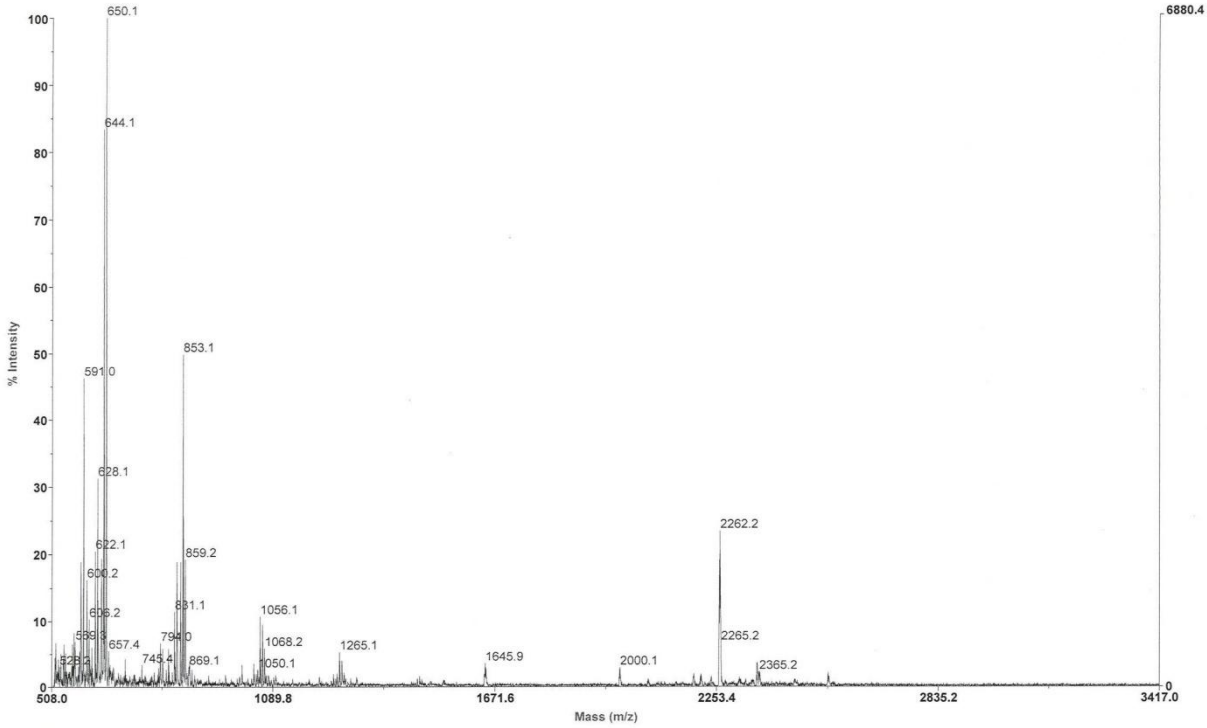




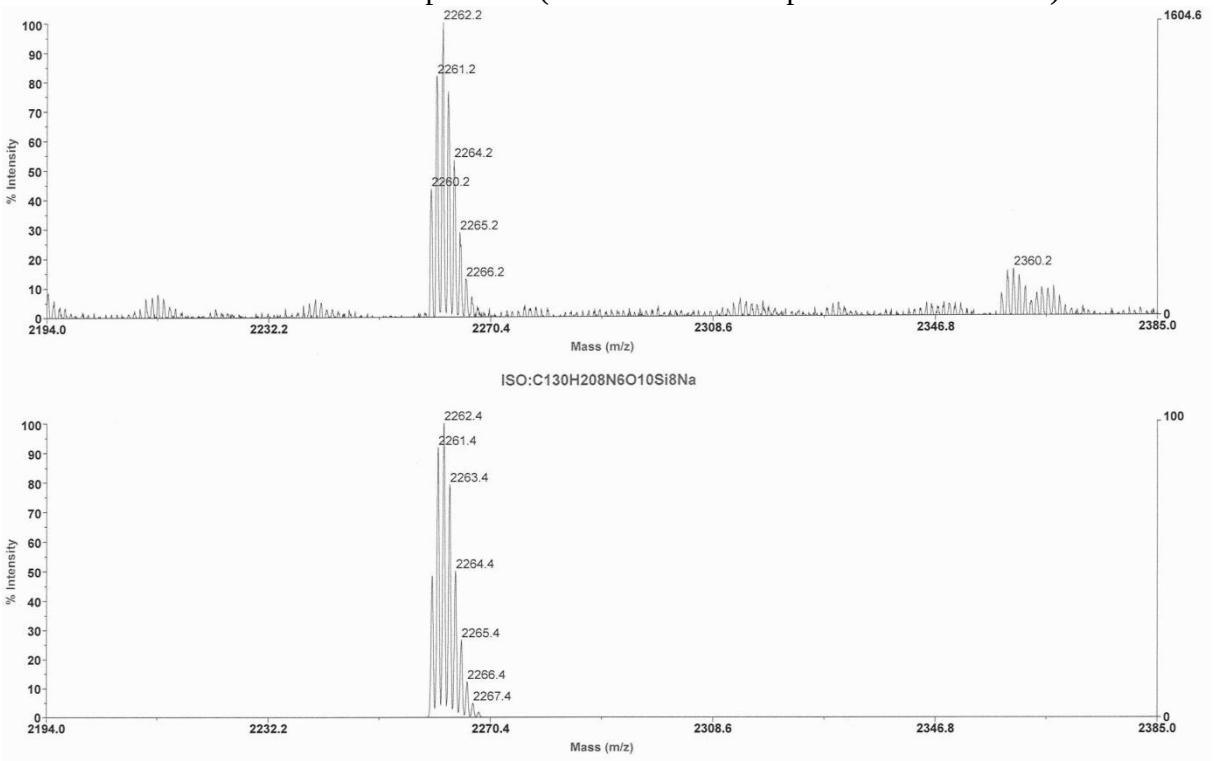
^{29}Si NMR spectrum



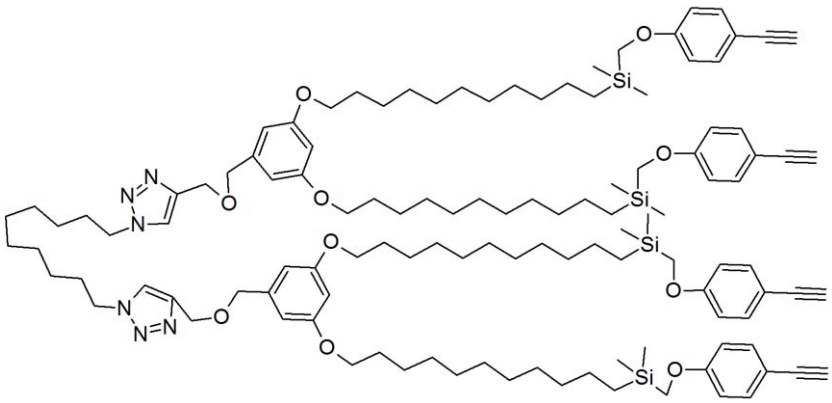
MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



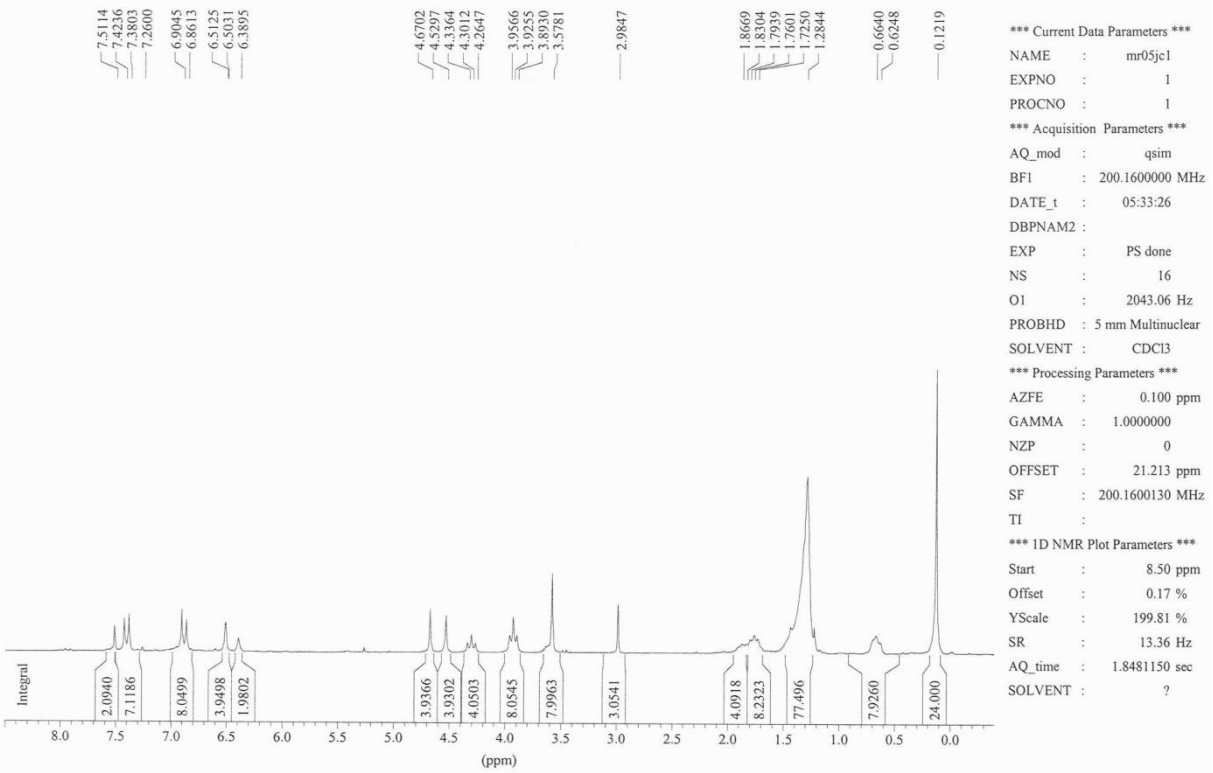
Synthesis of G_1-tetra alkynyl dendrimer 13



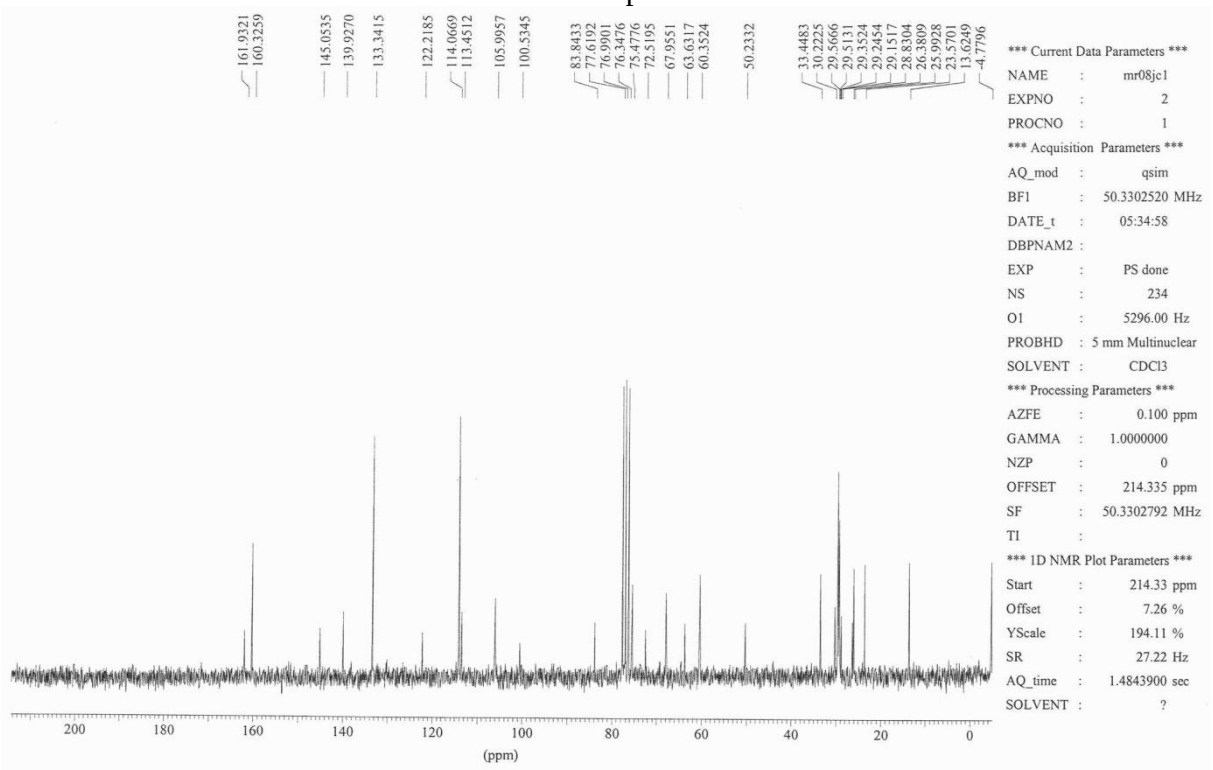
To a solution of G1-tetra trimethylsilyl dendrimer **12** (0.65g, 0.29mmol, 1eq) in a THF/MeOH 1:1 (v/v) mixture was added K_2CO_3 (160mg, 1.2mmol, 4eq). The medium was stirred for 2h at room temperature. The medium was filtered, and the solid was washed with diethyl ether. The filtrate was evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent. The diethyl ether layer was concentrated and precipitated using excess methanol.
The desired product was obtained as a colorless oil (0.53g, 0.27mmol) in 94% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.51 ppm (s, $H_{triazole}$, 2H); 7.40 ppm (d, H_{ar}, ^3J = 8.6Hz , 8H); 6.88 ppm (d, H_{Ar}, ^3J = 8.6Hz , 8H) ; 6.50 ppm (d, H_{Ar}, ^4J = 1.9Hz, 4H); 6.39 ppm (t, H_{Ar}, ^4J = 1.9Hz, 2H); 4.67 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.53 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.30 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.93 ppm (t, -O-CH_2-CH_2-, ^3J = 6.4Hz, 8H); 3.58 ppm (s, Si-CH_2-O, 8H); 2.98 ppm (s, -C≡C-*H*, 4H); 1.86 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, -O-CH_2-CH_2-, 8H); 1.50 to 1.25 ppm (m, -CH_2-, 76H) ; 0.65 ppm (t, -CH_2-CH_2-Si, ^3J = 7.8Hz, 8H) ; 0.12 ppm (s, Si-CH_3, 24H)
^{13}C NMR ($CDCl_3$ 50.3MHz): 161.93 and 160.33 ppm (C_{ar}-O); 145.05 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.93 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 133.34 ppm (C_{ar}-H); 122.22 ppm ($C_{triazole}$-H) ; 114.07 ppm (C_{ar}-H); 113.45 (C_{ar}-C≡C-); 106.00 and 100.53 ppm (C_{ar}-H); 83.84 ppm (C_{ar}-*C*≡C-H); 75.48 ppm (C_{ar}-C≡*C*-H); 72.48 ppm (C_{Ar}-*C*H_2-O-CH_2-$C_{triazole}$); 67.96 ppm (-O-*C*H_2-CH_2-); 63.63 ppm (C_{Ar}-CH_2-O-*C*H_2-$C_{triazole}$); 60.35 ppm (Si-*C*H_2-O-) ; 50.23 ppm (-*C*H_2-$N_{triazole}$); 33.45, 30.22, 29.57, 29.51, 29.35, 29.25, 29.15, 28.83, 26.38, 25.99 and 23.57 ppm (-*C*H_2-) ; 13.62 (-CH_2-*C*H_2-Si) ; -4.78 ppm (Si-*C*H_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 0.98 ppm
DOSY NMR gives a diffusion coefficient of 2.01×10^{-10} m².s^{-1} in chloroform at 20°C which corresponds to a diameter of 3.7nm.
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 1973.0
IR spectroscopy (cm-1): 3318.0 ; 3297.4; 2927.6 ; 2853.6 ; 2110.0
Polydispersity: 1.01

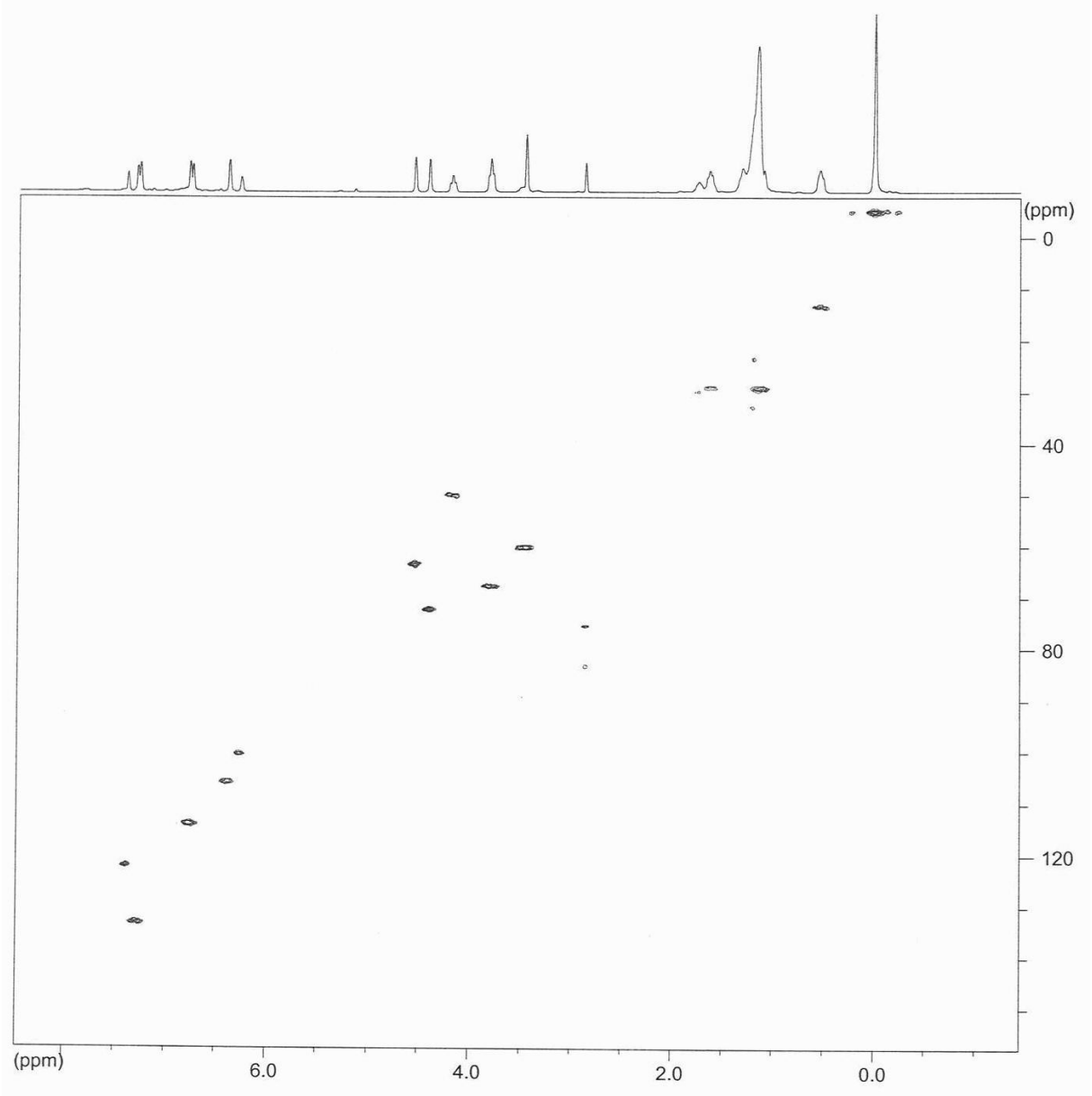
^{1}H NMR spectrum



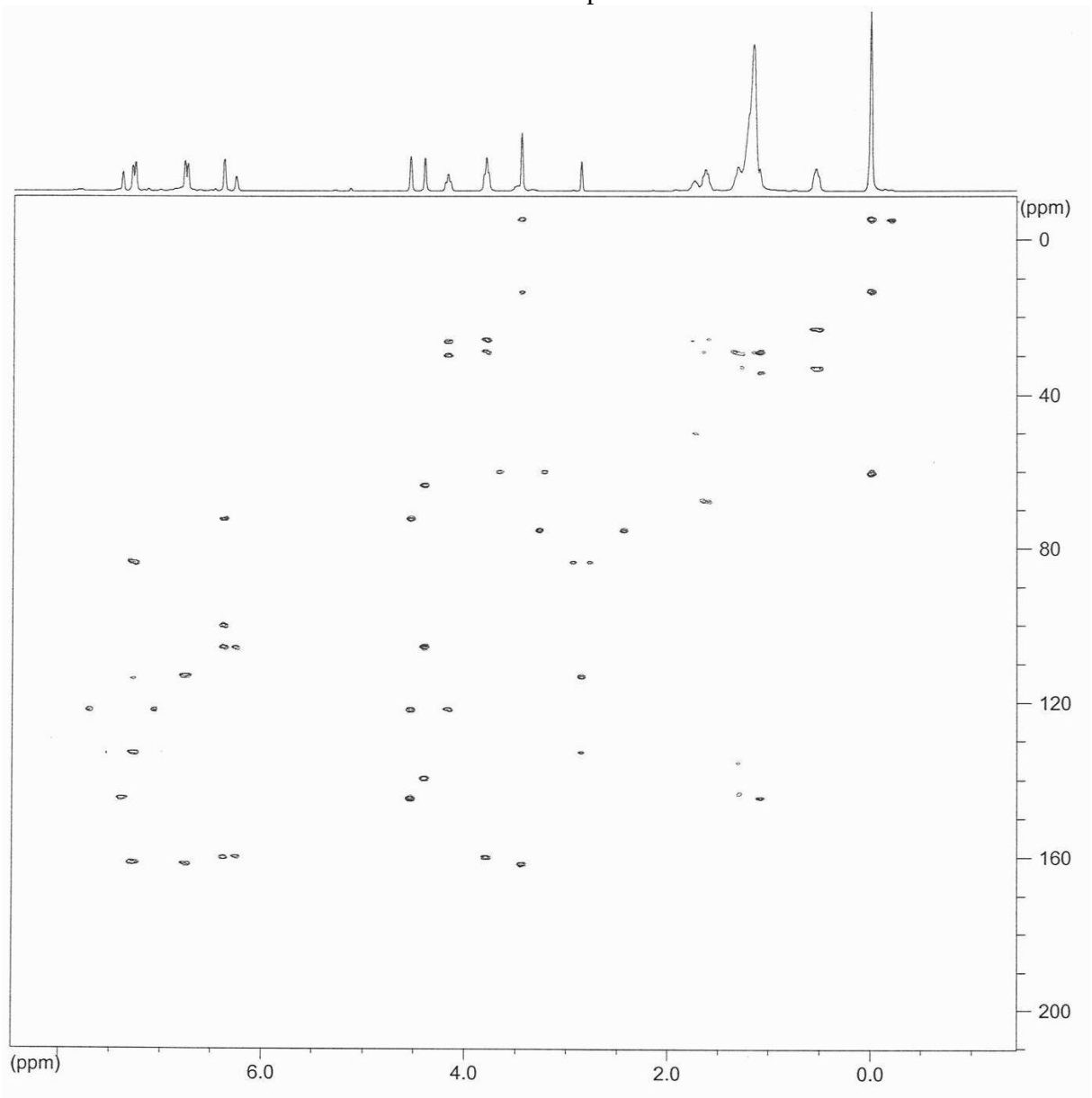
^{13}C NMR spectrum



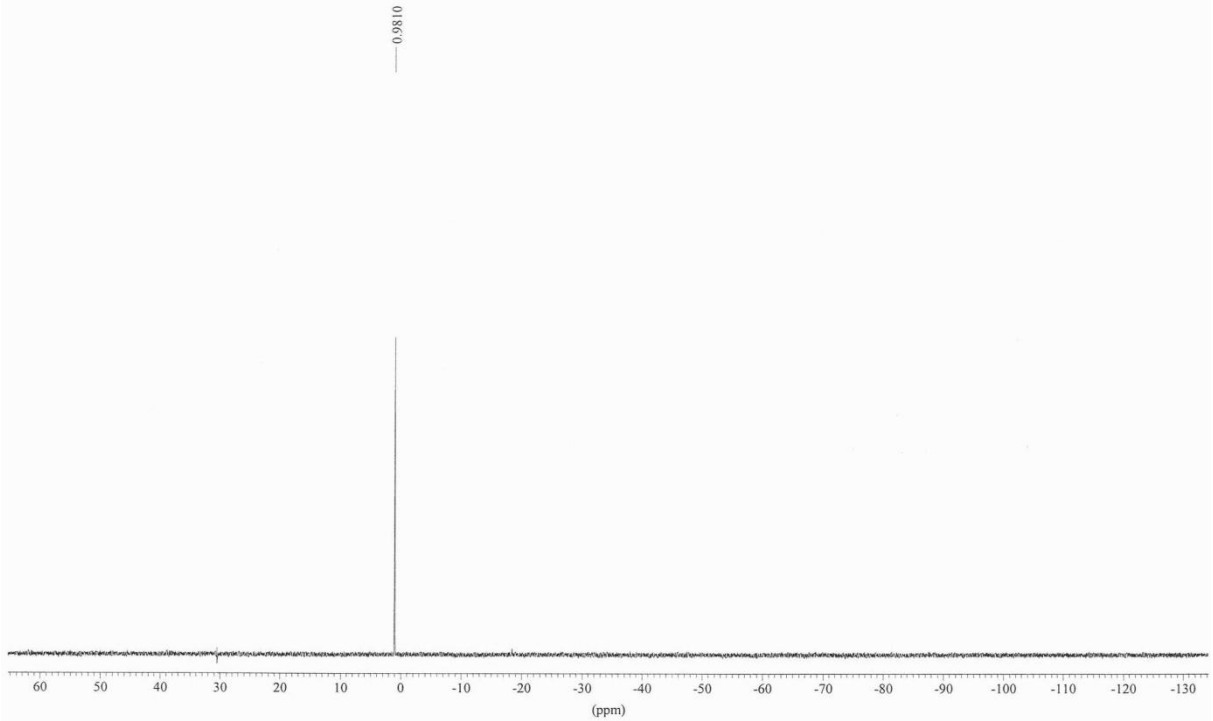
HMQC NMR spectrum



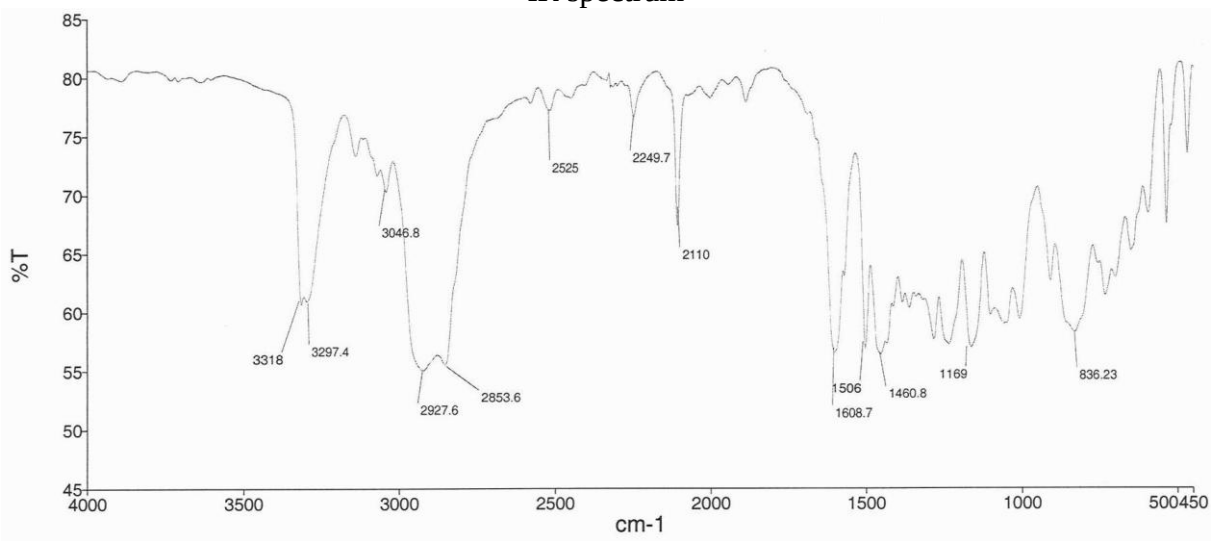
HMBC NMR spectrum



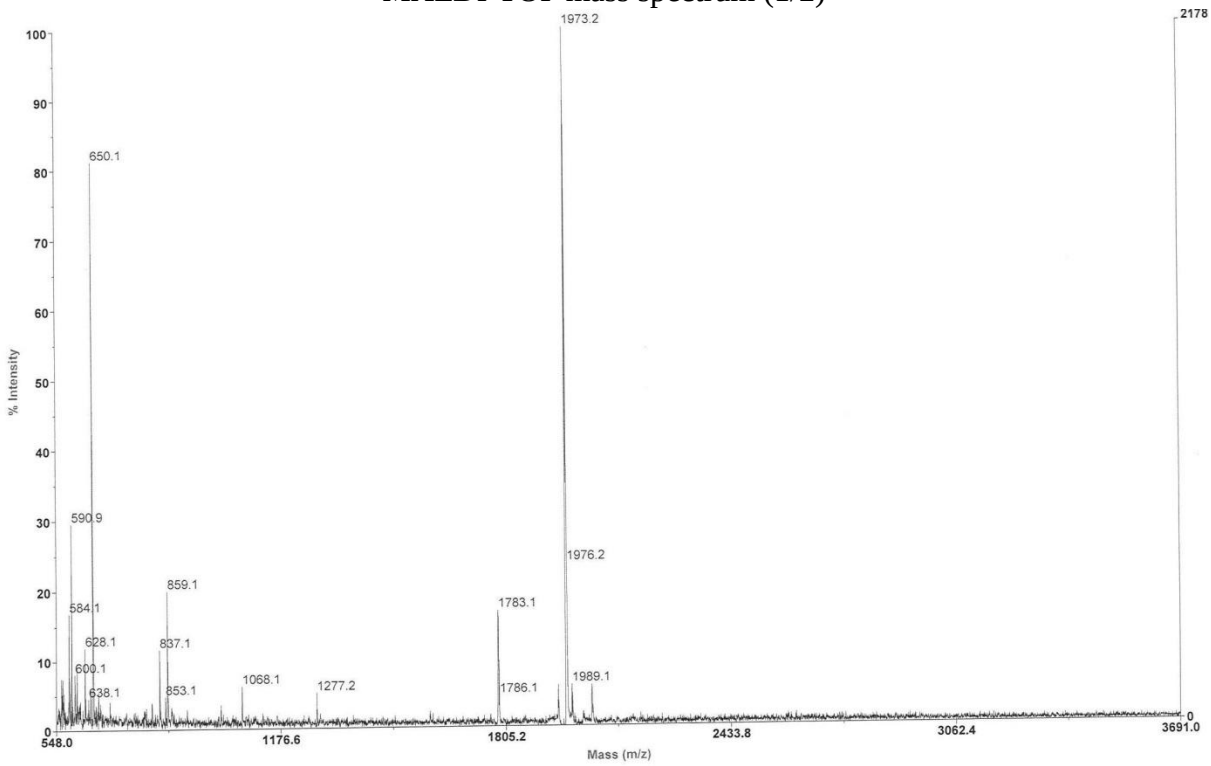
^{29}Si NMR spectrum



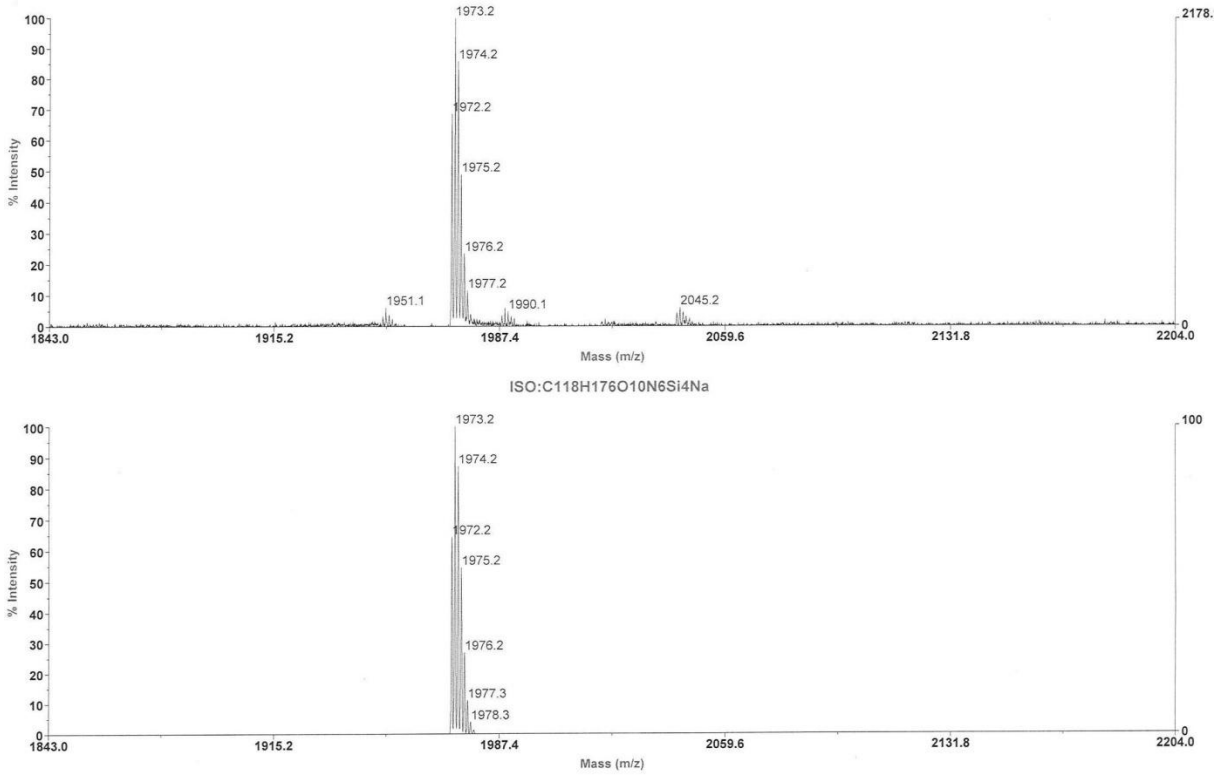
IR spectrum



MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



Sample Details

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Batch Name: ISM — K of Sample: 14.1000
Injection Volume: 100.0 ul — Alpha of Sample: 0.7000

Workbook Details

Eluent: DMF LiBr 1g/l — Flow Rate: 1.00 ml/min
Column Set: PLgel 5µm MIXED-D — Column Set Length: 650 mm
Detector: RI — Temperature: 80

Analysis Using Method: Calibration PS-M Easivial 26-04-10

Results File: C:\Cirrus Workbooks\Niko\Niko GPC DMF RI\ism-0008-Repeat (01).rst

Calibration Used: 29/04/2010 18:00:04

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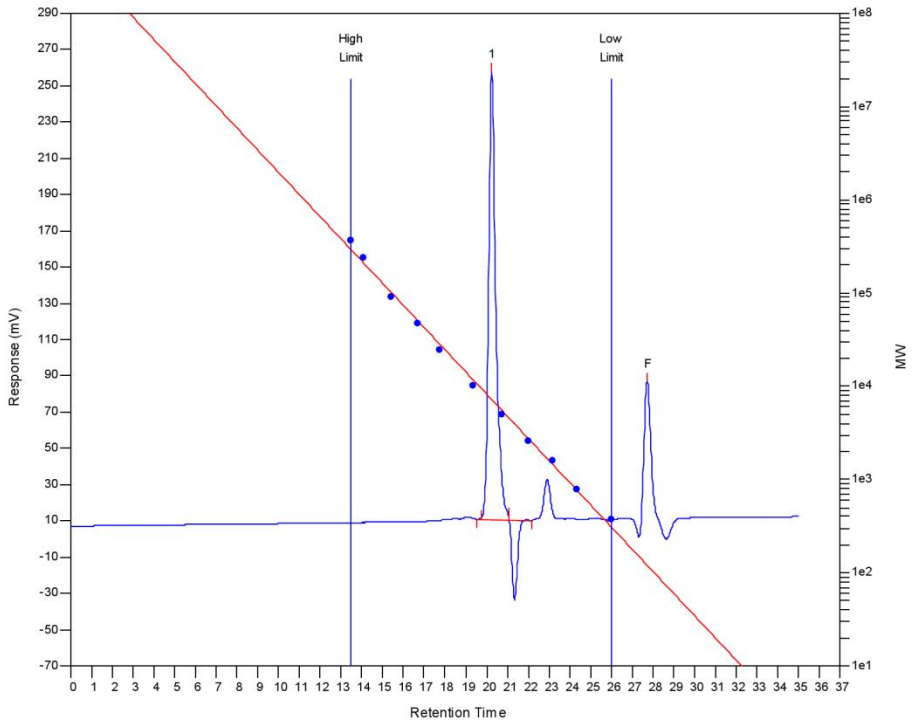

MW Averages

Peak No	Mp	Mn	Mw	Mz	Mz+1	Mv	PD
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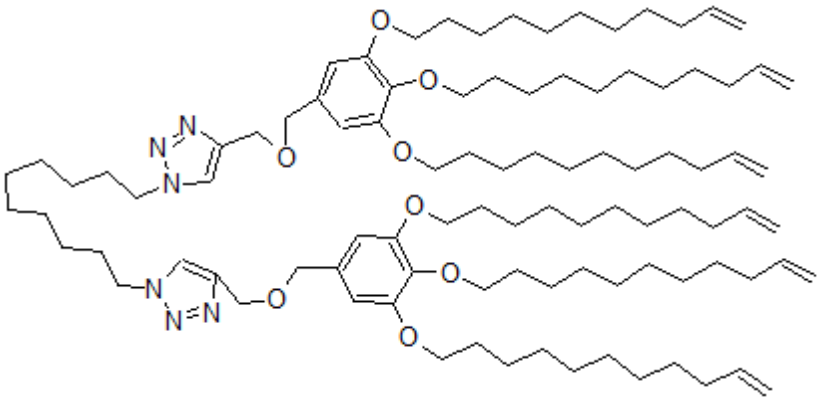
2	120	114	116	117	118	115	1.01754

Cirrus GPC Version 3.2 — Page 1 — 10/05/2010 16:52

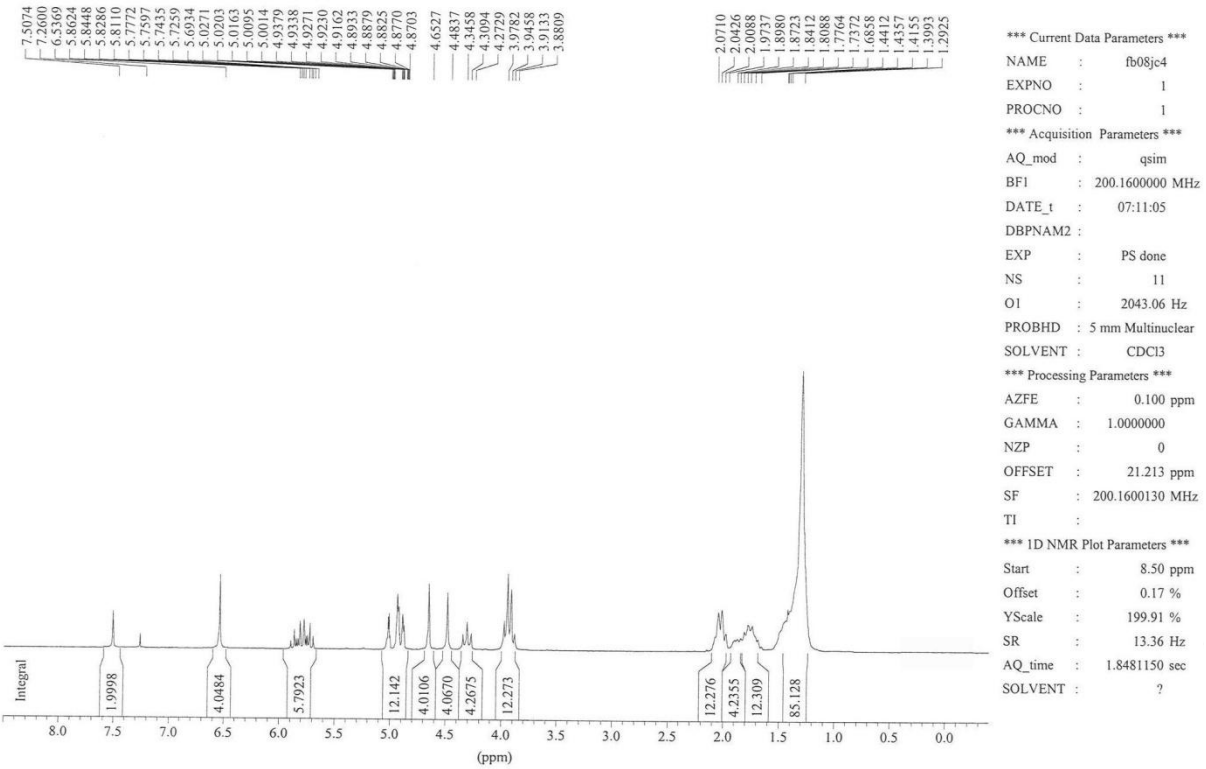
Synthesis of the G_1-hexa alkene dendrimer 14



1,10-diazidodecane **1** (0.27g, 1.20mmol, 1eq) and 1,2,3-tris(10-undecen-1-yloxy)-5-[(2-propyn-1-yloxy)methyl]benzene **7** (3.15g, 4.81mmol, 4eq) were dissolved in 20mL of dichloromethane. A solution of $CuSO_4.5H_2O$ (2.4g, 9.63mmol ,8eq) in 10mL of water was then added. The reaction mixture was energically stirred. A solution of sodium ascorbate (3.8g, 19.3mmol, 16eq) was then added dropwise. The medium was stirred at room temperature for one night. Dichloromethane was removed *in vacuo*. The aqueous layer was extracted two times with diethyl ether and the organic layers were mixed. The organic layer was then washed with an ammonia solution until the aqueous layer was colorless. The organic layer was then washed with water to neutrality. The organic layer was dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a yellow to light brown waxy product (1.37g, 0.90mmol) in 75% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.51 ppm (s, $H_{triazole}$, 2H); 6.54 ppm (s, H_{Ar}, 4H); 5.78 ppm (m, -C*H*=CH_2, 6H); 5.03 to 4.87 ppm (m, -CH=CH_2, 12H); 4.65 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.48 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.31 ppm (t, -CH_2-$N_{triazole}$, ^{3}J = 7.3Hz, 4H); 3.92 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 2.04 ppm (m, -CH_2-CH=CH_2, 12H); 1.88 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.50 to 1.25 ppm (m, -CH_2-, 84H)
JMOD NMR ($CDCl_3$ 50.3MHz): 153.07 ppm (meta C_{ar}-O); 144.97 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.05 ppm (-*C*H=CH_2); 137.71 ppm (para C_{ar}-O); 132.74 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.25 ppm ($C_{triazole}$-H) ; 114.02 ppm (-CH=*C*H_2); 106.42 ppm (C_{ar}-H); 73.28 ppm (para -O-*C*H_2-CH_2-) ; 72.78 ppm (C_{Ar}-*C*H_2-O-CH_2-$C_{triazole}$); 69.00 ppm (meta -O-*C*H_2-CH_2-); 63.51 ppm (C_{Ar}-CH_2-O-*C*H_2-$C_{triazole}$); 50.20 ppm (-*C*H_2-$N_{triazole}$); 33.69, 30.14, 29.41, 29.31, 29.27, 29.17, 29.07, 29.01, 28.81, 26.30 and 25.95 ppm (-*C*H_2-)
IR spectroscopy (cm^{-1}) : 3081.5 ; 2934.8 ; 2861.5
MALDI-TOF mass spectrometry : $[M+Na]^+$ m/z 1548.61

^{1}H NMR spectrum

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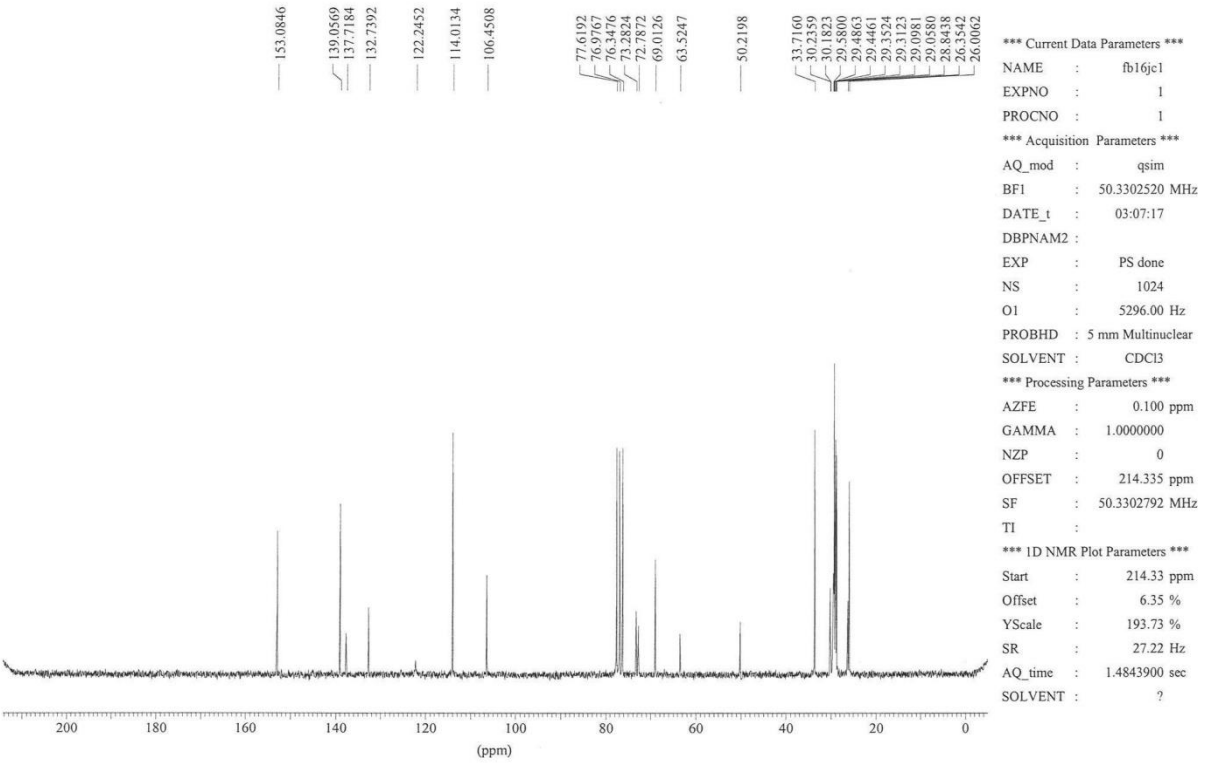
^{13}C NMR spectrum

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TI        :
*** 1D NMR Plot Parameters ***
Start     :     214.33 ppm
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SR        :      27.22 Hz
AQ_time   :  1.4843900 sec
SOLVENT   :          ?
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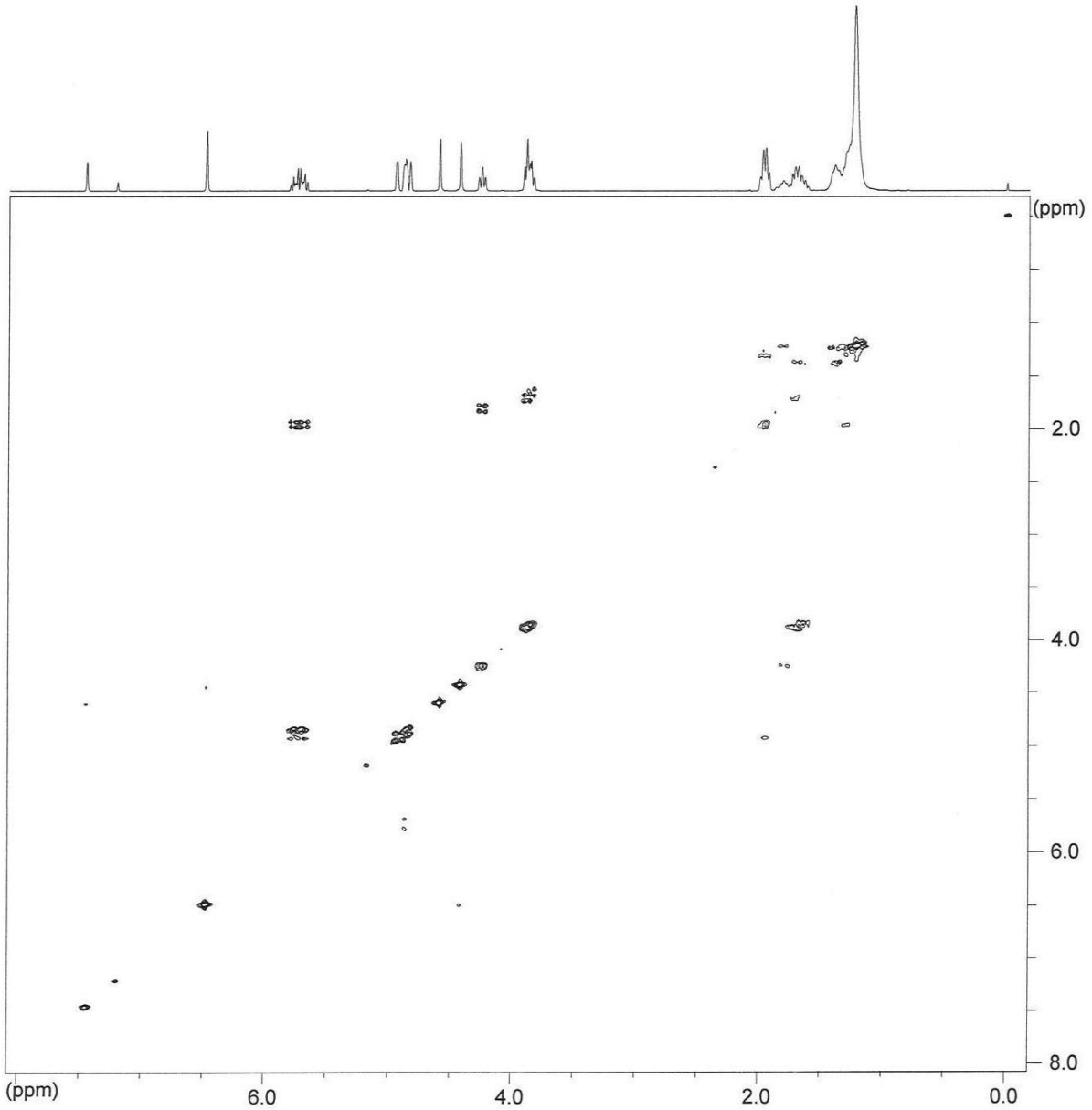
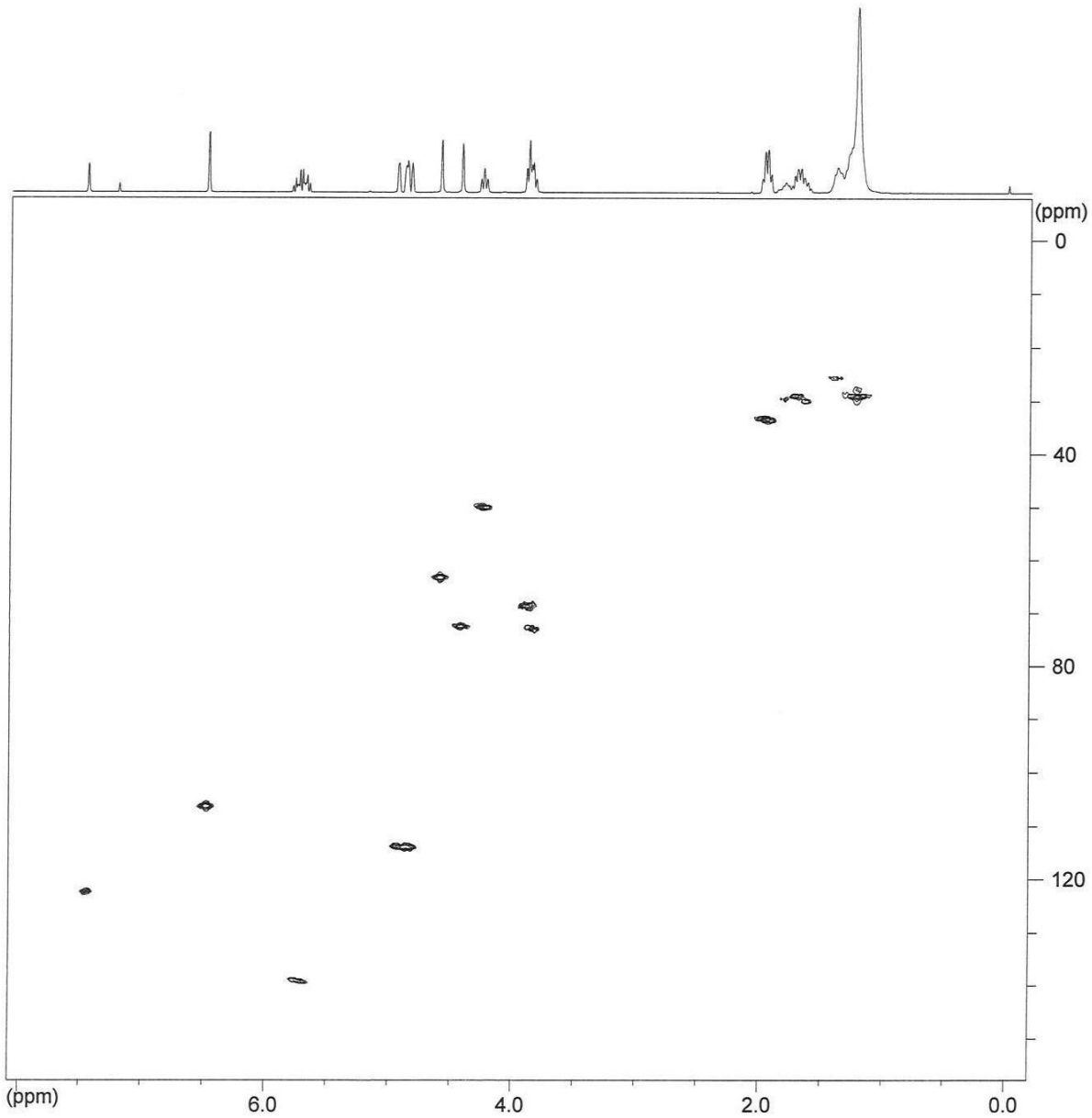
COSY NMR spectrum



HMQC NMR spectrum



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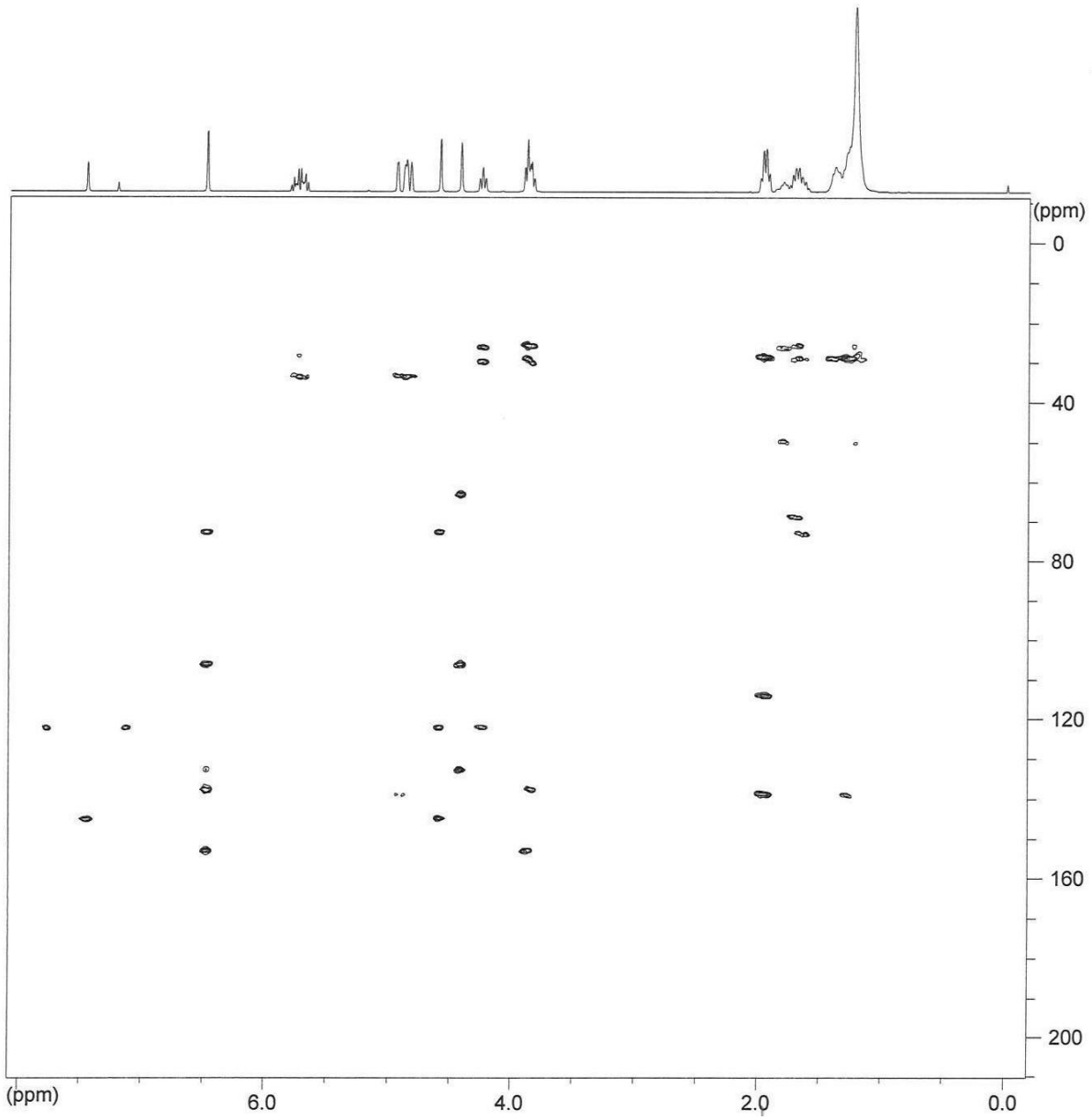
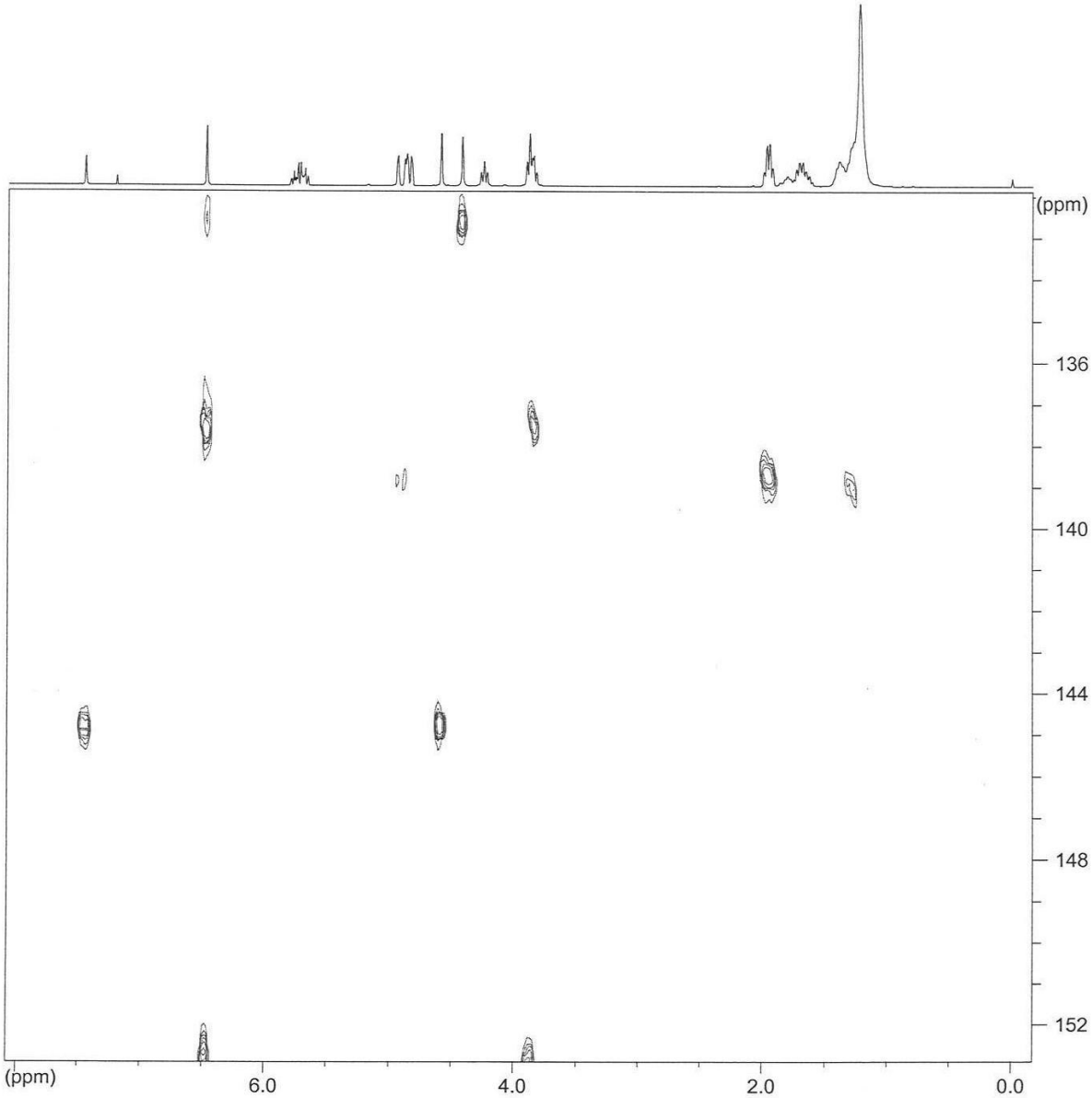
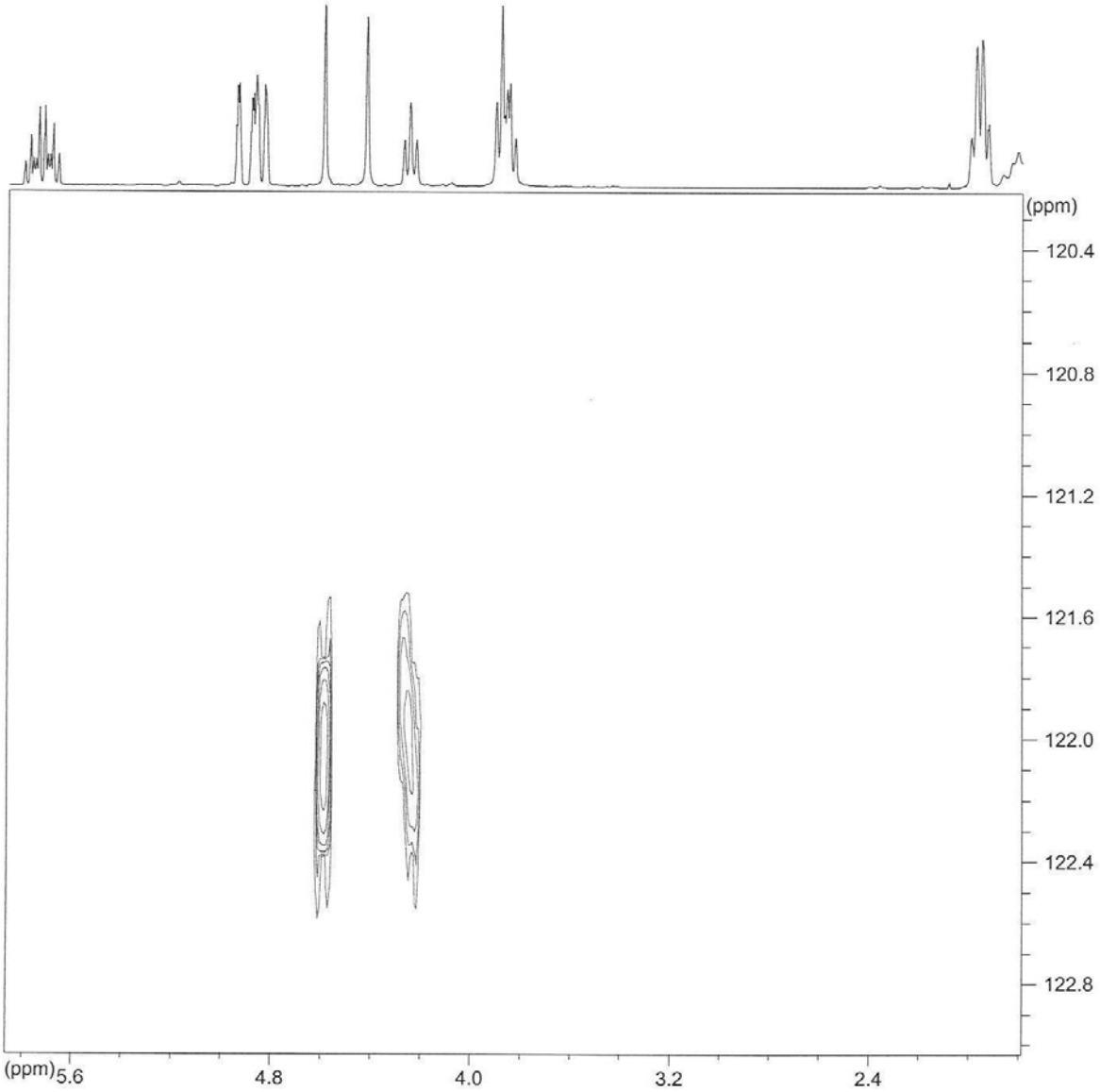


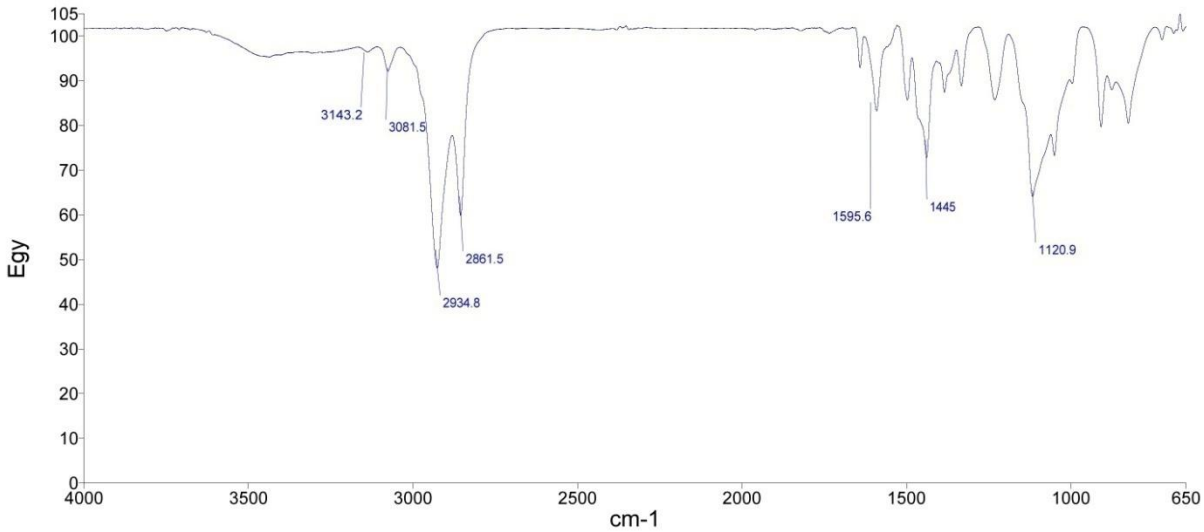
HMBC NMR spectrum (zoom)



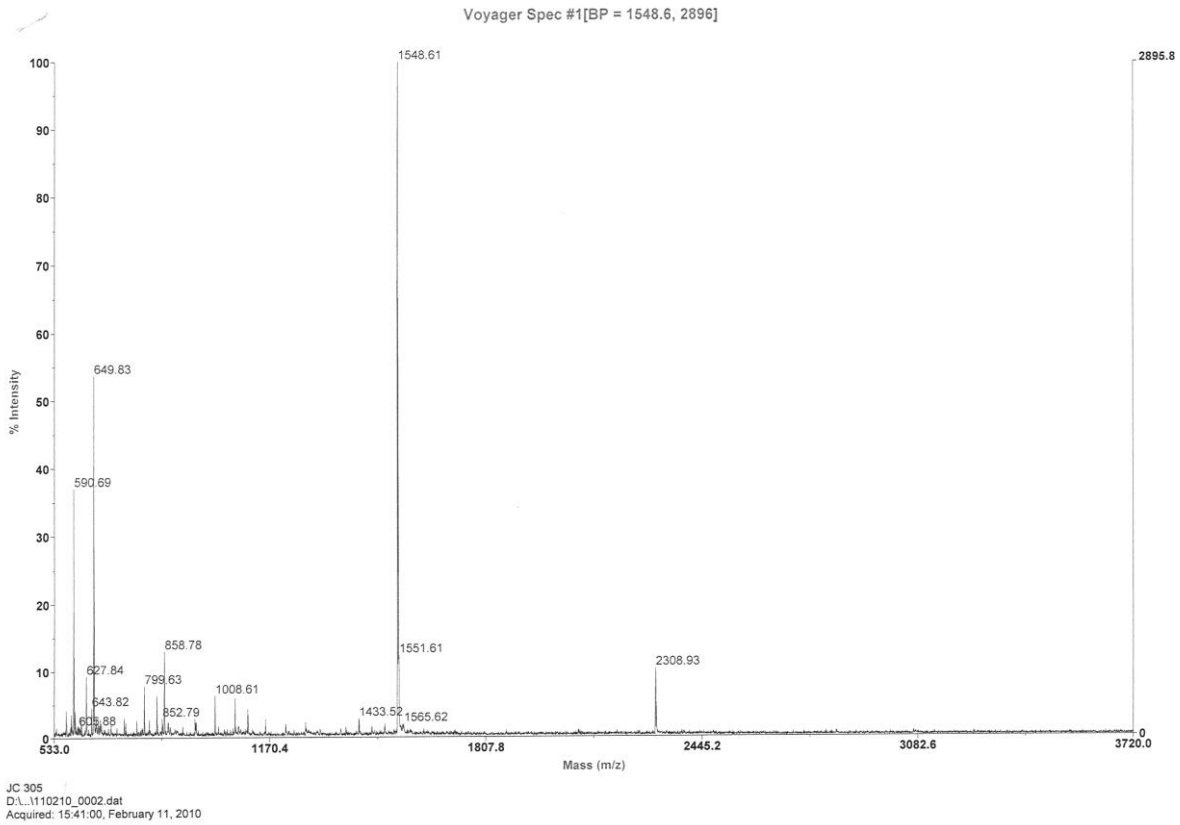
HMBC NMR spectrum (zoom)



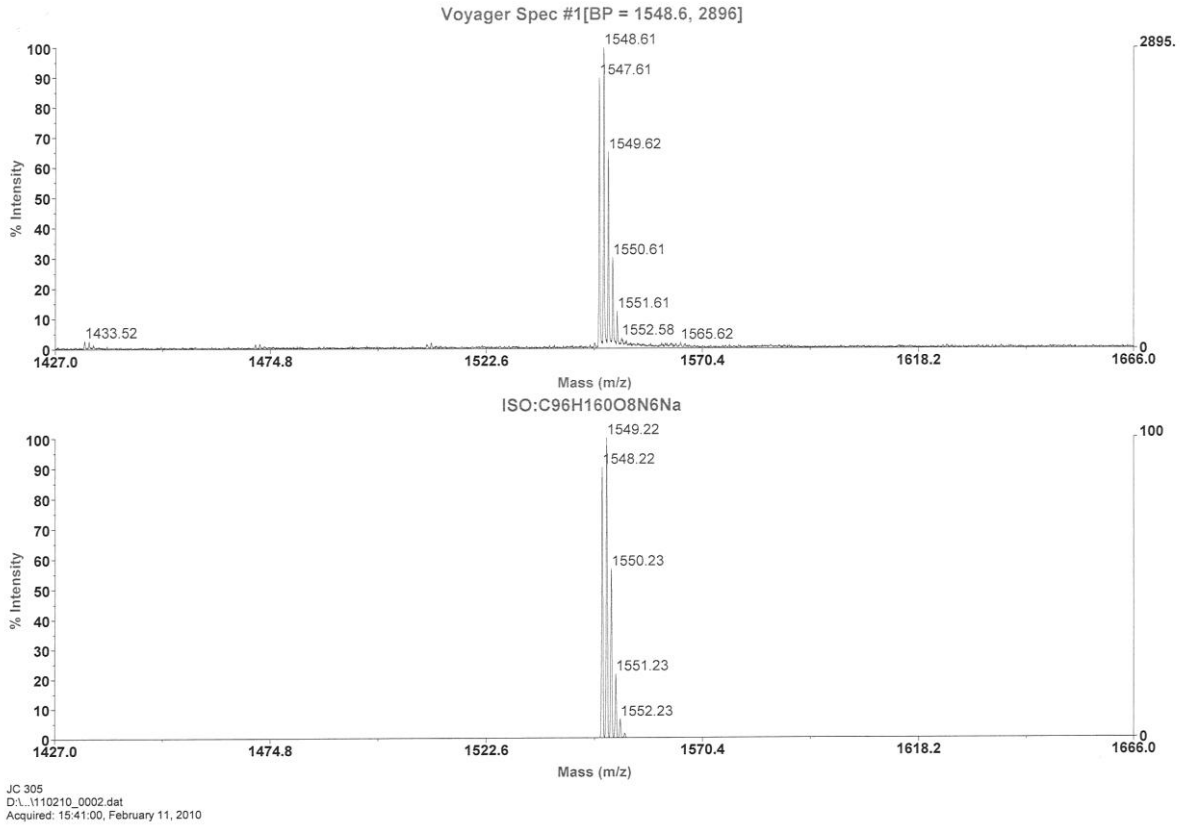
IR spectrum



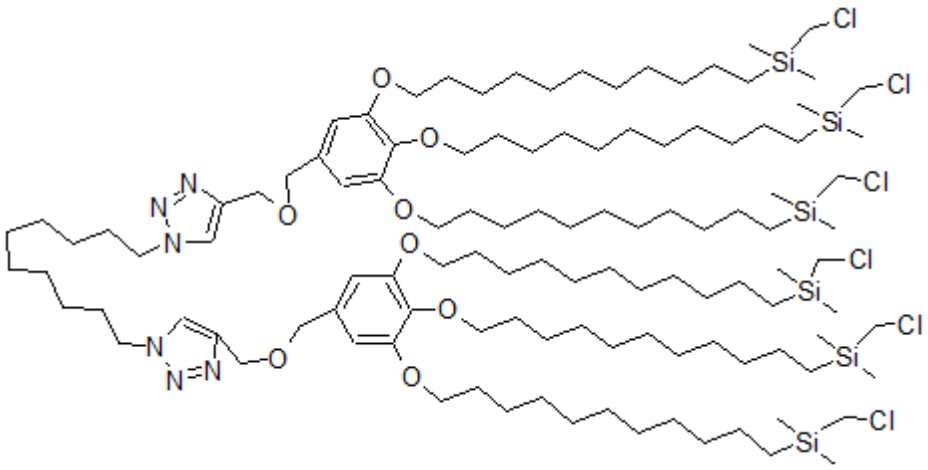
MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



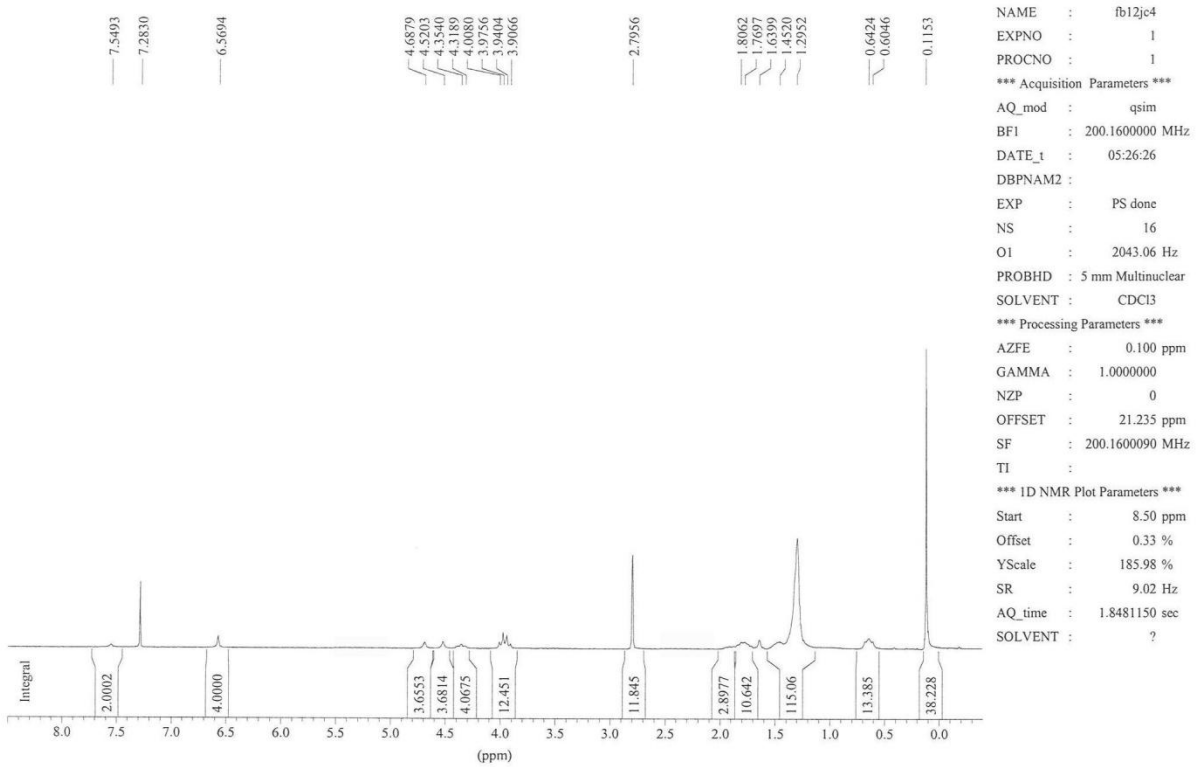
Synthesis of G_1-hexa chloro dendrimer 15



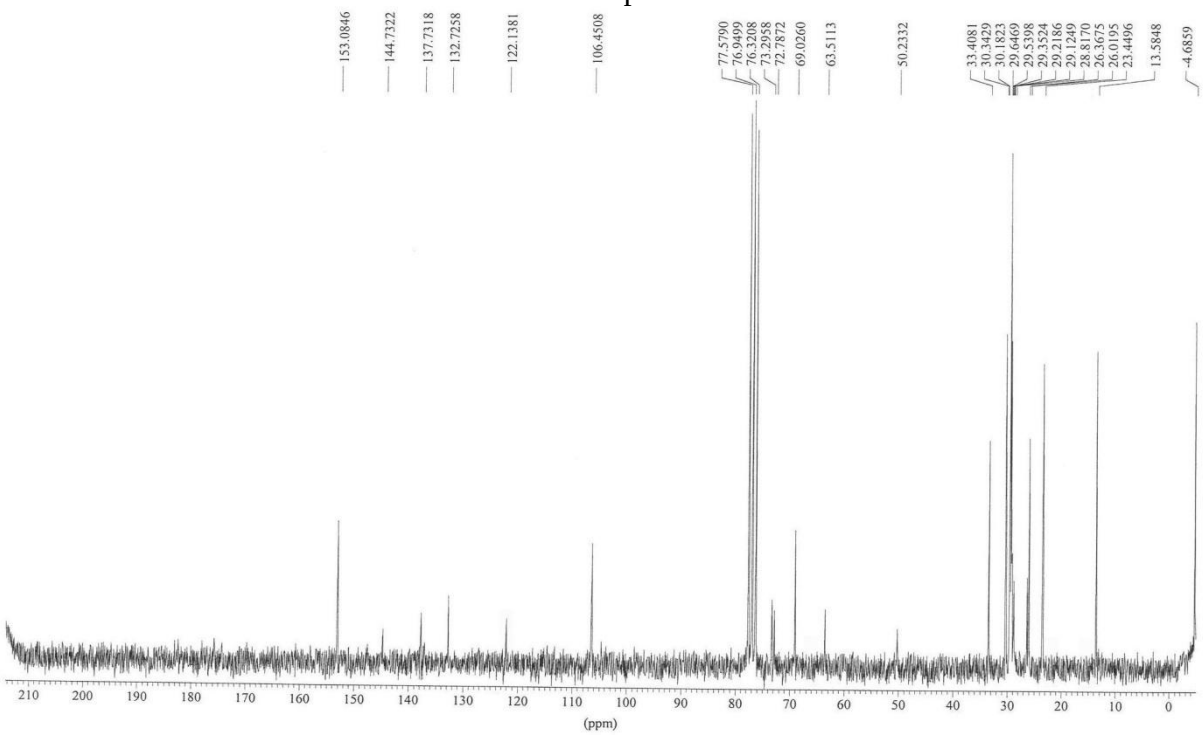
Dry G1-hexa alkene dendrimer **14** (1.1g, 0.72mmol, 1eq) was dissolved in 30mL distillated diethyl ether. In a glove box, chloromethyldimethylsilane (1.1mL, 8.65mmol, 12eq) and then Karstedt catalyst (10 drops) were added. The medium was stirred at room temperature for one night. The solvant and the excess silane were removed *in vacuo*. Dichloromethane was added and the medium was stirred in contact with the air. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a yellow waxy product (1.37g, 0.63mmol) in 87% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.55 ppm (s, $H_{triazole}$, 2H); 6.57 ppm (s, H_{Ar}, 4H) ; 4.69 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.52 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.32 ppm (t, -CH_2-$N_{triazole}$, ^{3}J = 7.0Hz, 4H); 3.94 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 2.80 ppm (s, Si-CH_2-Cl, 12H); 1.81 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.50 to 1.25 ppm (m, -CH_2-, 108H) ; 0.62 ppm (t, -CH_2-CH_2-Si, ^{3}J = 7.6Hz, 12H) ; 0.11 ppm (s, Si-CH_3, 36H)
JMOD NMR ($CDCl_3$ 50.3MHz): 153.09 ppm (meta C_{ar}-O); 144.73 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 137.72 ppm (para C_{ar}-O); 132.73 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.14 ppm ($C_{triazole}$-H) ; 106.45 ppm (C_{ar}-H); 73.29 ppm (para -O-CH_2-CH_2-) ; 72.79 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 69.02 ppm (meta -O-CH_2-CH_2-); 63.51 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 50.22 ppm (-CH_2-$N_{triazole}$); 33.40, 30.34 and 30.25 ppm (-CH_2-) ; 29.64 ppm (-Si-CH_2-Cl) ; 29.55, 29.50, 29.35, 29.23, 29.12, 28.81, 26.37, 26.03 and 23.45 ppm (-CH_2-); 13.58 ppm (-CH_2-CH_2-Si) ; -4.68 ppm (Si-CH_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 4.00 ppm
MALDI-TOF mass spectrometry : $[M+Na]^+$ m/z = 2199.2

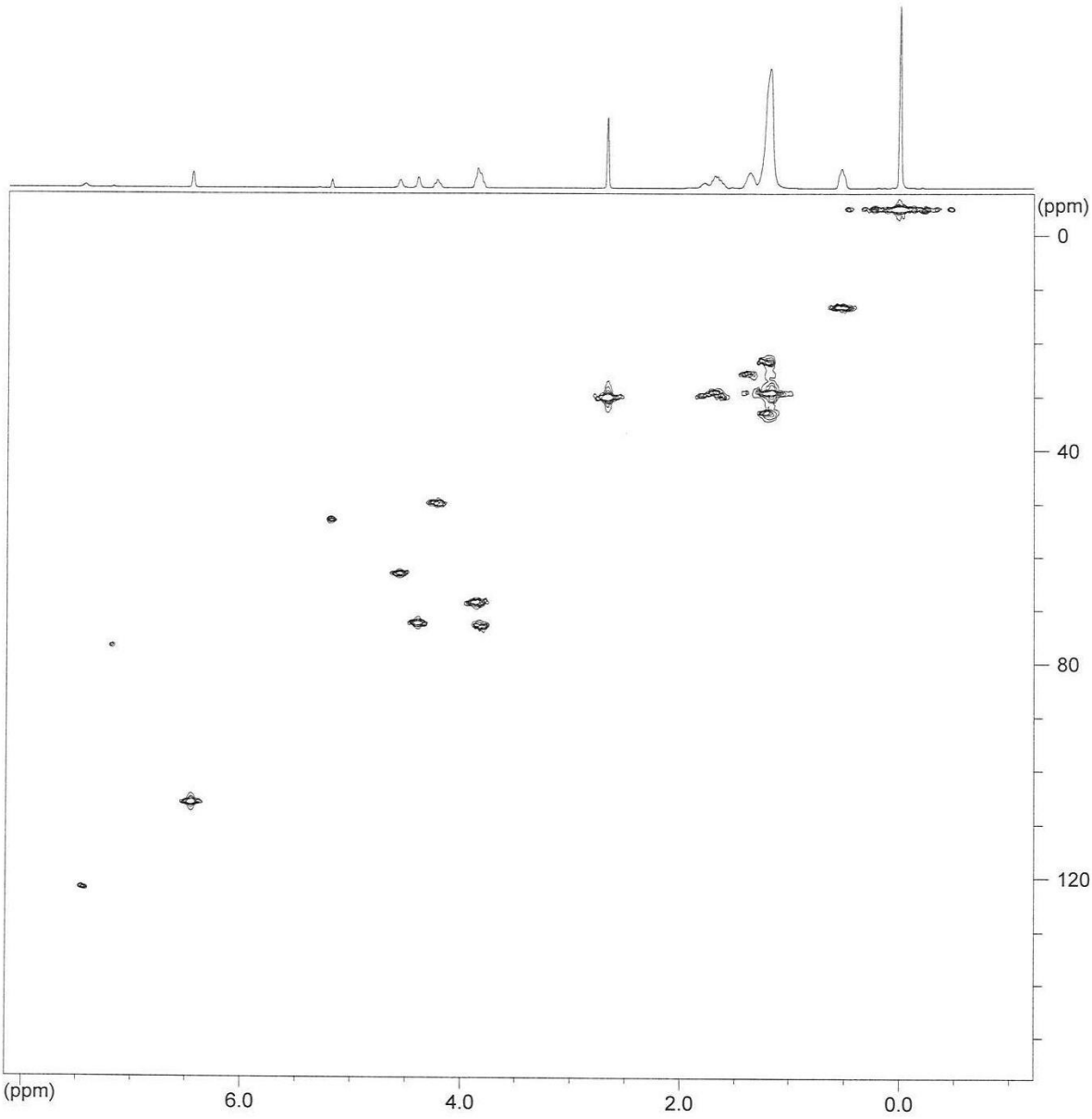
^{1}H NMR spectrum



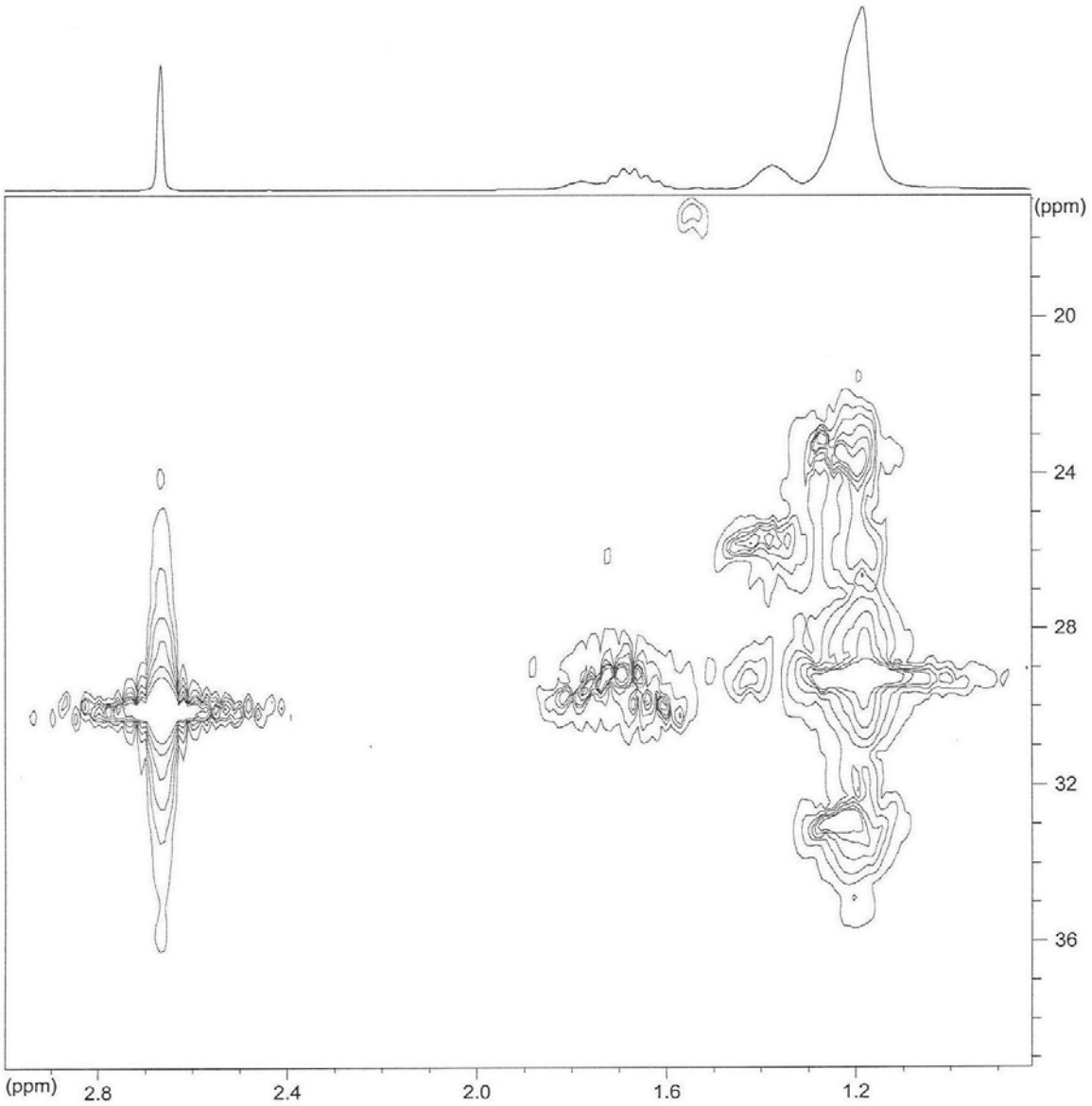
^{13}C NMR spectrum



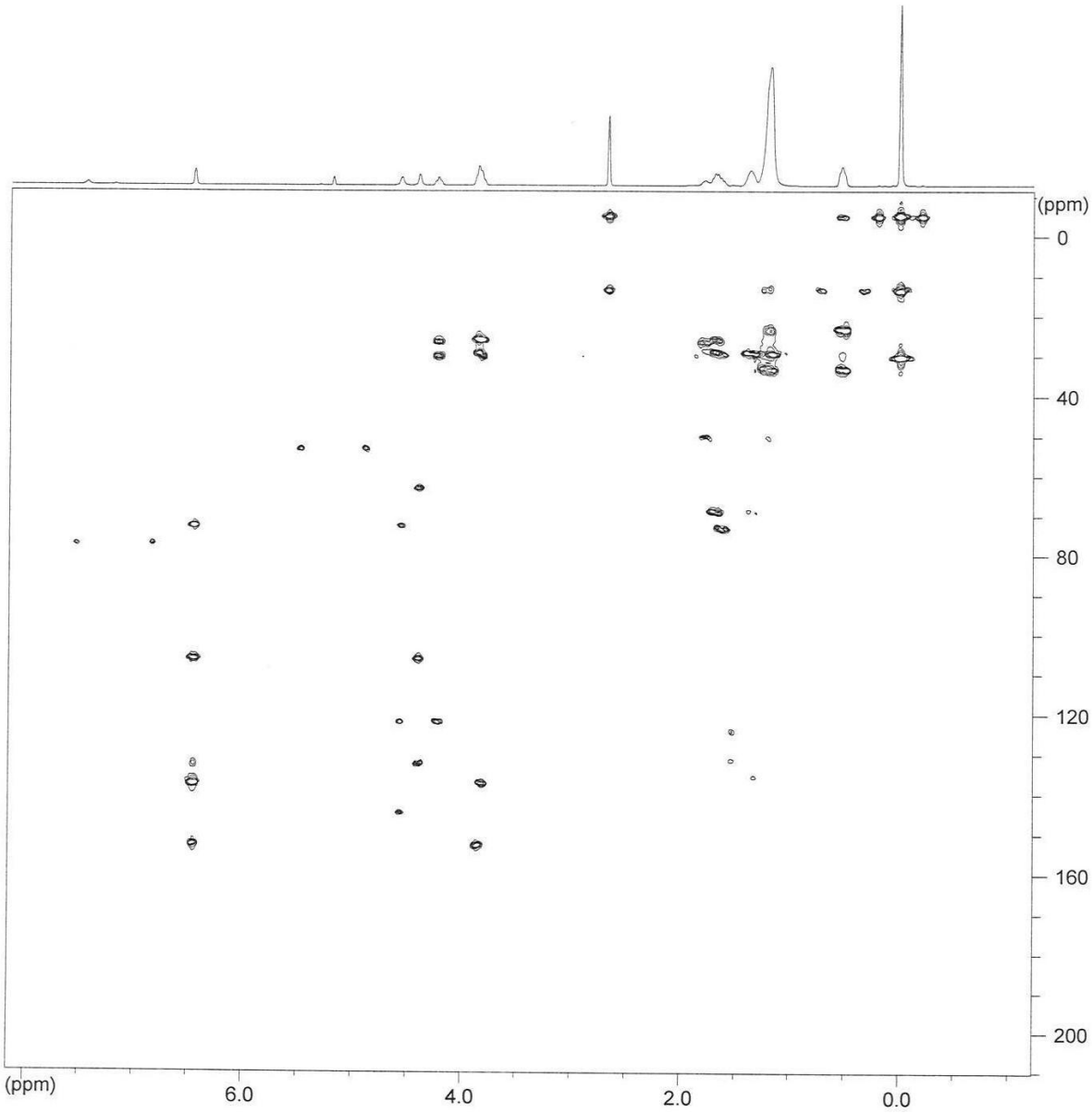
HMQC NMR spectrum



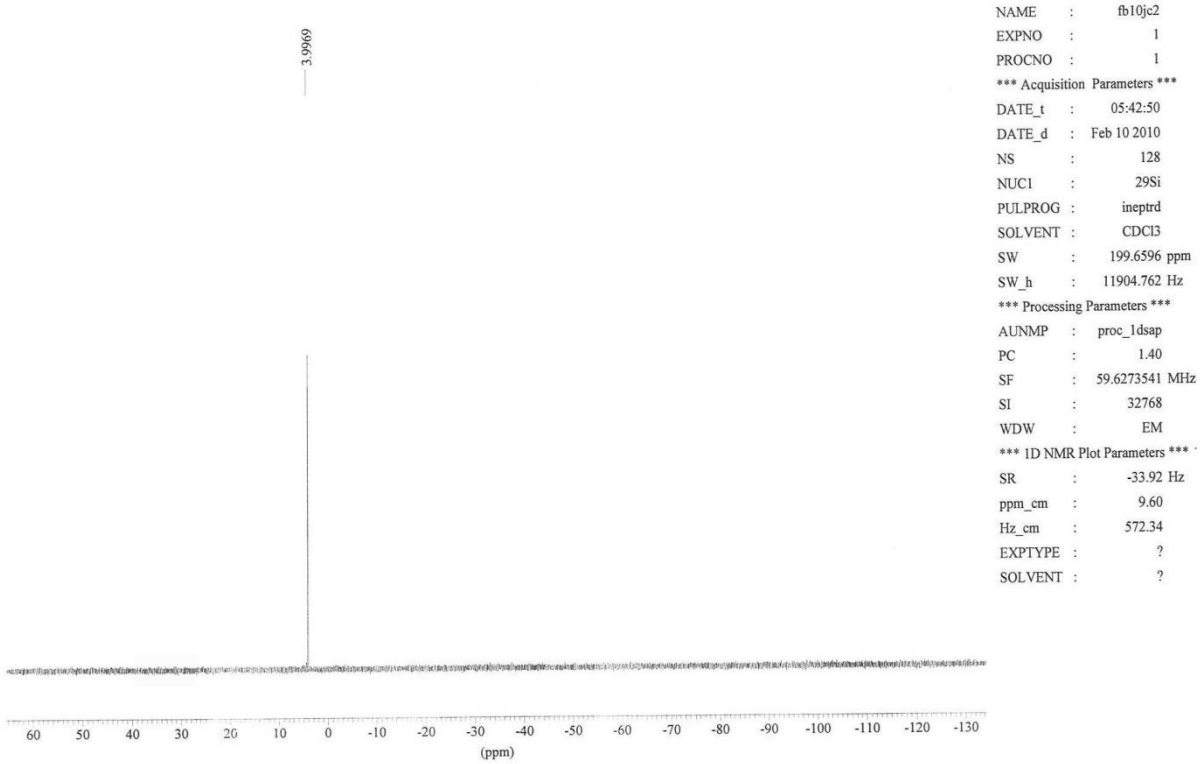
HMQC NMR spectrum (zoom)



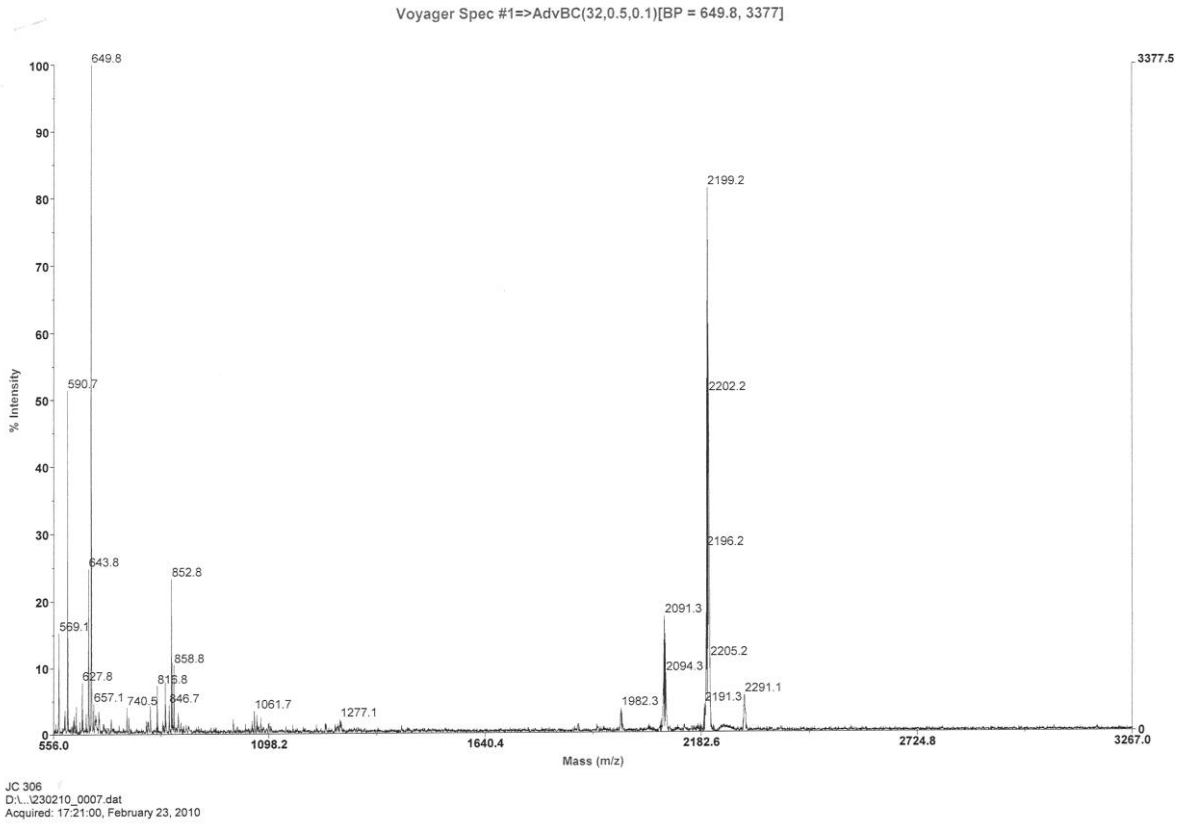
HMBC NMR spectrum



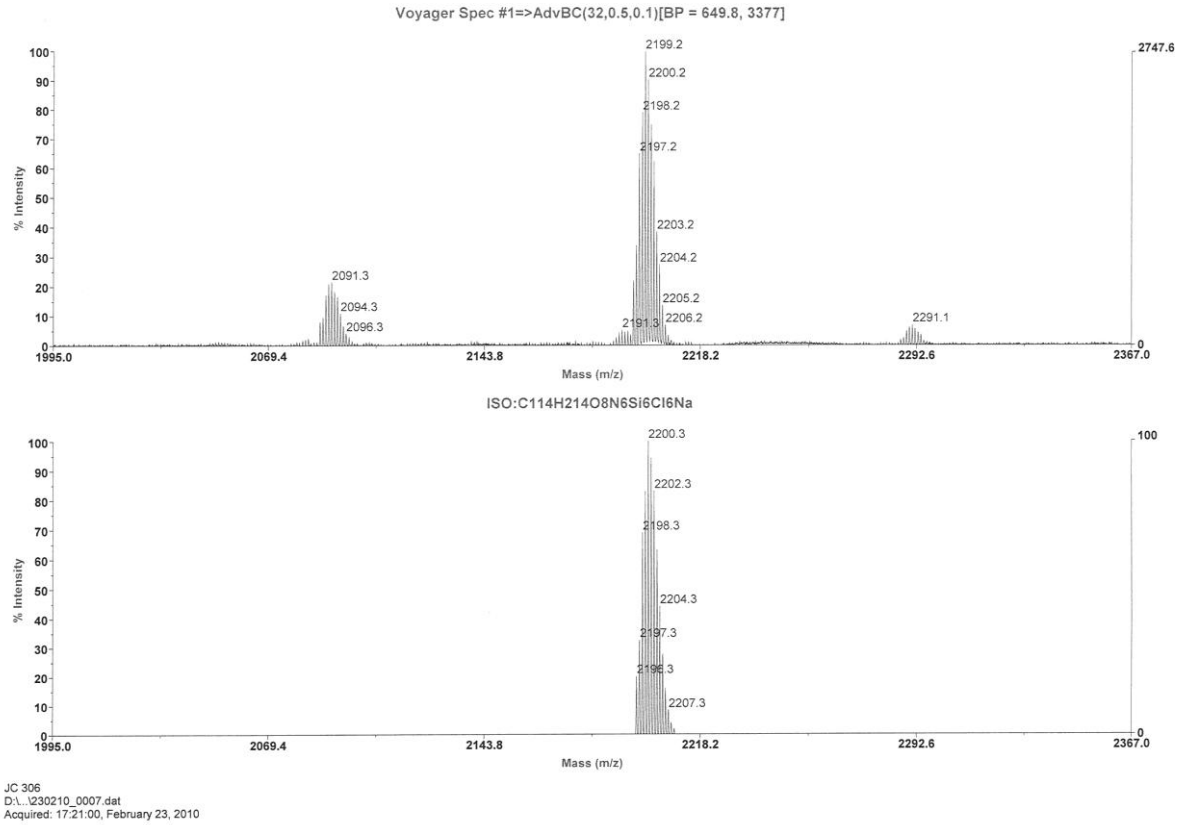
^{29}Si NMR spectrum



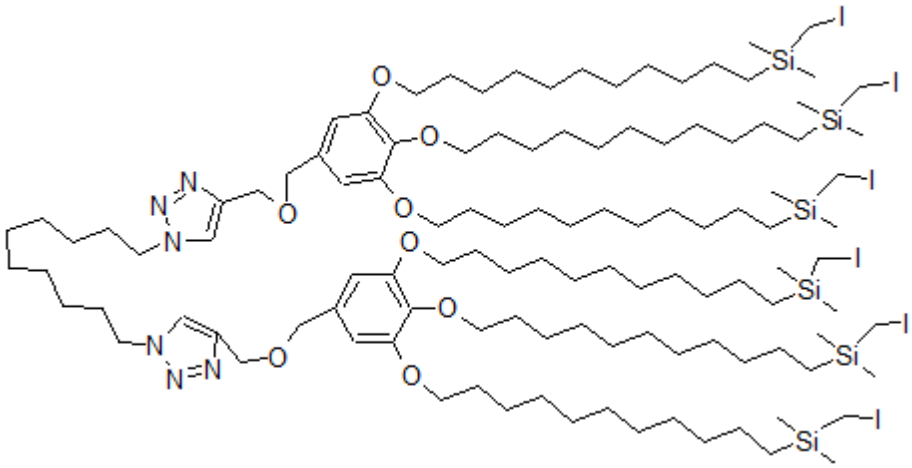
MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



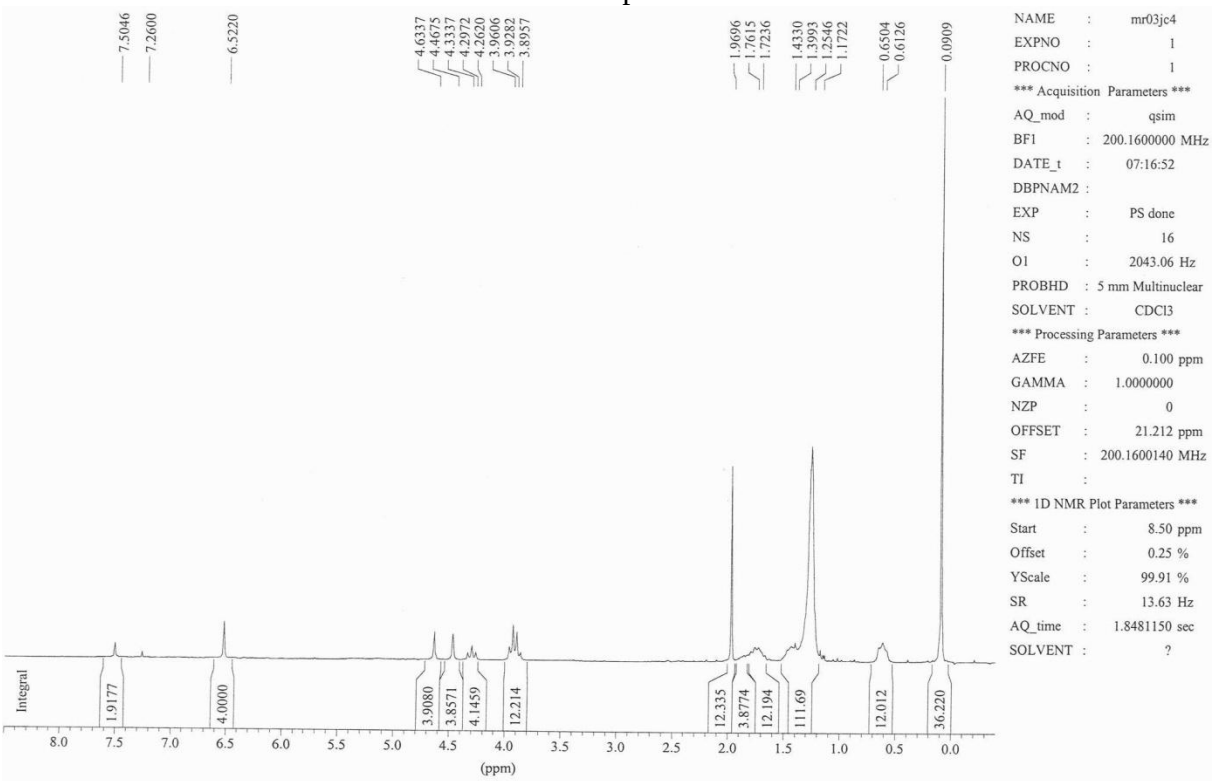
Synthesis of G_1-hexa iodo dendrimer 16



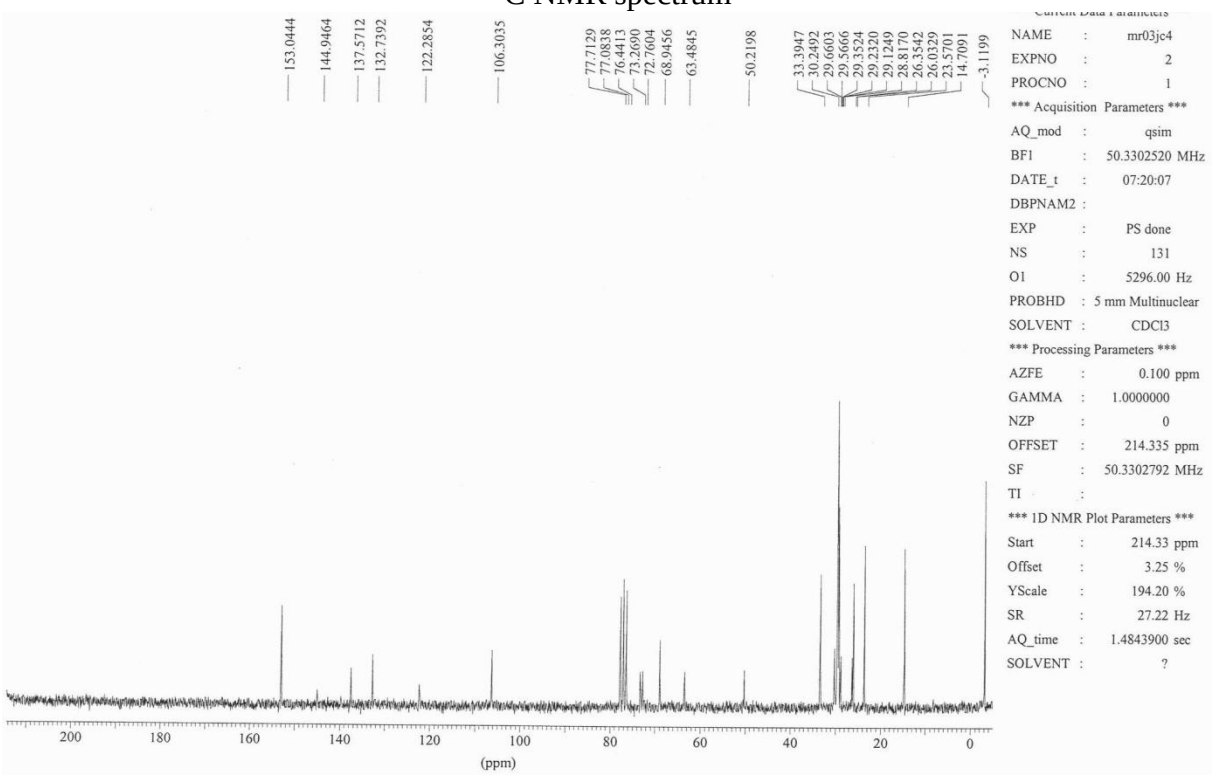
To a solution of G_1-hexa chloro dendrimer **15** (1.37g, 0.63mmol, 1eq) in 50mL butanone was added NaI (1.13g, 7.55mmol, 12eq). The medium was stirred under reflux for 5h. Solvent was removed *in vacuo*. Dichloromethane was added. The medium was filtered. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a yellow waxy product (1.61g, 0.59mmol) in 94% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.50 ppm (s, $H_{triazole}$, 2H); 6.52 ppm (s, H_{Ar}, 4H) ; 4.63 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.47 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.30 ppm (t, -CH_2-$N_{triazole}$, ^{3}J = 7.2Hz, 4H); 3.93 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.97 ppm (s, Si-CH_2-I, 12H); 1.81 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.50 to 1.25 ppm (m, -CH_2-, 108H) ; 0.61 ppm (t, -CH_2-CH_2-Si, ^{3}J = 7.6Hz, 12H) ; 0.09 ppm (s, Si-CH_3, 36H)
JMOD NMR ($CDCl_3$ 100.6MHz): 153.36 ppm (meta-C_{ar}-O); 144.27 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 137.88 ppm (para-C_{ar}-O) ; 133.02 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.59 ppm ($C_{triazole}$-H) ; 106.63 ppm (C_{ar}-H); 73.59 ppm (para -O-CH_2-CH_2-) ; 73.10 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 69.27 ppm (meta -O-CH_2-CH_2-); 63.80 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 50.53 ppm (-CH_2-$N_{triazole}$); 33.70, 30.54, 30.51, 29.97, 29.88, 29.82, 29.66, 29.58, 29.55, 29.45, 29.13, 26.67, 26.34 and 23.87 ppm (-CH_2-); 15.02 ppm (-CH_2-CH_2-Si) ; -2.83 ppm (Si-CH_3); -12.77 ppm (Si-CH_2-I)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 5.1 ppm
^{127}I NMR ($CDCl_3$ 80.1MHz) : only one peak at 6358.0 ppm
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 2749.16

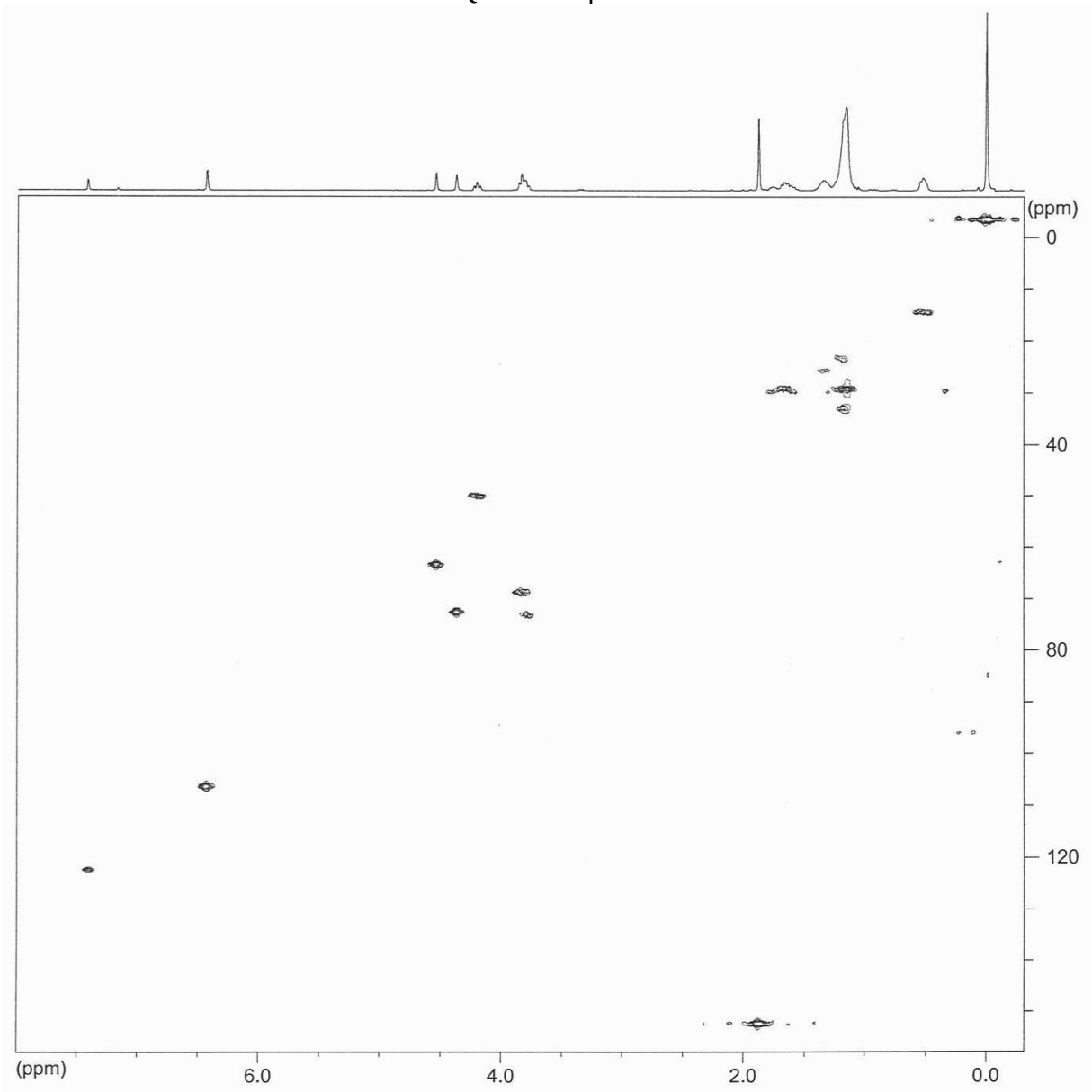
^{1}H NMR spectrum



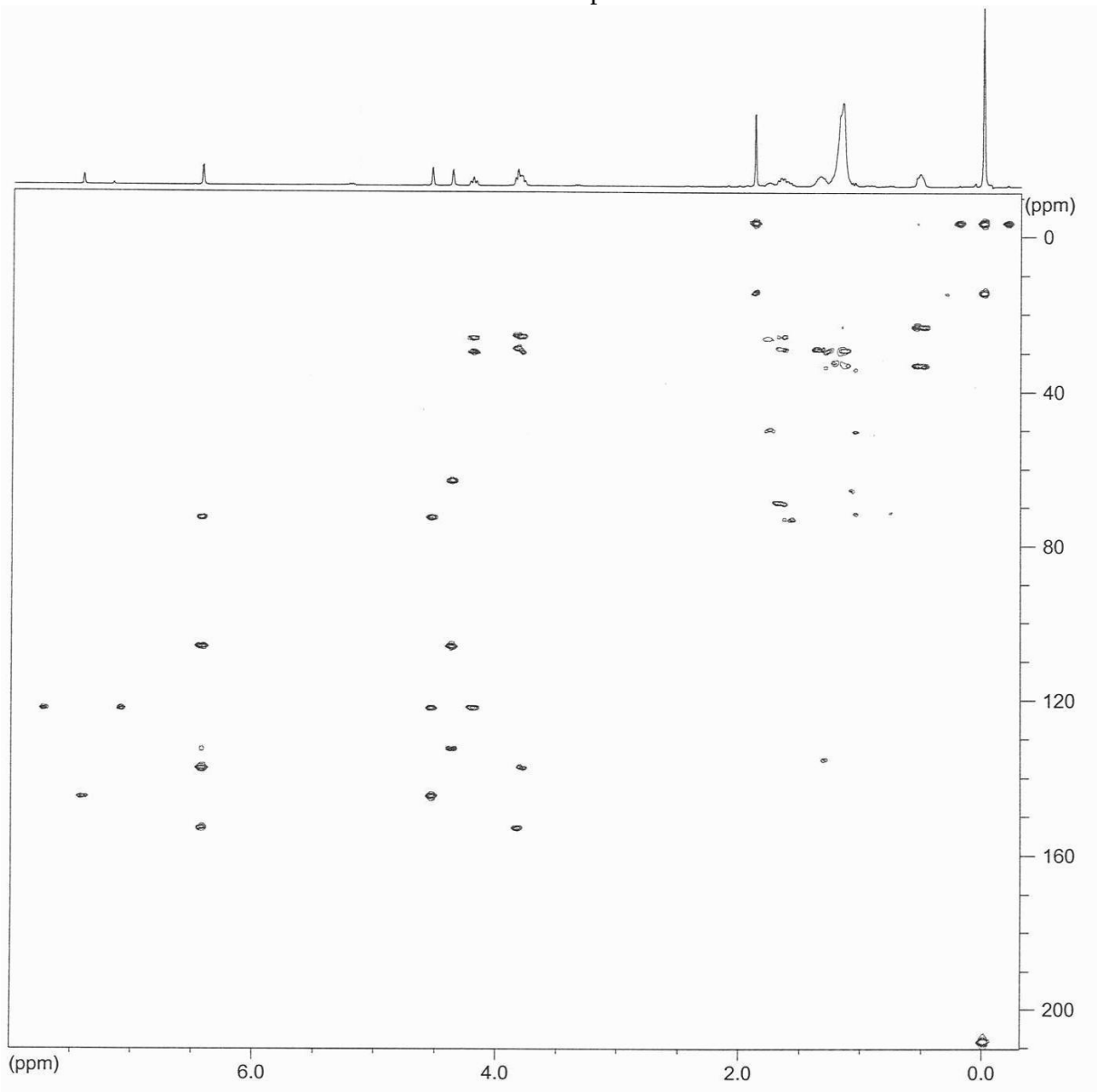
^{13}C NMR spectrum



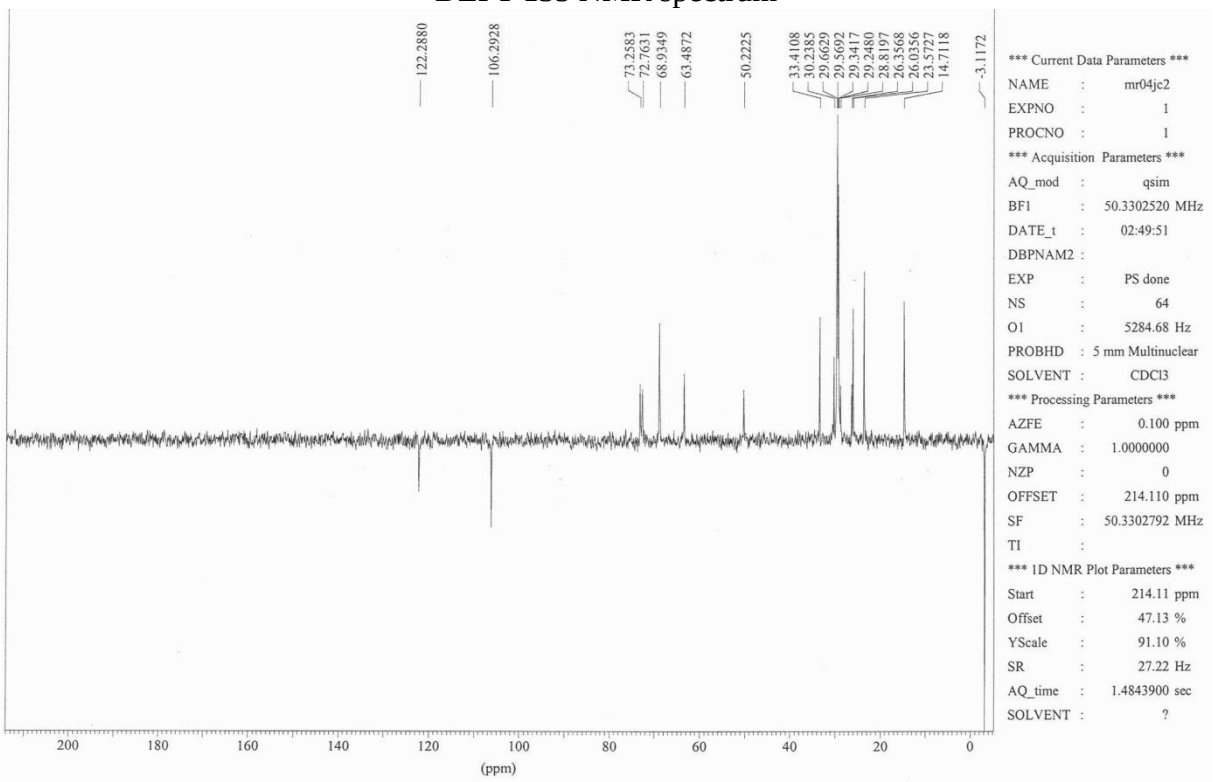
HMQC NMR spectrum



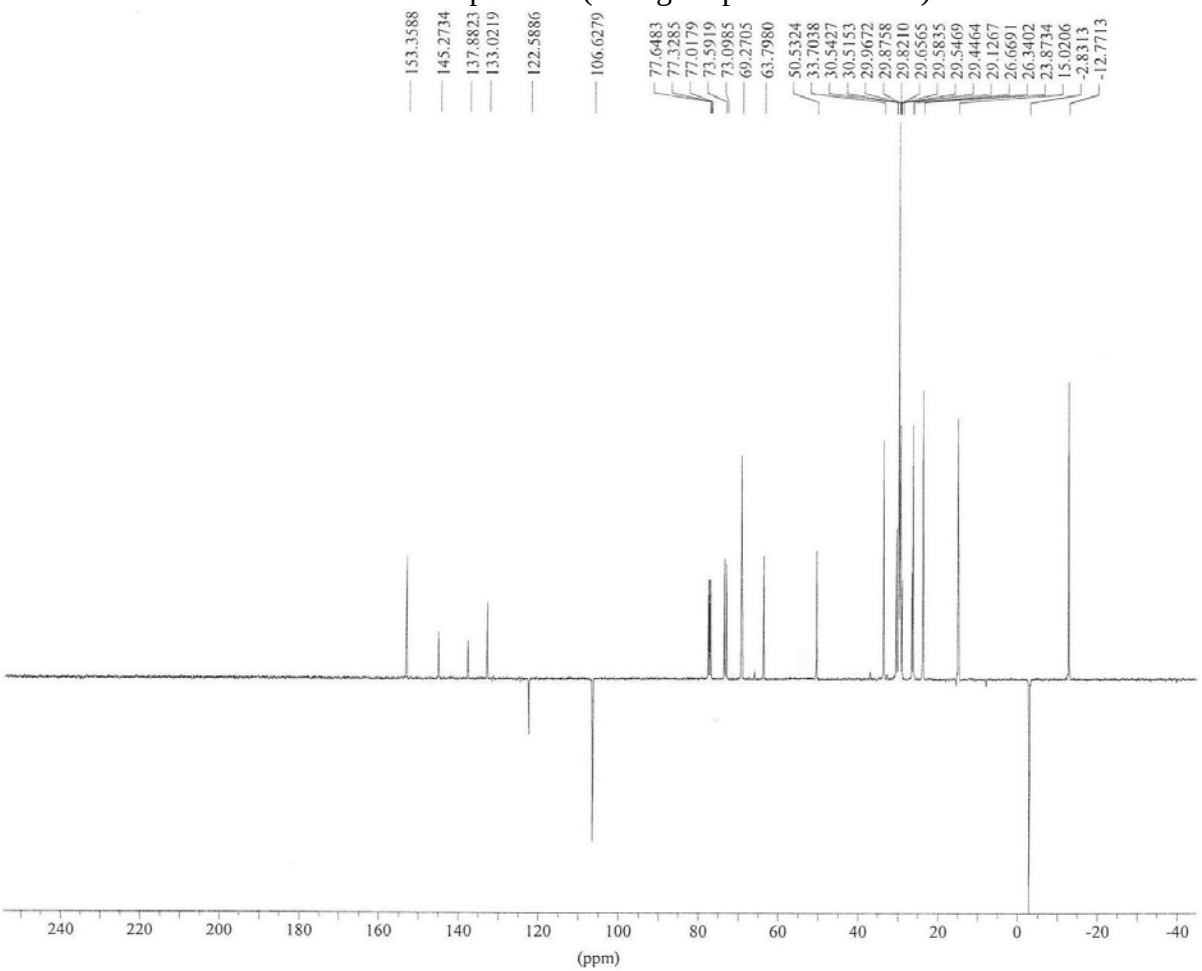
HMBC NMR spectrum



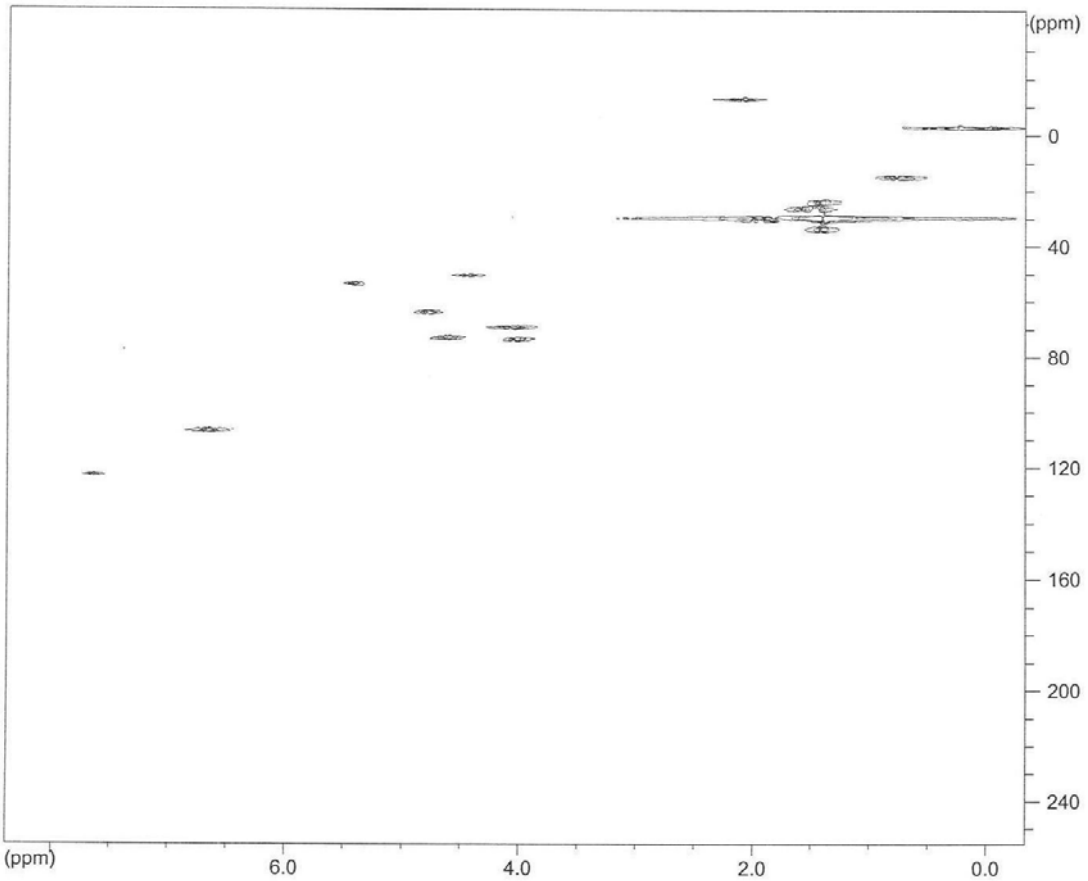
DEPT-135 NMR spectrum

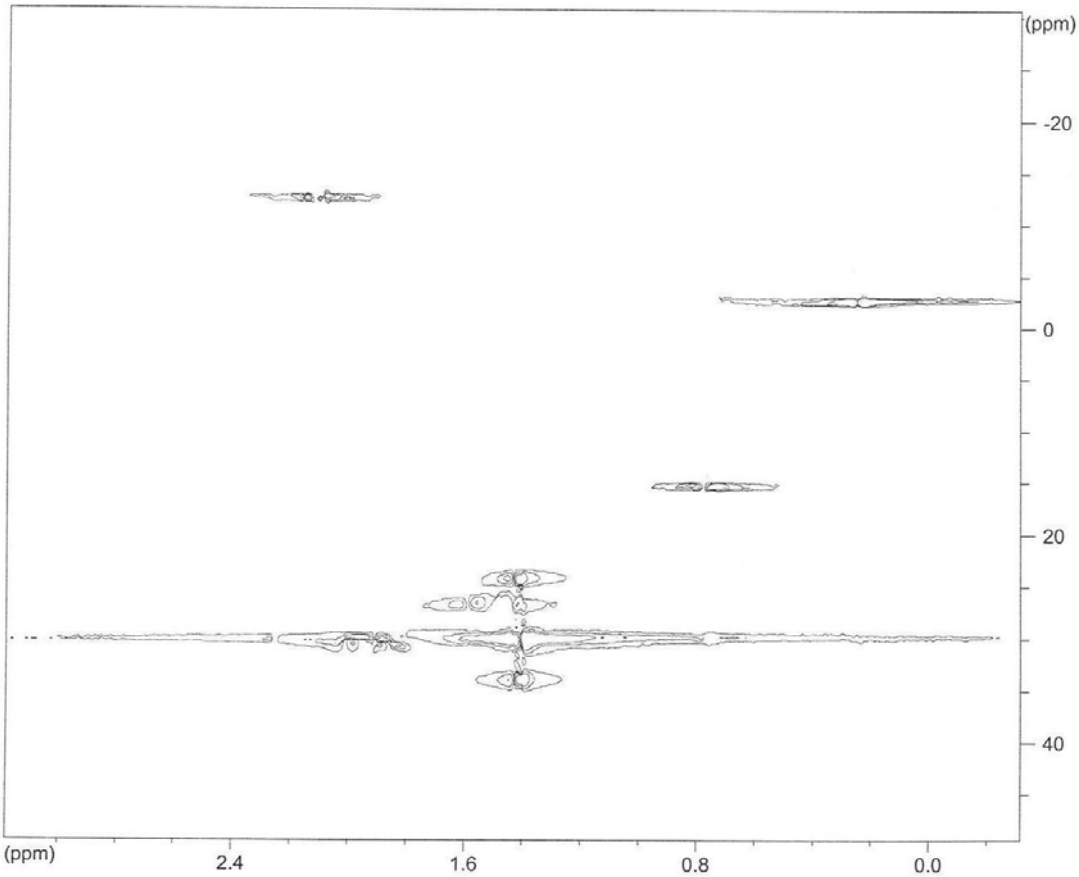


JMOD NMR spectrum (enlarged spectral window)

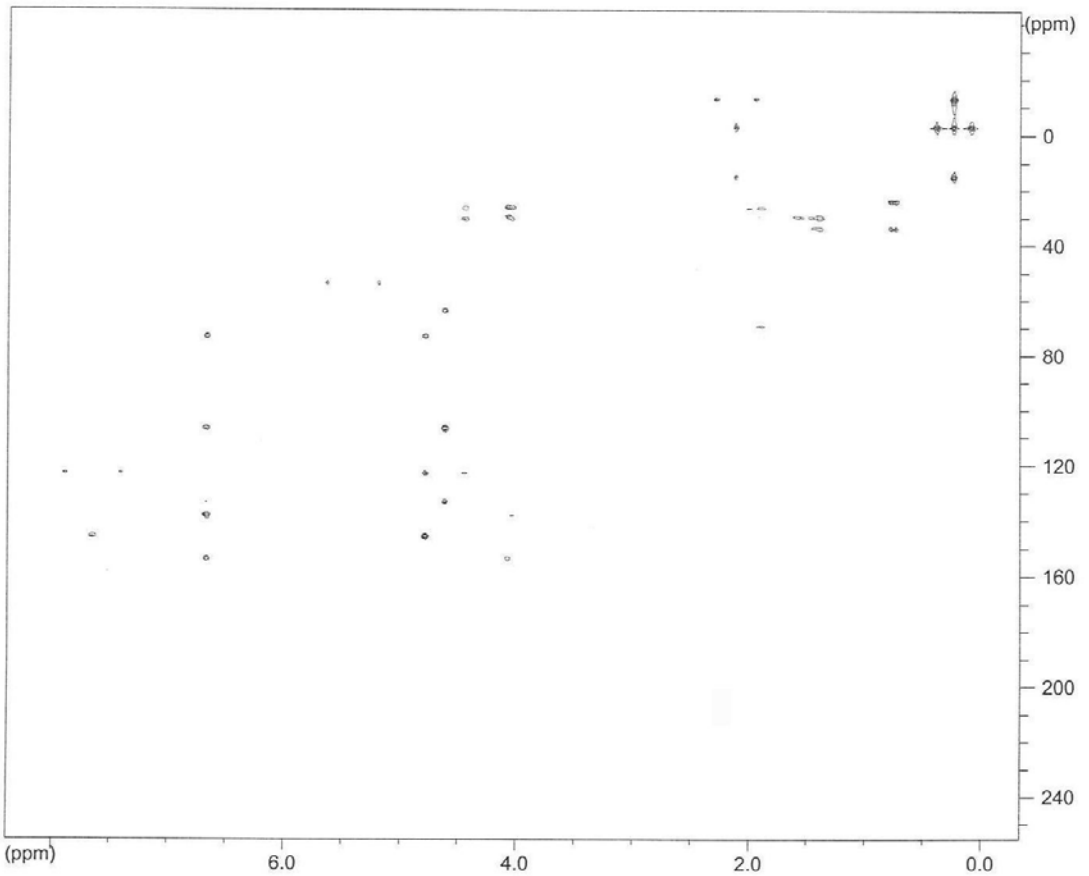


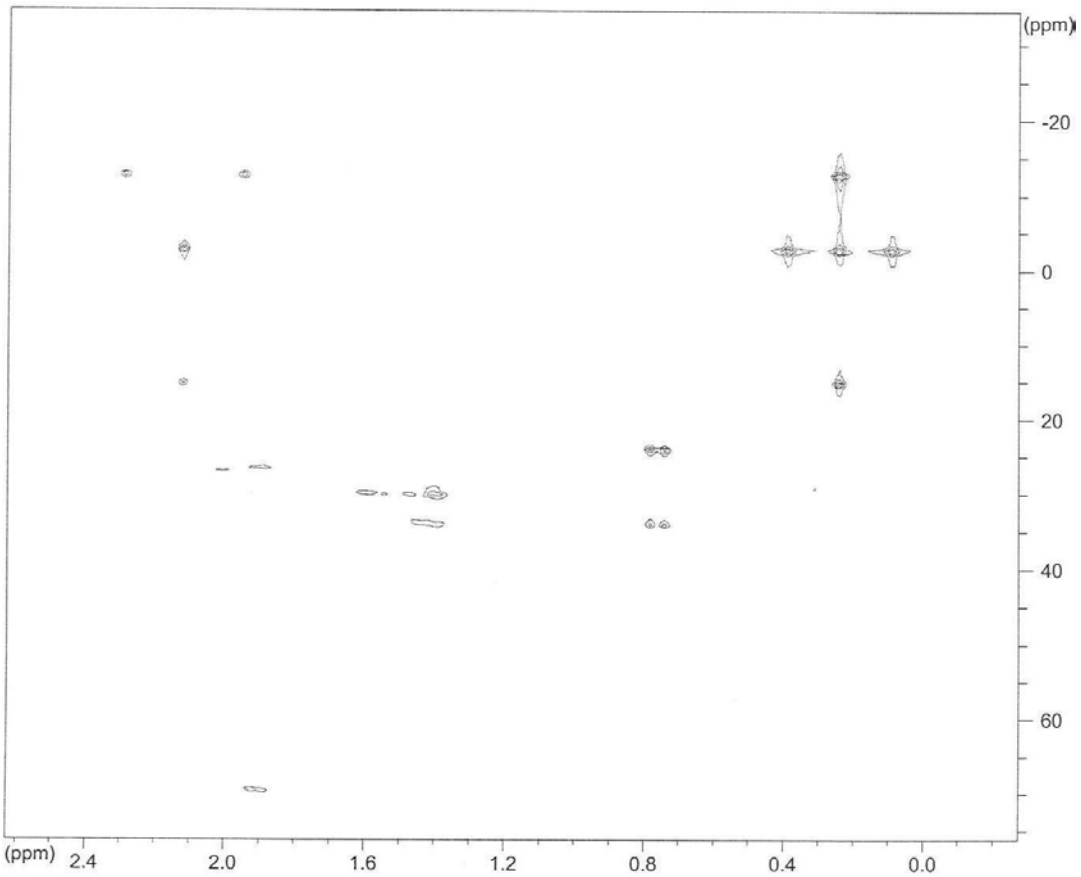
HSQC NMR spectrum (enlarged spectral window)



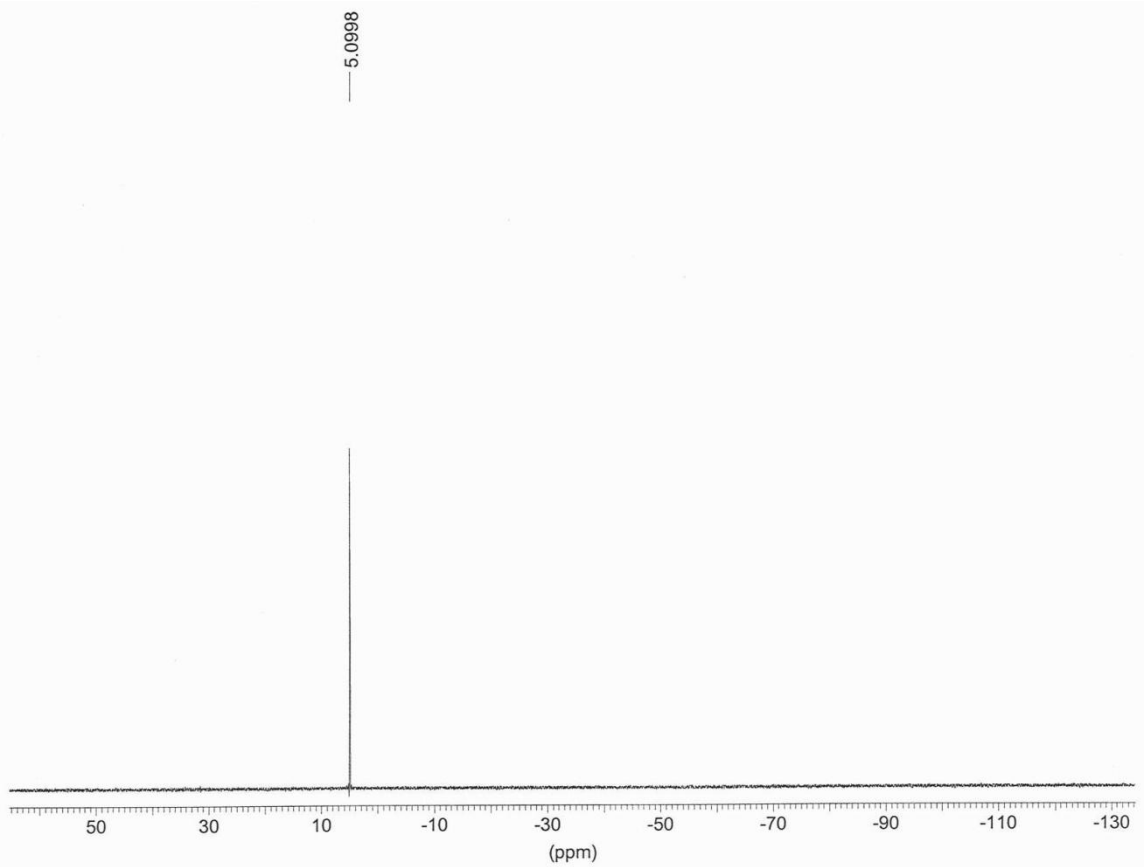


HMBC NMR spectrum (enlarged spectral window)

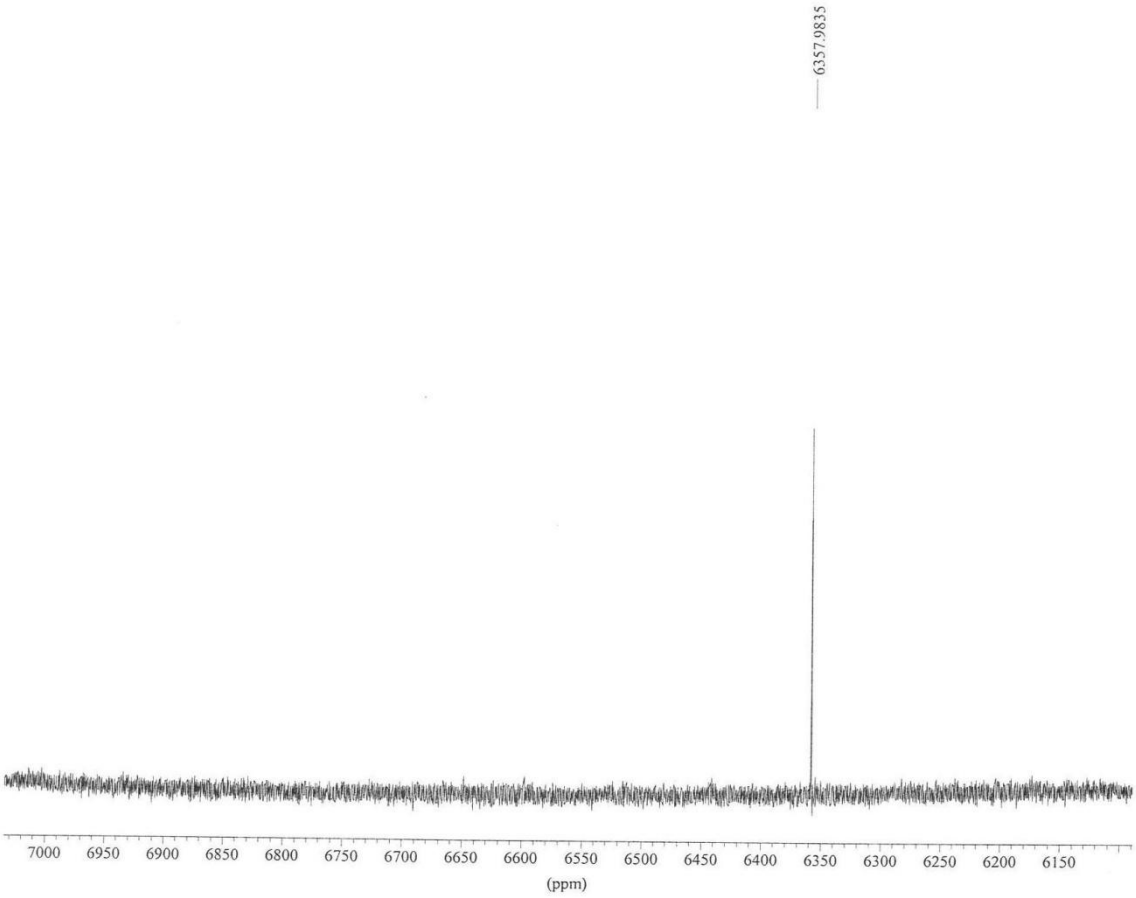




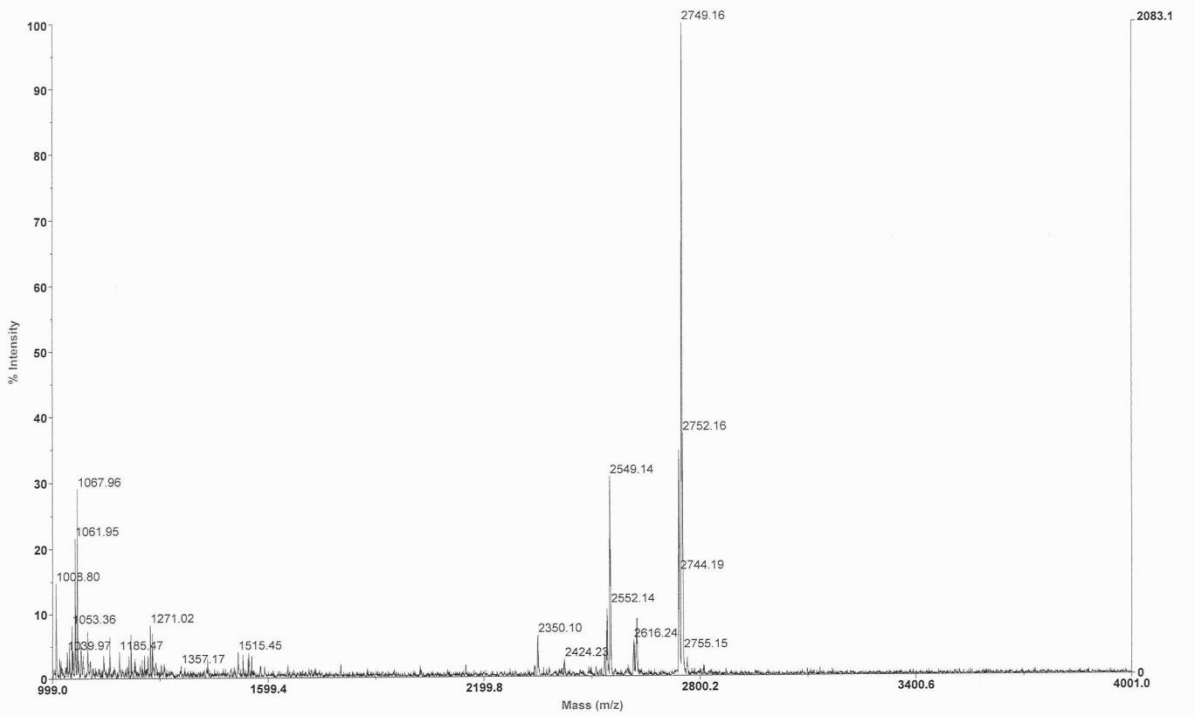
^{29}Si NMR spectrum



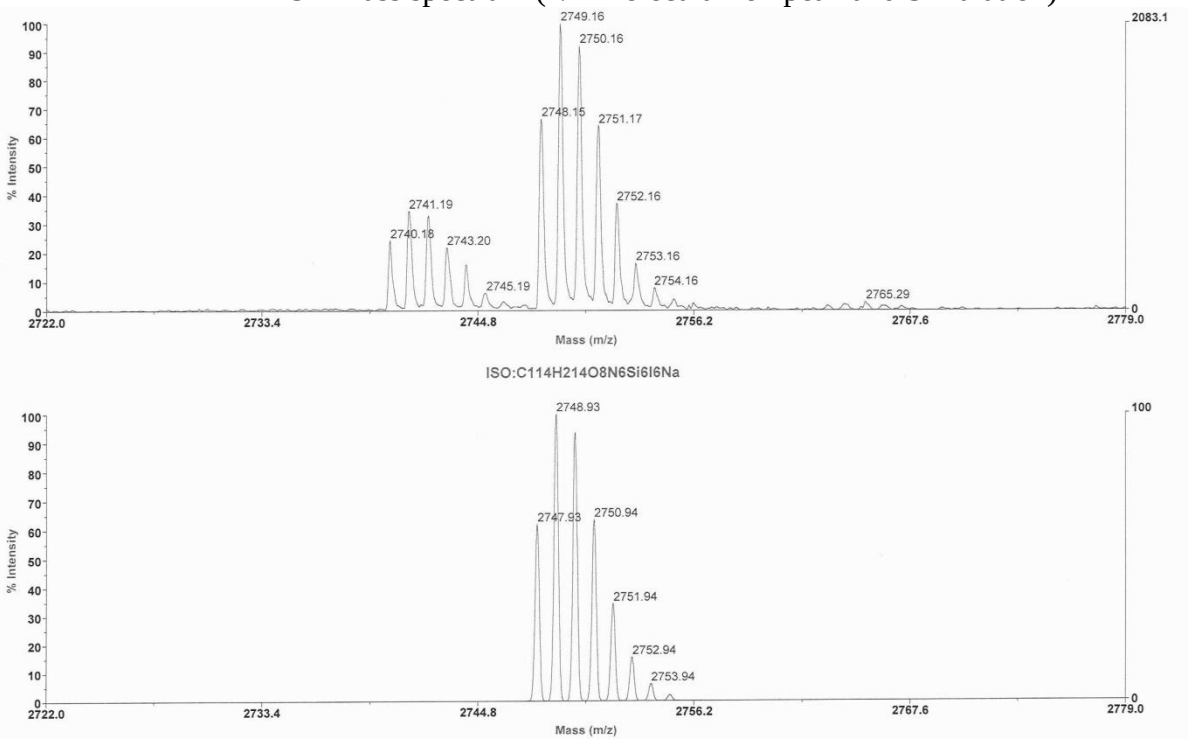
^{127}I NMR spectrum



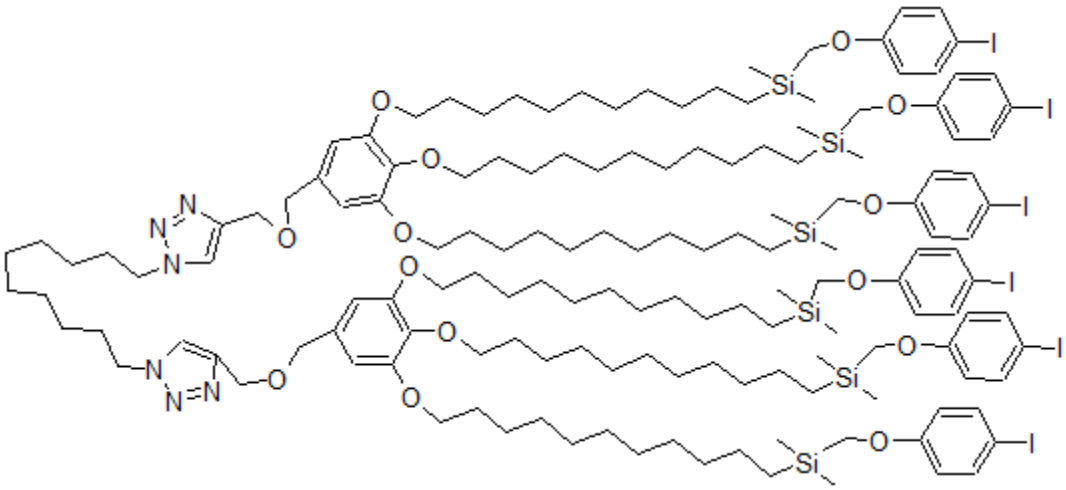
MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



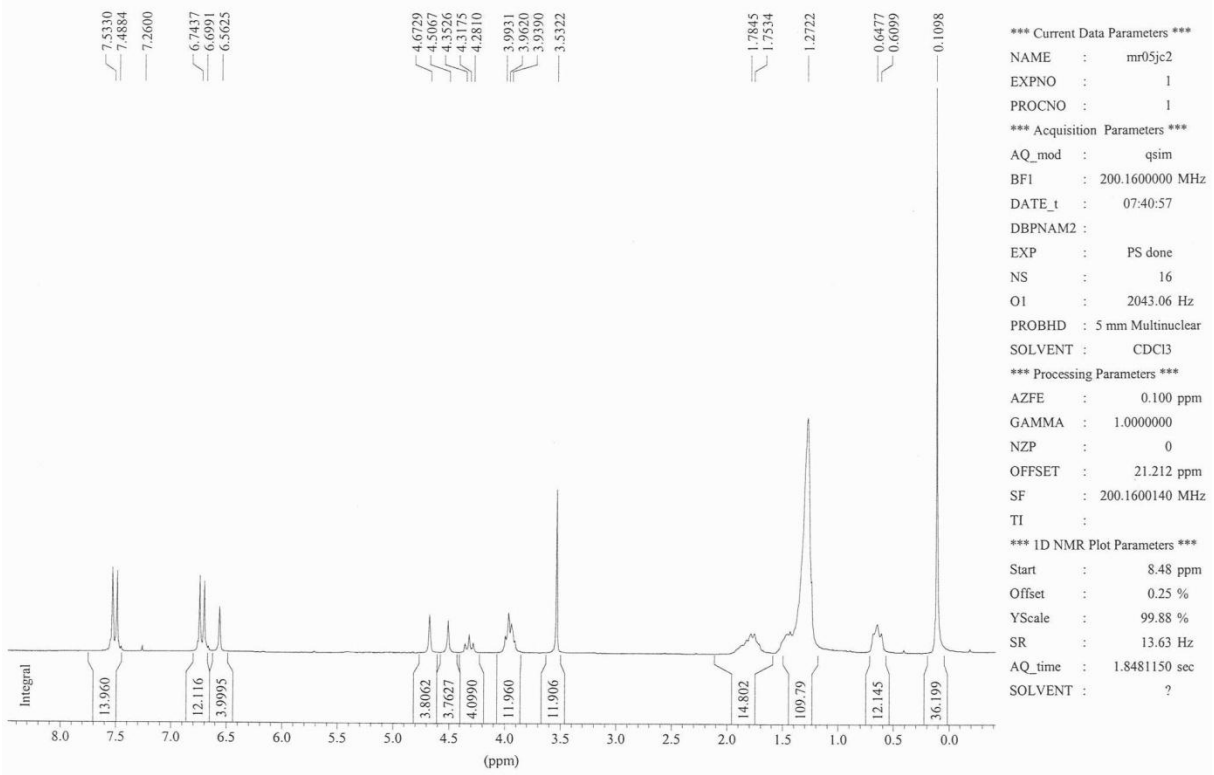
Synthesis of G_1-hexa iodophenyl dendrimer 17



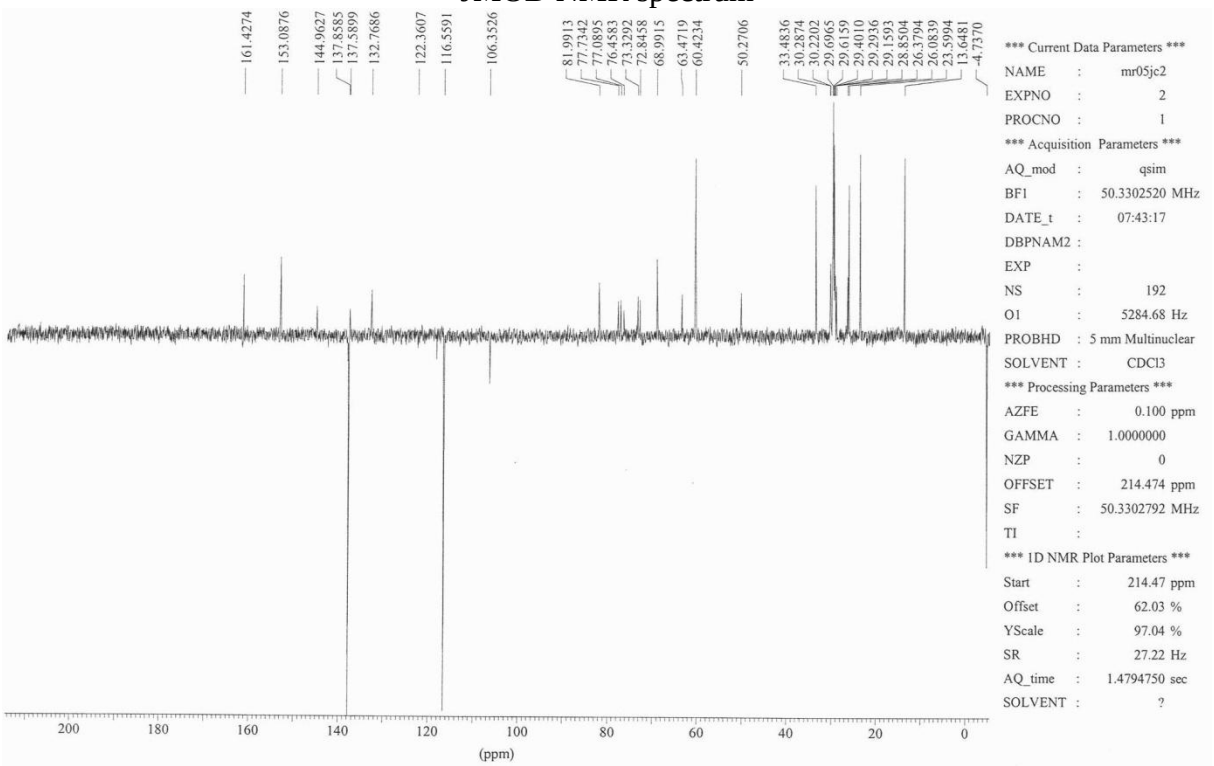
To a solution of G1-hexa iodo dendrimer **16** (0.91g, 0.33mmol, 1eq) in 20mL of anhydrous DMF was added p-iodophenol (0.88g, 4.0mmol, 12eq) and K_2CO_3 (1.38g, 10.0mmol, 30eq). The mixture was stirred at 70°C for one night. The mixture was authorized to cool down to room temperature and diethyl ether and water were added. The organic layer was washed two times with water, dried over anhydrous sodium sulfate, filtered and evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluents.
The desired product was obtained as a light brown oil (0.95g, 0.26mmol) in 87% yield

^{1}H NMR ($CDCl_3$ 200MHz): 7.50 ppm (m, $H_{triazole}$ and H_{Ar}, 14H); 6.74 ppm (d, H_{Ar}, ^3J = 8.9Hz, 12H) ; 6.56 ppm (s, H_{Ar}, 4H) ; 4.67 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.51 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.32 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.96 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 3.53 ppm (s, Si-CH_2-O, 12H); 1.81 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.50 to 1.25 ppm (m, -CH_2-, 108H) ; 0.61 ppm (t, -CH_2-CH_2-Si, ^3J = 7.6Hz, 12H) ; 0.11 ppm (s, Si-CH_3, 36H)
^{13}C NMR ($CDCl_3$ 50.3MHz): 161.43 and 153.09 ppm (C_{ar}-O); 144.96 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 137.86 ppm (C_{ar}-H); 137.59 ppm (C_{ar}-O) ; 132.77 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.36 ppm ($C_{triazole}$-H) ; 116.56 and 106.35 ppm (C_{ar}-H); 81.99 ppm (C_{ar}-I) ; 73.33 ppm (para -O-CH_2-CH_2-) ; 72.85 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 68.99 ppm (meta -O-CH_2-CH_2-); 63.47 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 60.42 ppm (Si-CH_2-O) ; 50.27 ppm (-CH_2-$N_{triazole}$); 33.48, 30.29, 30.22, 29.70, 29.62, 29.40, 29.29, 29.16, 28.85, 26.38, 26.08 and 23.60 ppm (-CH_2- and Si-CH_2-I) ; 13.65 ppm (-CH_2-CH_2-Si) ; -4.74 ppm (Si-CH_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 0.94 ppm
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 3301.35

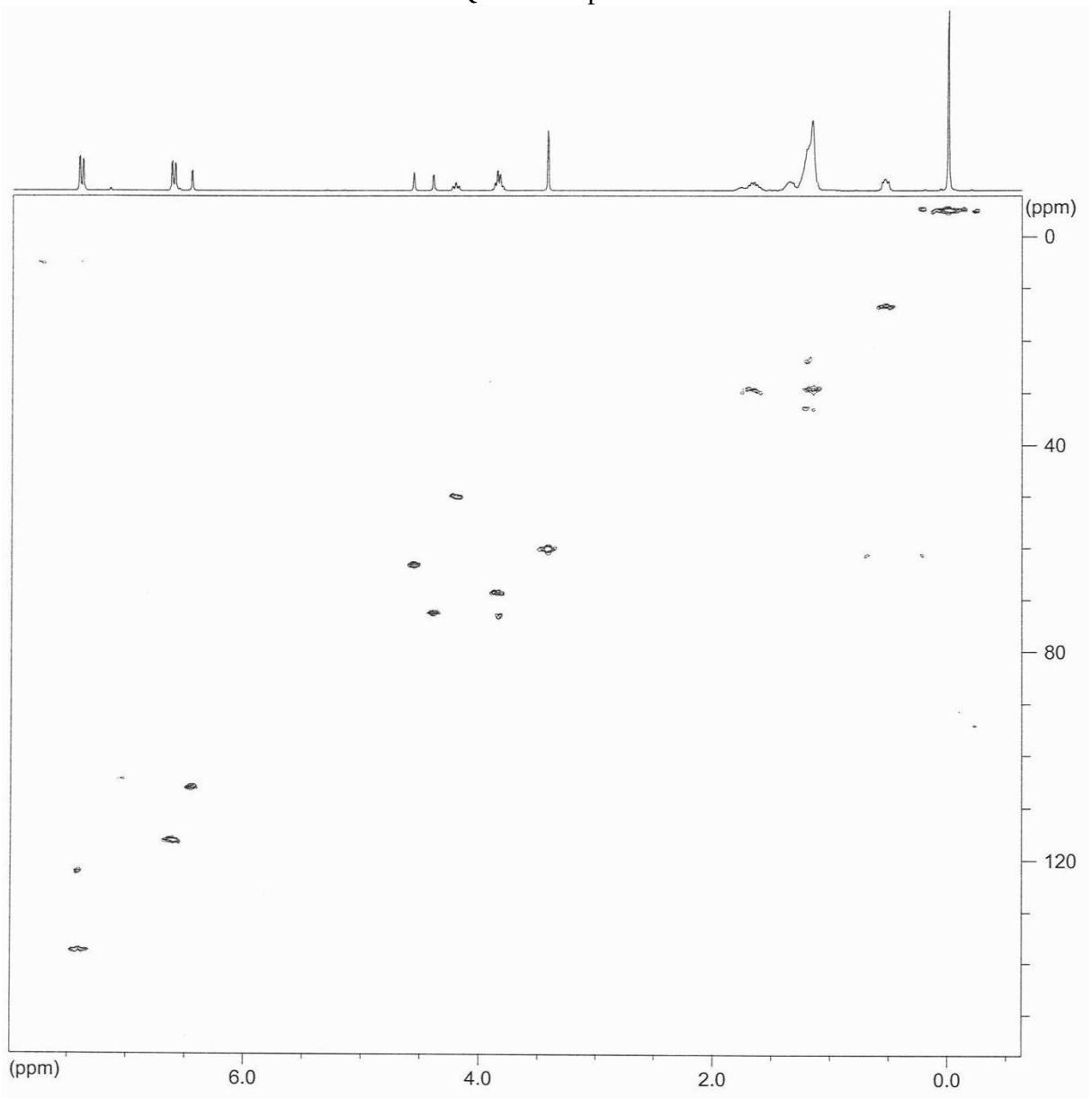
^{1}H NMR spectrum



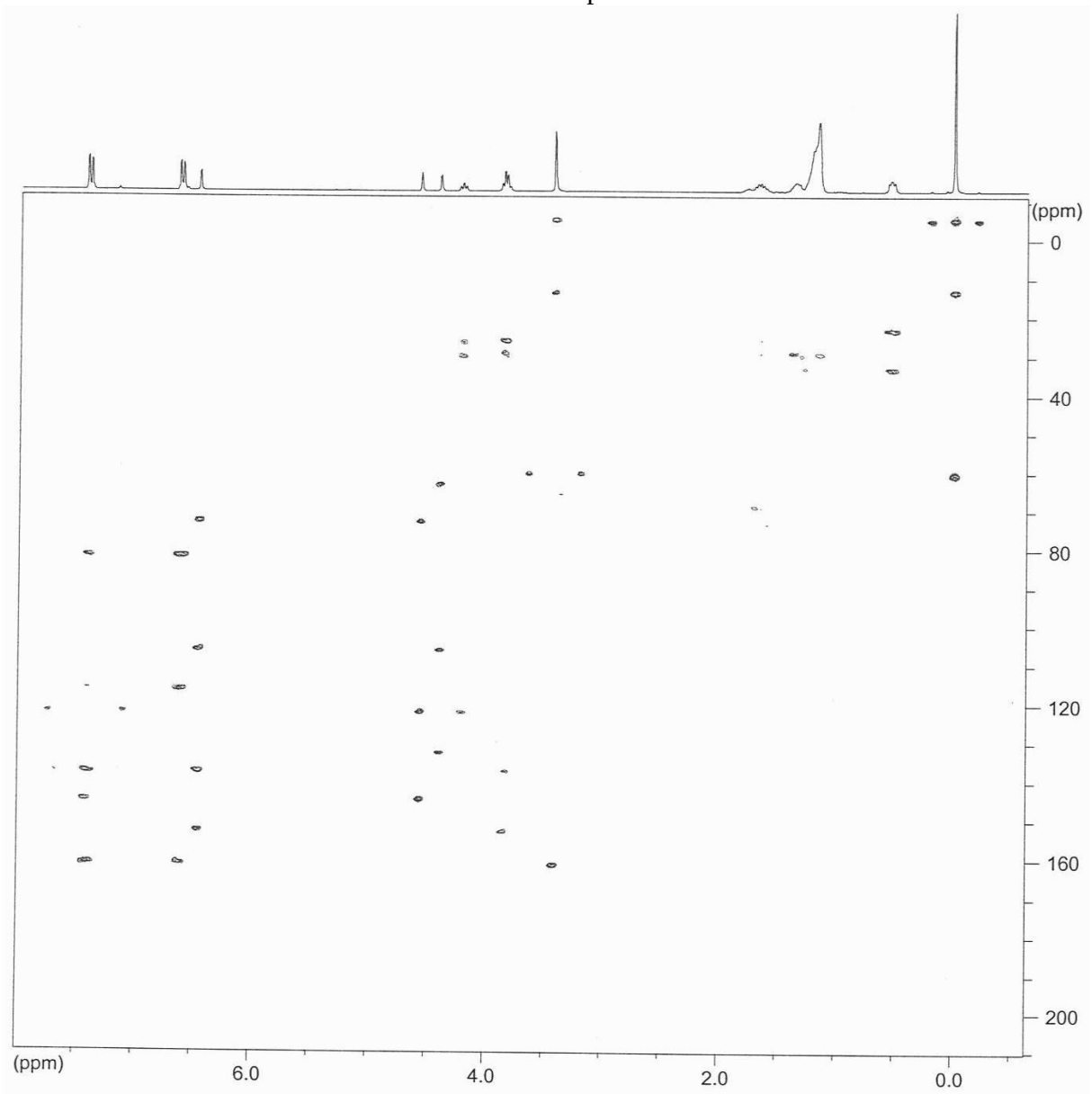
JMOD NMR spectrum



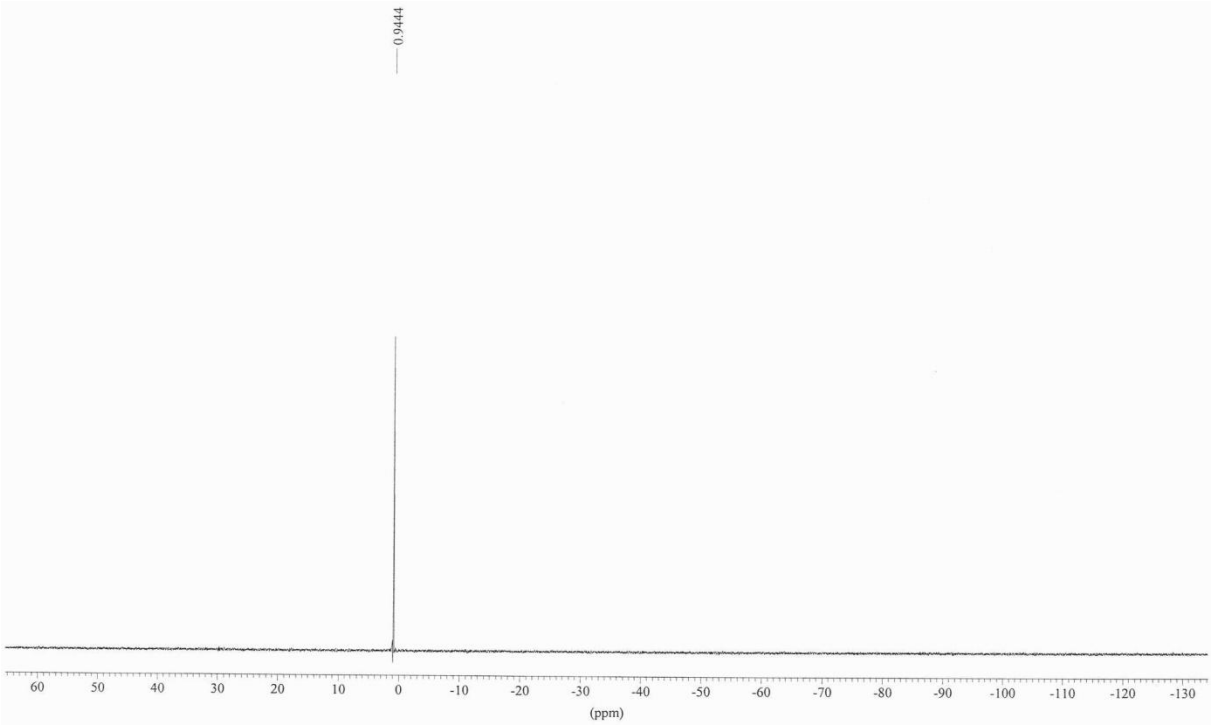
HMQC NMR spectrum



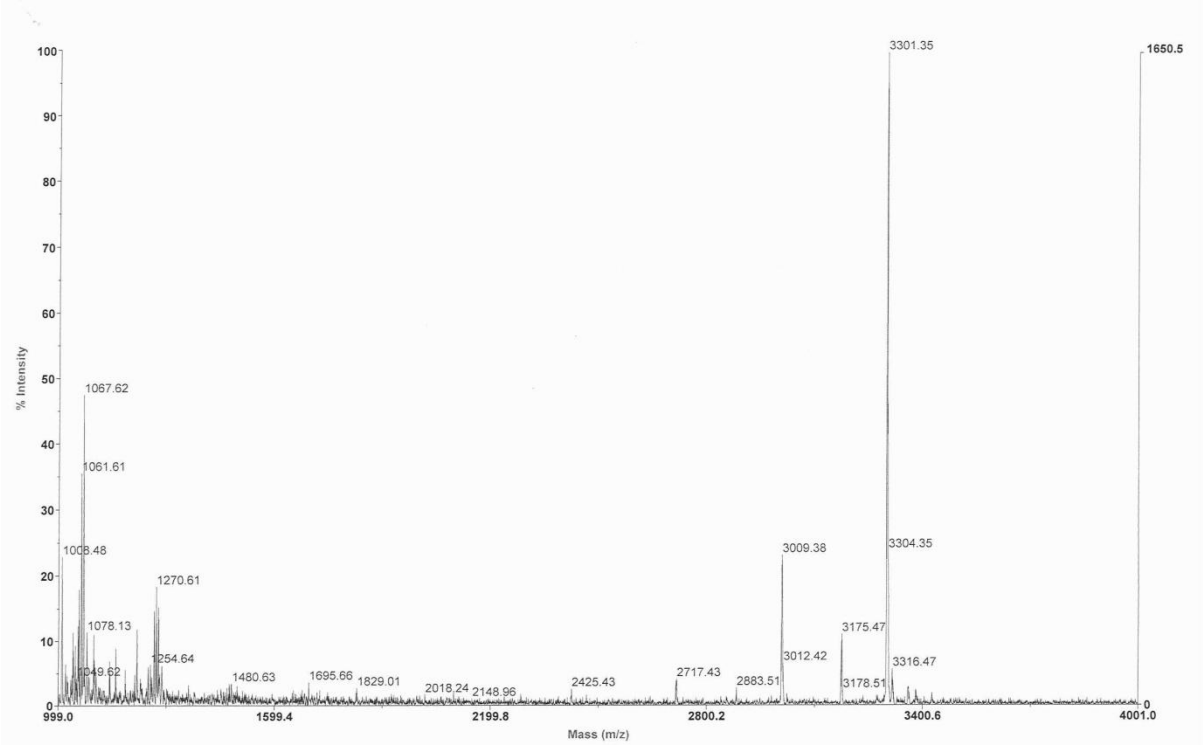
HMBC NMR spectrum



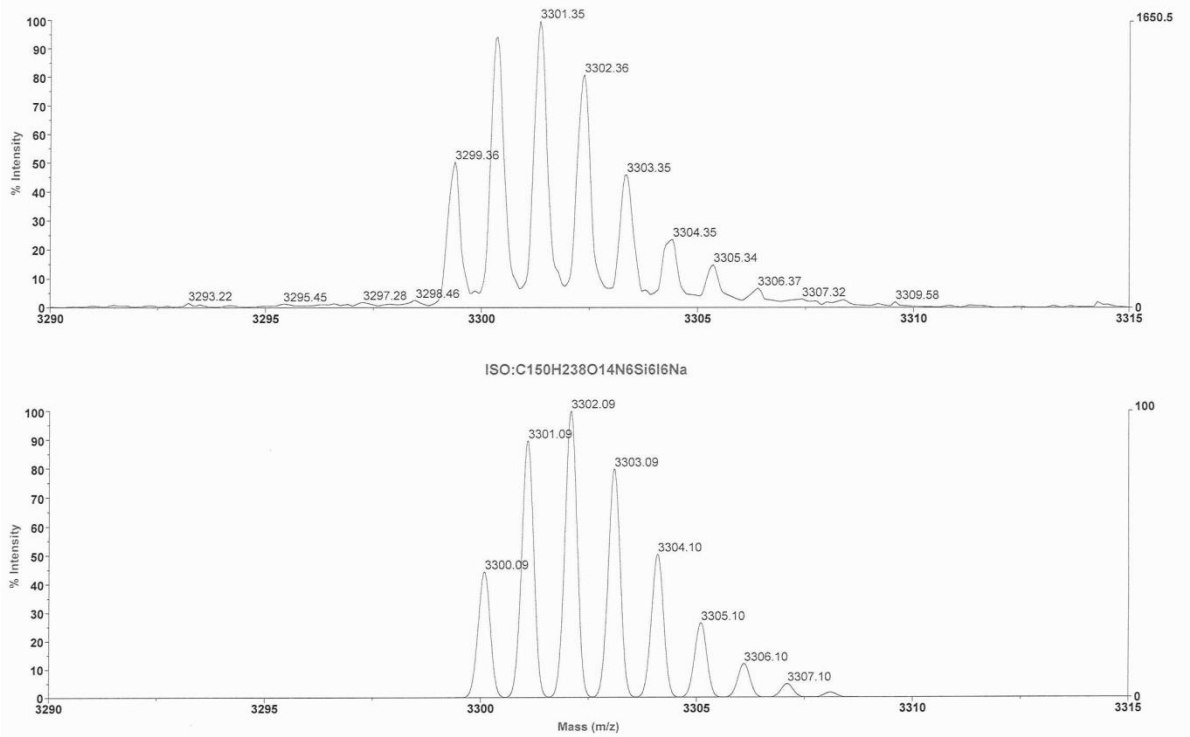
^{29}Si NMR spectrum



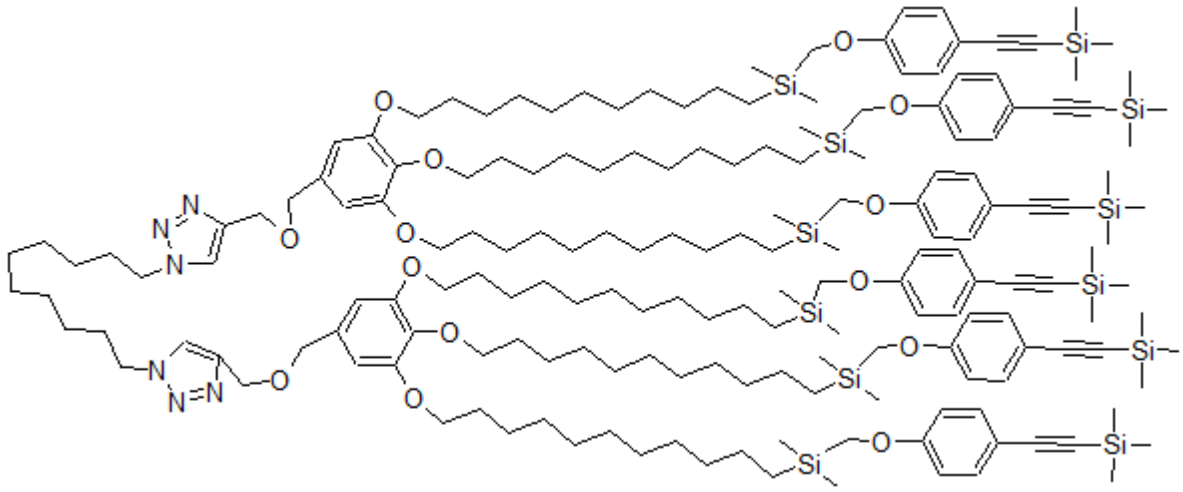
MALDI-TOF mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



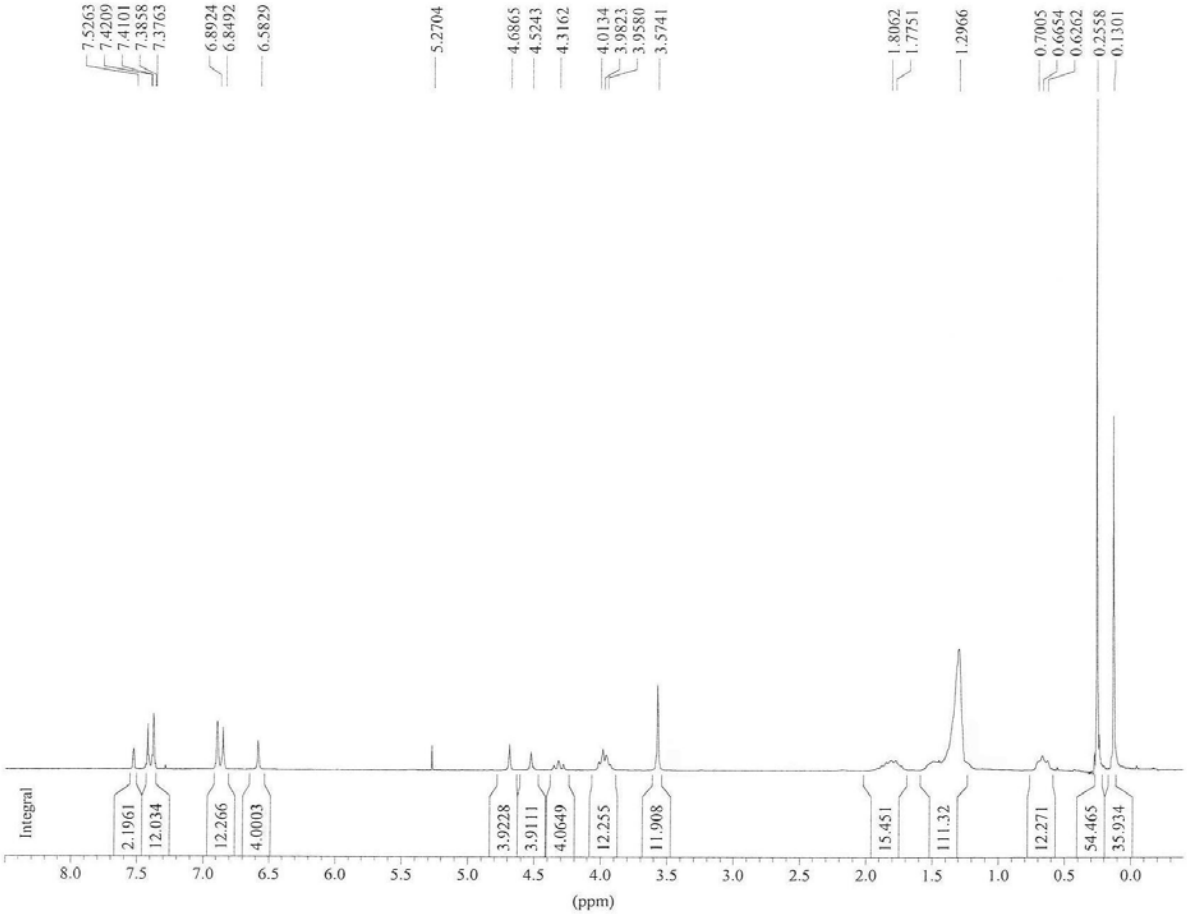
Synthesis of G_1-hexa trimethylsilyl dendrimer 18



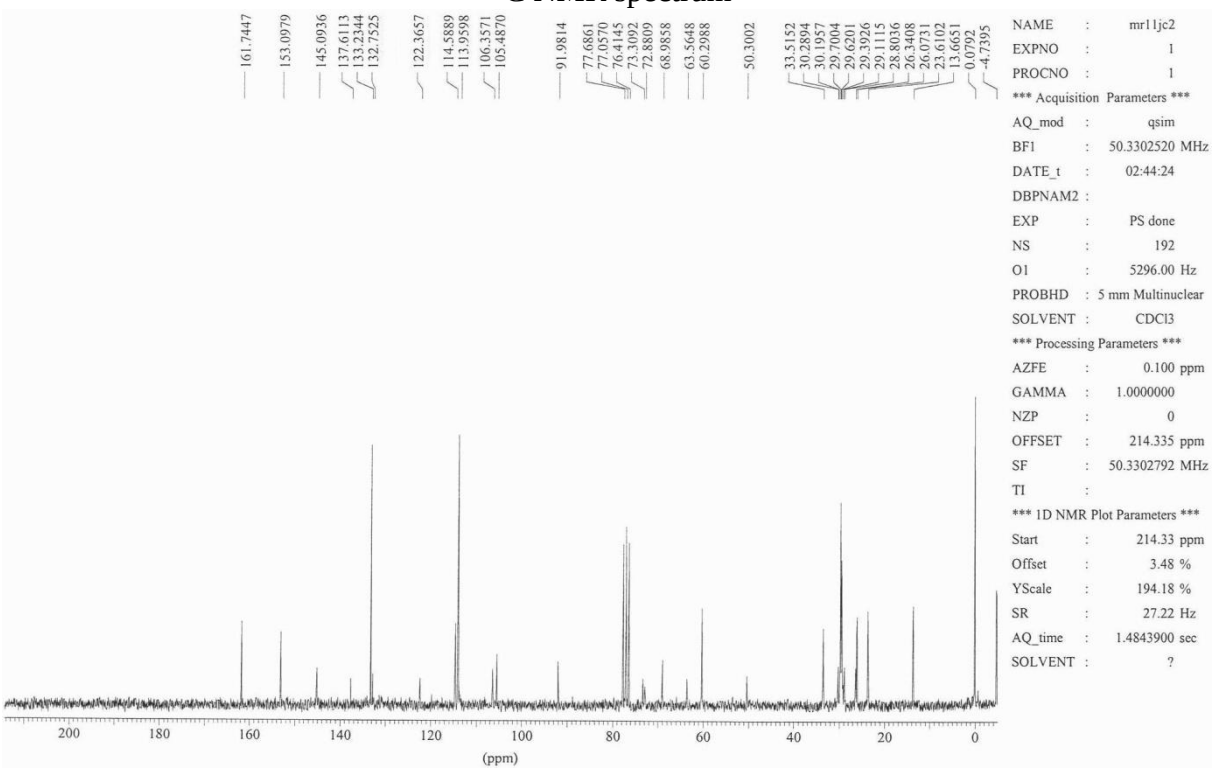
To a solution of G1-hexa iodophenyl dendrimer **17** (4.6g, 1.40mmol, 1eq) in 40mL distillated triethylamine was added $PdCl_2(PPh_3)_2$ (295mg, 0.42mmol, 0.3eq), and CuI (290mg, 1.51mmol, 1.08eq). The reaction mixture was stirred for 10 minutes at 50°C and then trimethylsilylacetylene (2.4mL, 16.84mmol, 12eq) was added dropwise. The reaction mixture was stirred for 24h at 65°C. Solvent was removed *in vacuo*. Diehtyl ether and water were added. The organic layer was washed three times with water, dried over anhydrous sodium sulfate, filtered and then evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent.
The desired product was obtained as a slightly yellow oil (3.95g, 1.27mmol) in 91% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.52 ppm (s, $H_{triazole}$, 2H); 7.38 ppm (d, H_{Ar}, ^3J = 8.7Hz, 12H); 6.86 ppm (d, H_{Ar}, ^3J = 8.9Hz, 12H) ; 6.55 ppm (s, H_{Ar}, 4H) ; 4.68 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.50 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.32 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.2Hz, 4H); 3.95 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 3.56 ppm (s, Si-CH_2-O, 12H); 1.81 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.50 to 1.25 ppm (m, -CH_2-, 108H) ; 0.64 ppm (t, -CH_2-CH_2-Si, ^3J = 7.3Hz, 12H) ; 0.23 ppm (s, external Si-CH_3, 54H); 0.10 ppm (s, internal Si-CH_3, 36H)
^{13}C NMR ($CDCl_3$ 50.3MHz): 161.74 and 153.10 ppm (C_{ar}-O); 145.09 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 137.61 ppm (C_{ar}-O) ; 133.23 ppm (C_{ar}-H); 132.75 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.37 ppm ($C_{triazole}$-H) ; 114.59 ppm (C_{ar}-C≡C); 113.96 and 106.36 ppm (C_{ar}-H); 105.49 ppm (C_{ar}-*C*≡C); 91.98 ppm (C_{ar}-C≡*C*); 73.31 ppm (para -O-*C*H_2-CH_2-) ; 72.88 ppm (C_{Ar}-*C*H_2-O-CH_2-$C_{triazole}$); 68.99 ppm (meta -O-*C*H_2-CH_2-); 63.56 ppm (C_{Ar}-CH_2-O-*C*H_2-$C_{triazole}$); 60.30 ppm (Si-*C*H_2-O) ; 50.30 ppm (-*C*H_2-$N_{triazole}$); 33.52, 30.29, 30.20, 29.70, 29.62, 29.39, 29.31, 29.11, 28.80, 26.34, 26.07 and 23.61 ppm (-*C*H_2-) ; 13.67 ppm (-CH_2-*C*H_2-Si) ; 0.08 ppm (external Si-*C*H_3); -4.74 ppm (internal Si-*C*H_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : two peaks at 0.97 and -17.97 ppm
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 3123.56

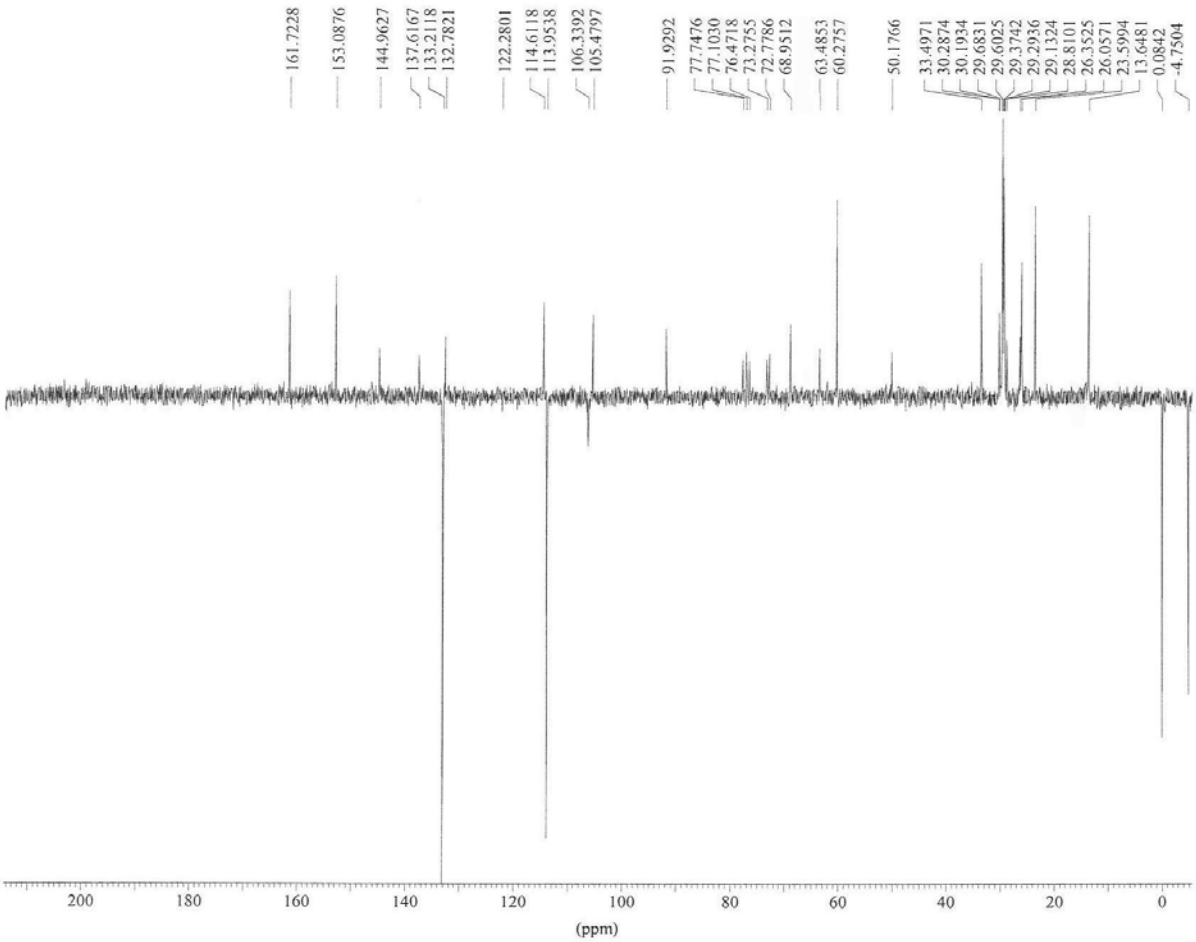
^{1}H NMR spectrum



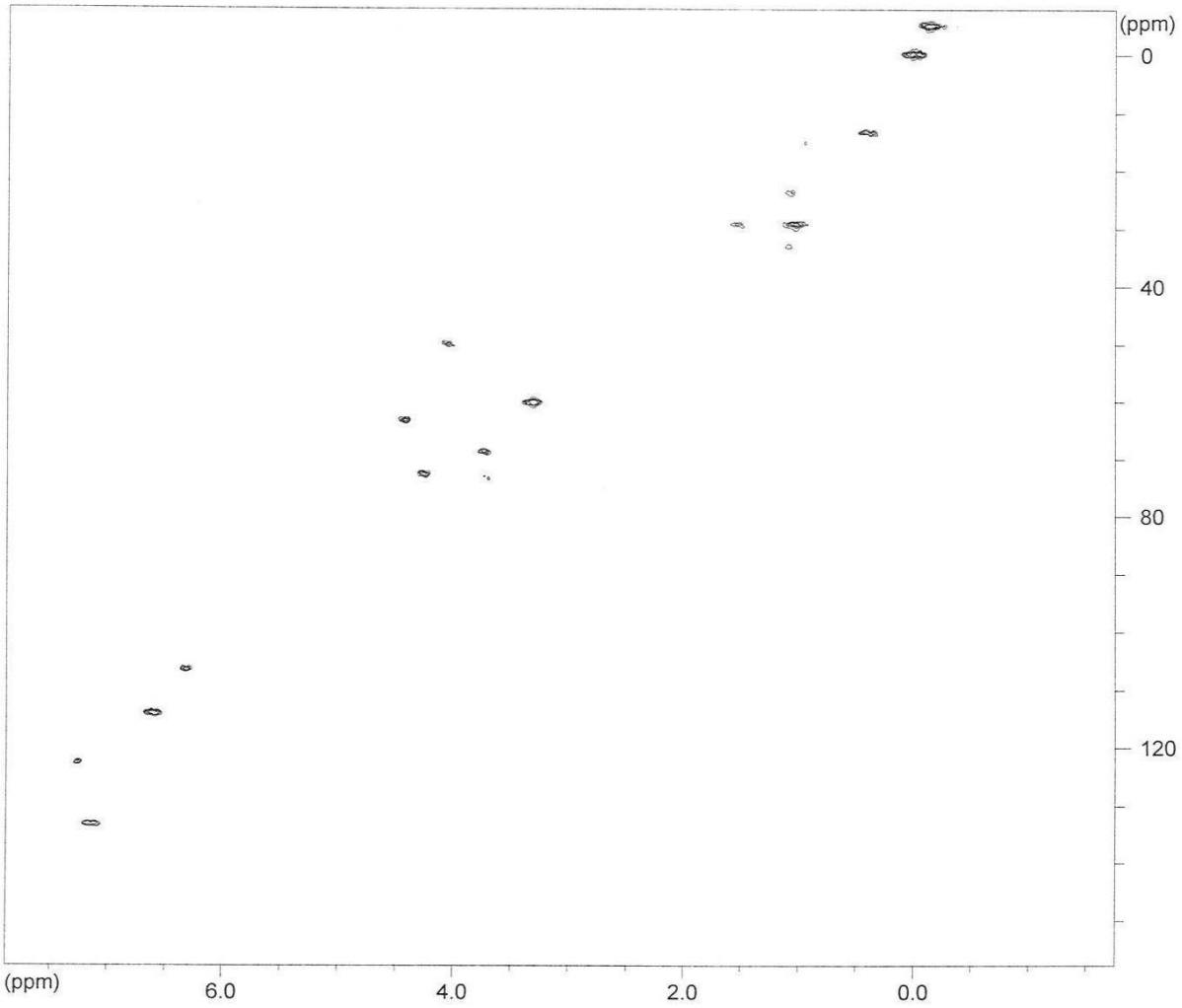
^{13}C NMR spectrum



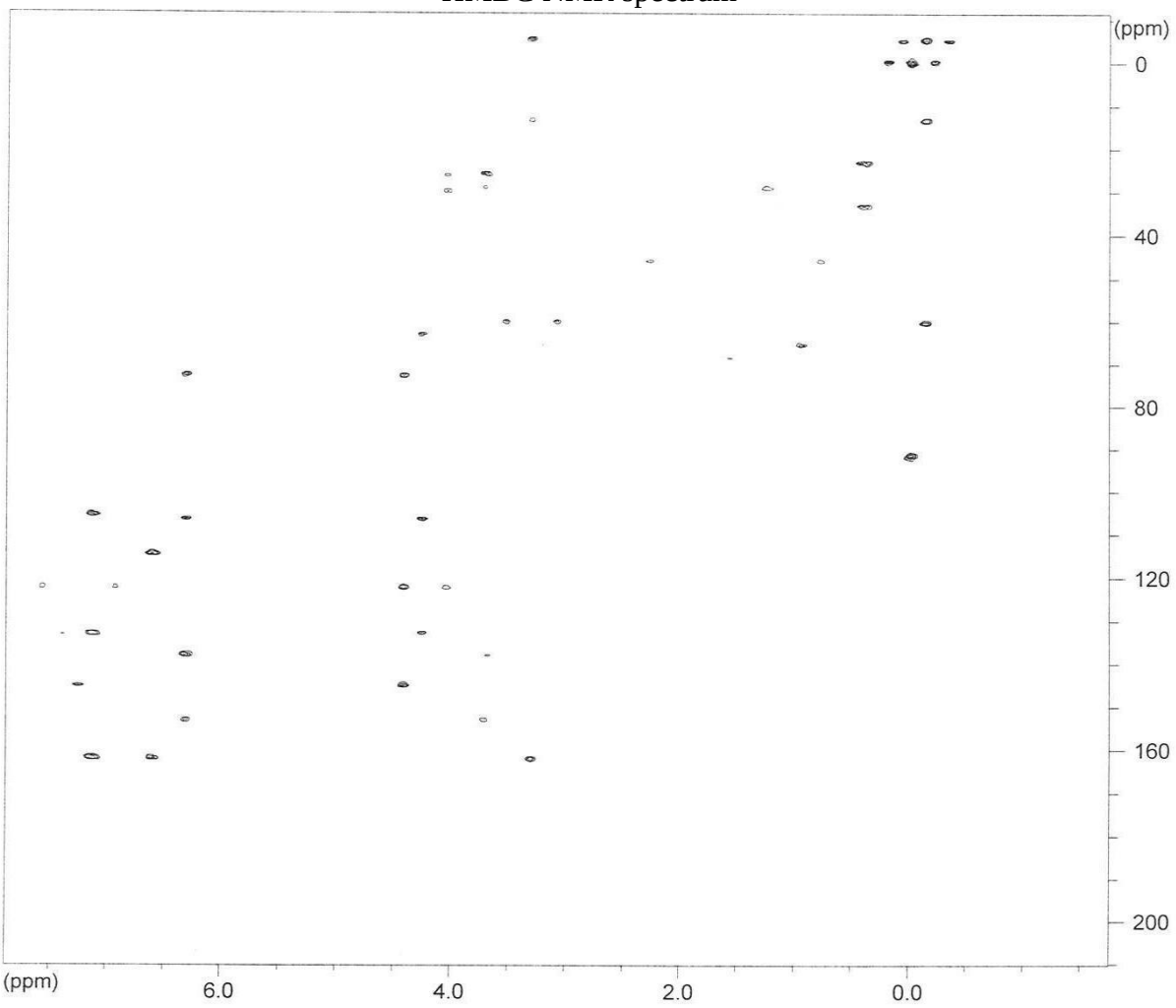
JMOD NMR spectrum



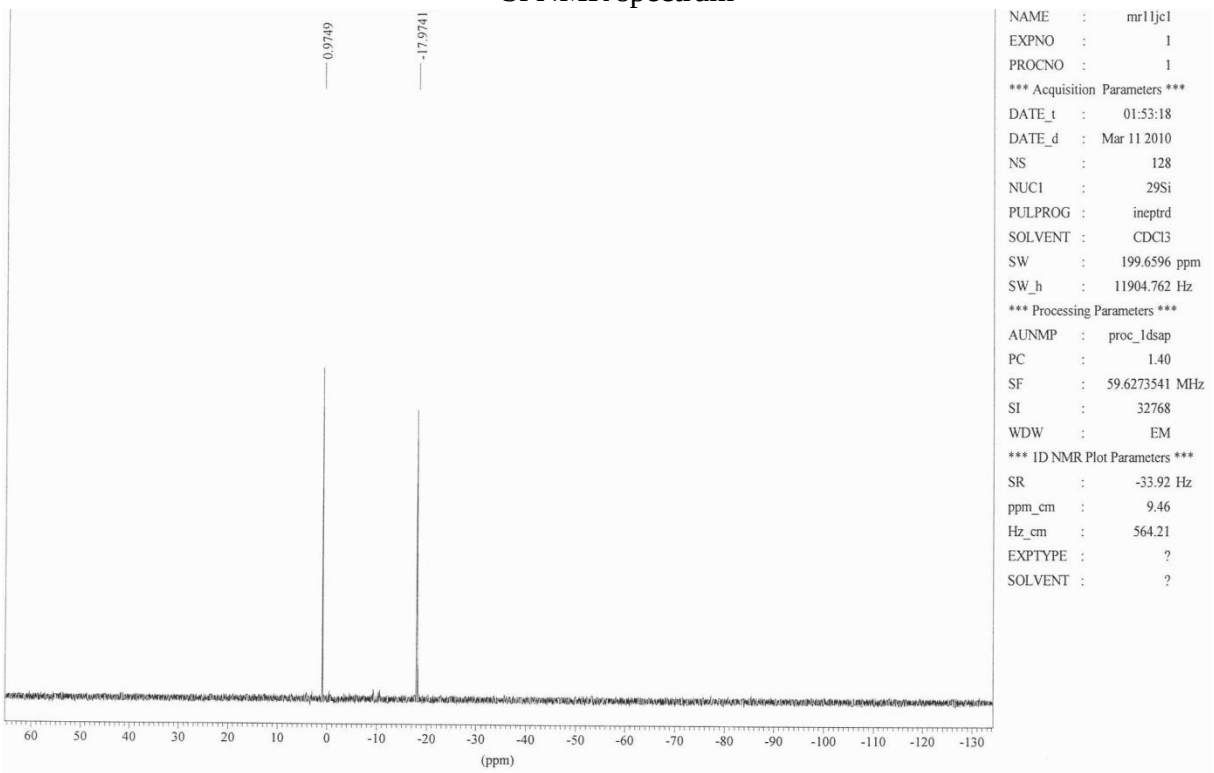
HMQC NMR spectrum



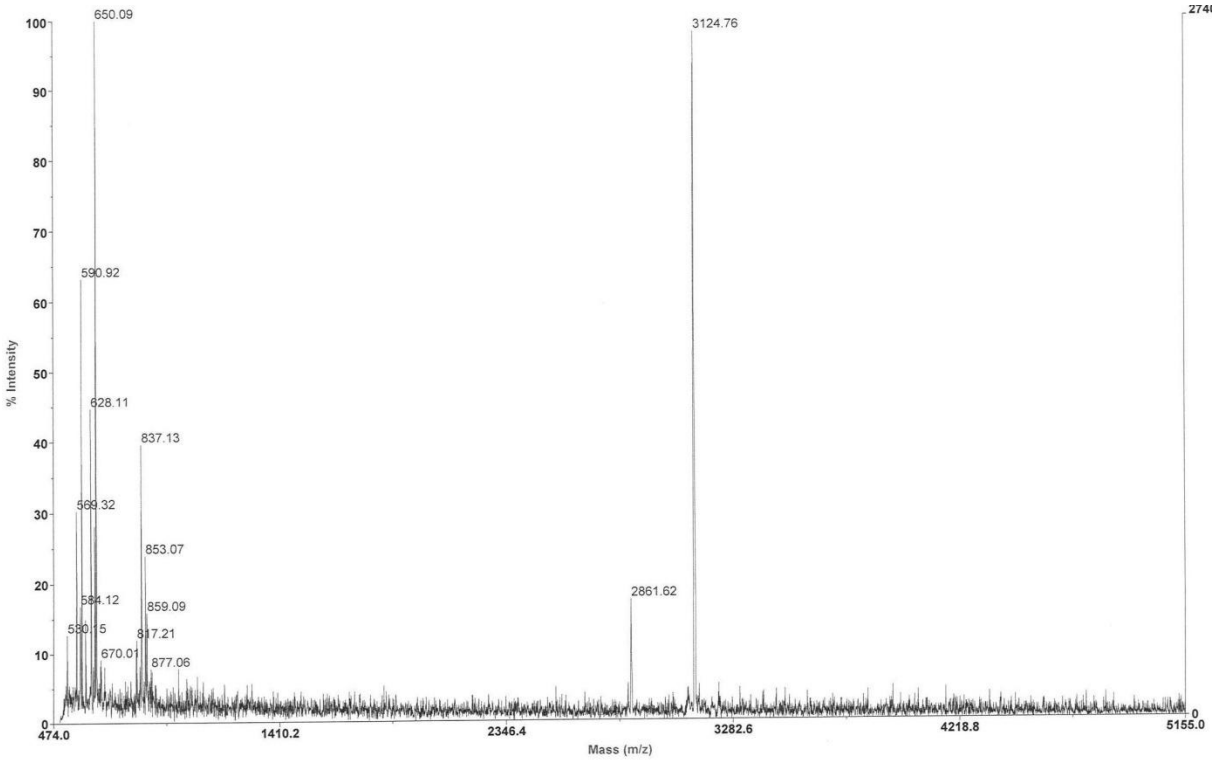
HMBC NMR spectrum



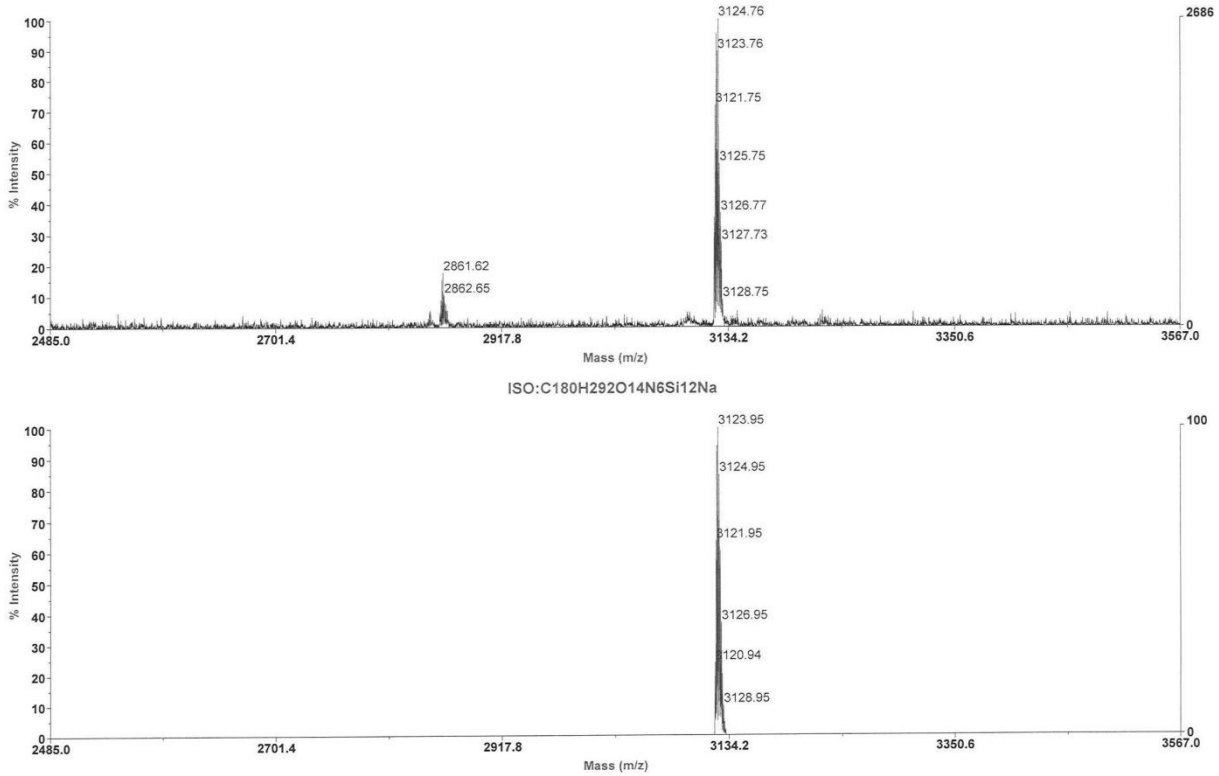
^{29}Si NMR spectrum



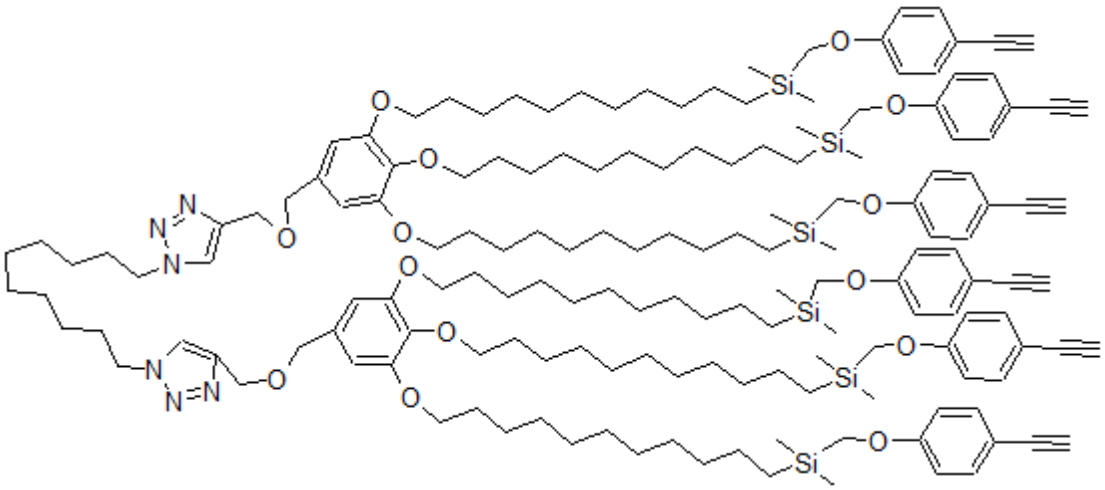
MALDI-TOF Mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



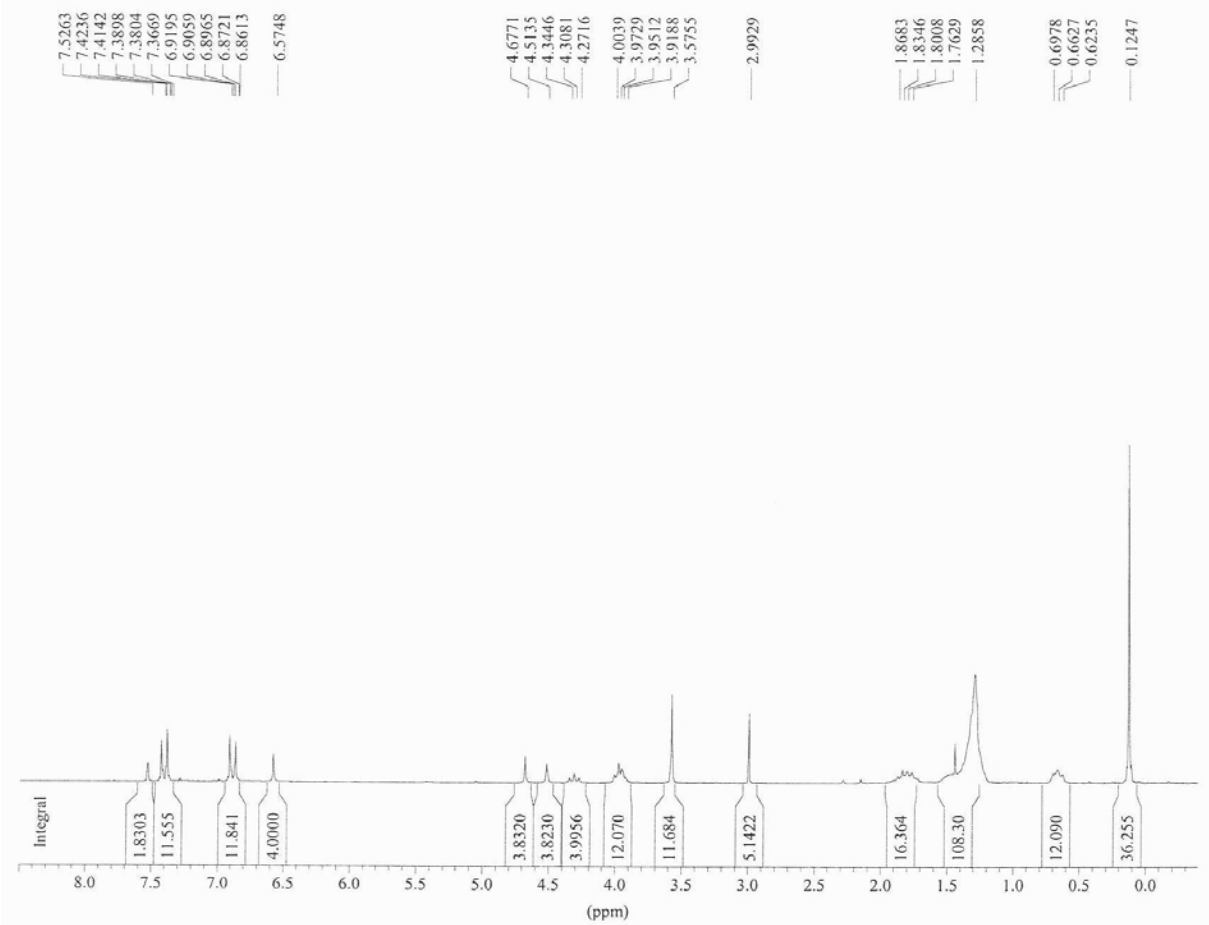
Synthesis of G_1-hexa alkynyl dendrimer 19



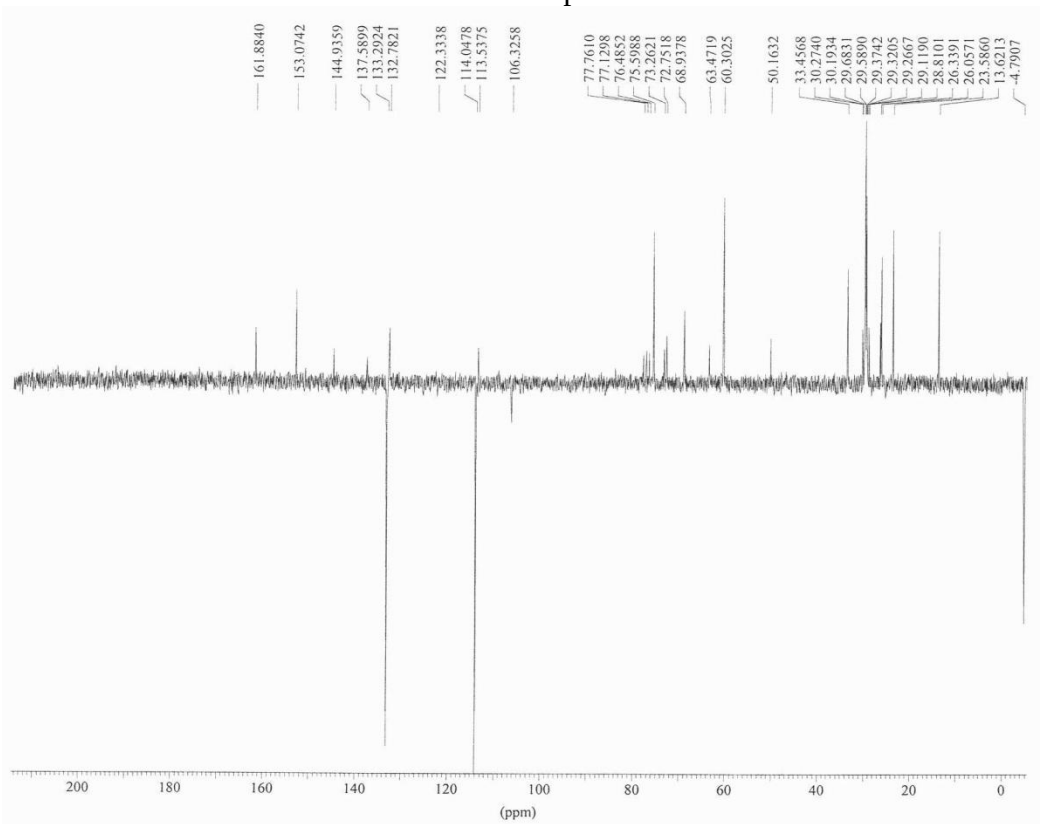
To a solution of G1-hexa trimethylsilyl dendrimer **18** (2.2g, 0.71mmol, 1eq) in a THF/MeOH 1:1 (v/v) mixture was added K_2CO_3 (390mg, 2.84mmol, 4eq). The reaction mixture was stirred for 2h at room temperature. The reaction mixture was filtered, and the solid was washed with diethyl ether. The filtrate was evaporated to dryness *in vacuo*. The crude product was purified by flash column chromatography using dichloromethane and then diethyl ether as eluent. The diethyl ether layer was concentrated and precipitated using excess methanol.
The desired product was obtained as a slightly yellow oil (1.36g, 0.51mmol) in 75% yield.

^{1}H NMR ($CDCl_3$ 200MHz): 7.53 ppm (s, $H_{triazole}$, 2H); 7.40 ppm (d, H_{Ar}, ^3J = 8.6Hz, 12H); 6.88 ppm (d, H_{Ar}, ^3J = 8.9Hz, 12H) ; 6.57 ppm (s, H_{Ar}, 4H) ; 4.68 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.51 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.31 ppm (t, -CH_2-$N_{triazole}$, ^3J = 7.3Hz, 4H); 3.97 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 3.58 ppm (s, Si-CH_2-O, 12H); 2.99 ppm (s, C≡C-*H*, 6H); 1.86 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.76 ppm (m, meta and para -O-CH_2-CH_2-, 12H); 1.50 to 1.25 ppm (m, -CH_2-, 108H) ; 0.66 ppm (t, -CH_2-CH_2-Si, ^3J = 7.4Hz, 12H); 0.12 ppm (s, Si-CH_3, 36H)
^{13}C NMR ($CDCl_3$ 50.3MHz): 161.92 and 153.10 ppm (C_{ar}-O); 144.99 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 137.60 ppm (C_{ar}-O) ; 133.34 ppm (C_{ar}-H); 132.74 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 122.31 ppm ($C_{triazole}$-H) ; 114.07 ppm (C_{ar}-H); 113.48 ppm (C_{ar}-C≡C); 106.34 ppm (C_{ar}-H); 83.84 ppm (C_{ar}-*C*≡CH); 75.52 ppm (C_{ar}-C≡*C*H); 73.32 ppm (para -O-*C*H_2-CH_2-) ; 72.83 ppm (C_{Ar}-*C*H_2-O-CH_2-$C_{triazole}$); 68.99 ppm (meta -O-*C*H_2-CH_2-); 63.51 ppm (C_{Ar}-CH_2-O-*C*H_2-$C_{triazole}$); 60.34 ppm (Si-*C*H_2-O) ; 50.23 ppm (-*C*H_2-$N_{triazole}$); 33.50, 30.25, 29.70, 29.61, 29.37, 29.29, 29.17, 28.84, 26.39, 26.07 and 23.60 ppm (-*C*H_2-) ; 13.64 ppm (-CH_2-*C*H_2-Si) ; -4.75 ppm (Si-*C*H_3)
^{29}Si NMR ($CDCl_3$ 59.6MHz) : one peak at 0.99 ppm
DOSY NMR gives a diffusion coefficient of 6.371m².s^{-1} at 20°C in chloroform which corresponds to a diameter of 11.6nm.
IR spectroscopy (cm^{-1}): 3301.8, 2931.7, 2857.8, 2106.6
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 2690.58
Polydispersity: 1.01

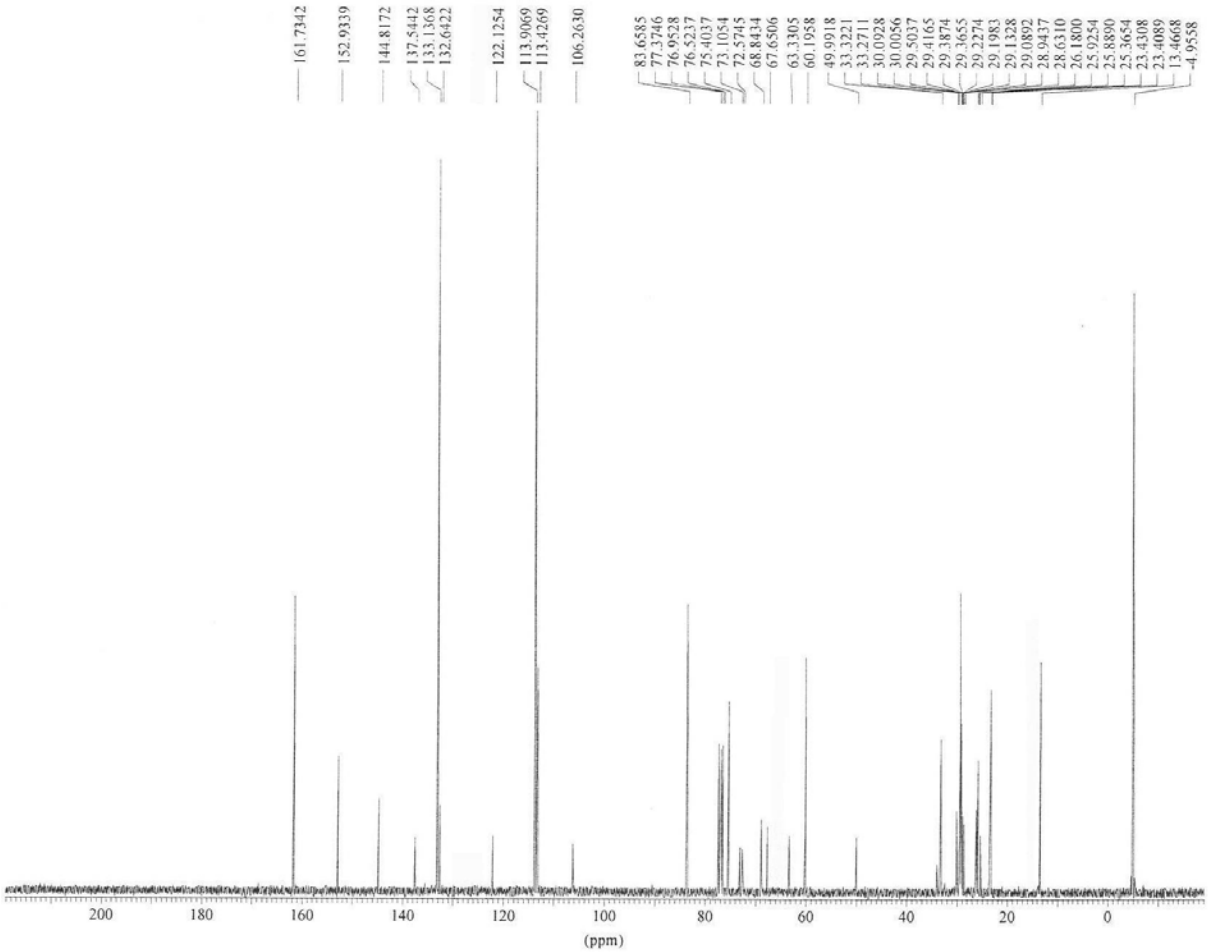
^{1}H NMR spectrum



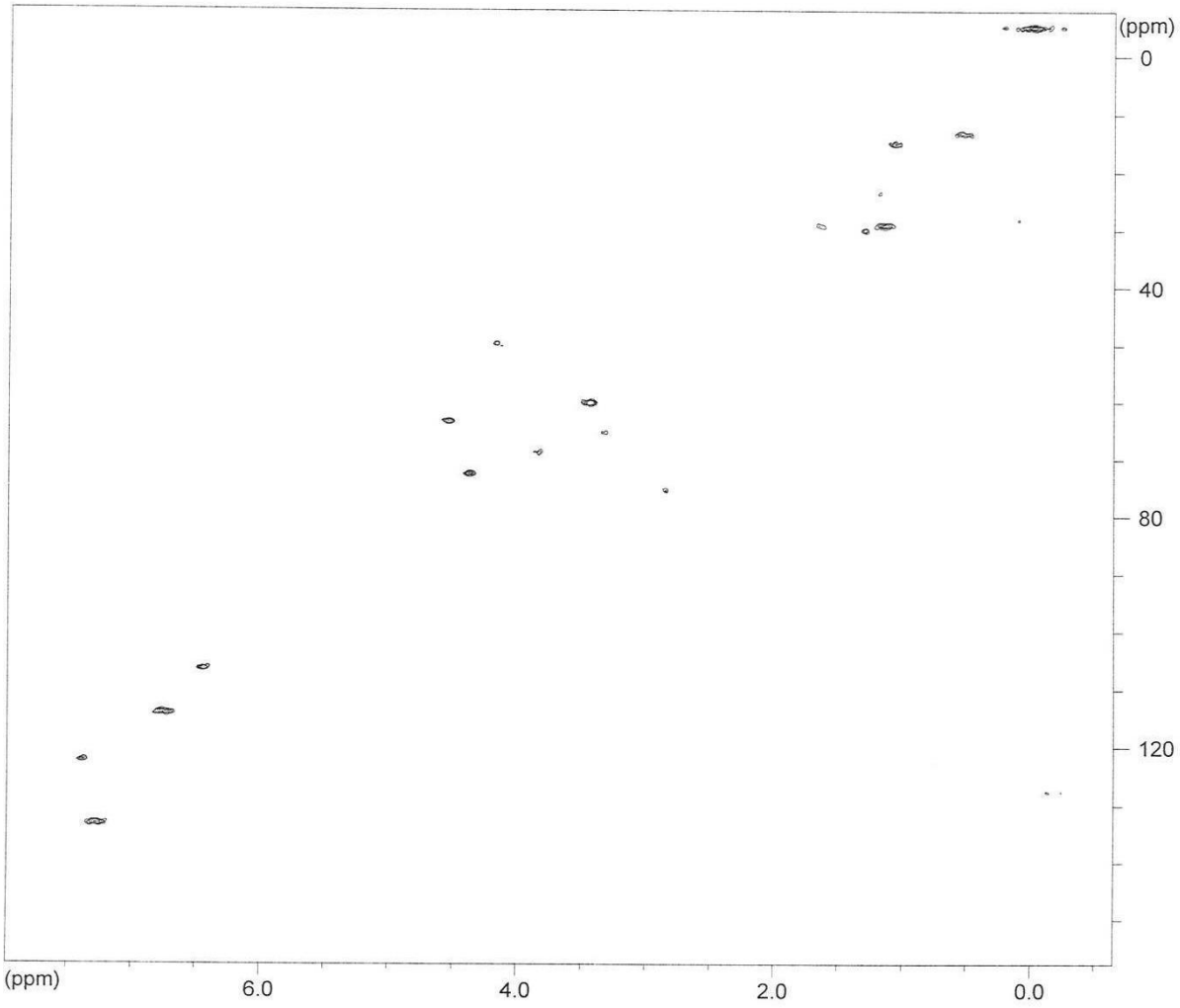
JMOD NMR spectrum



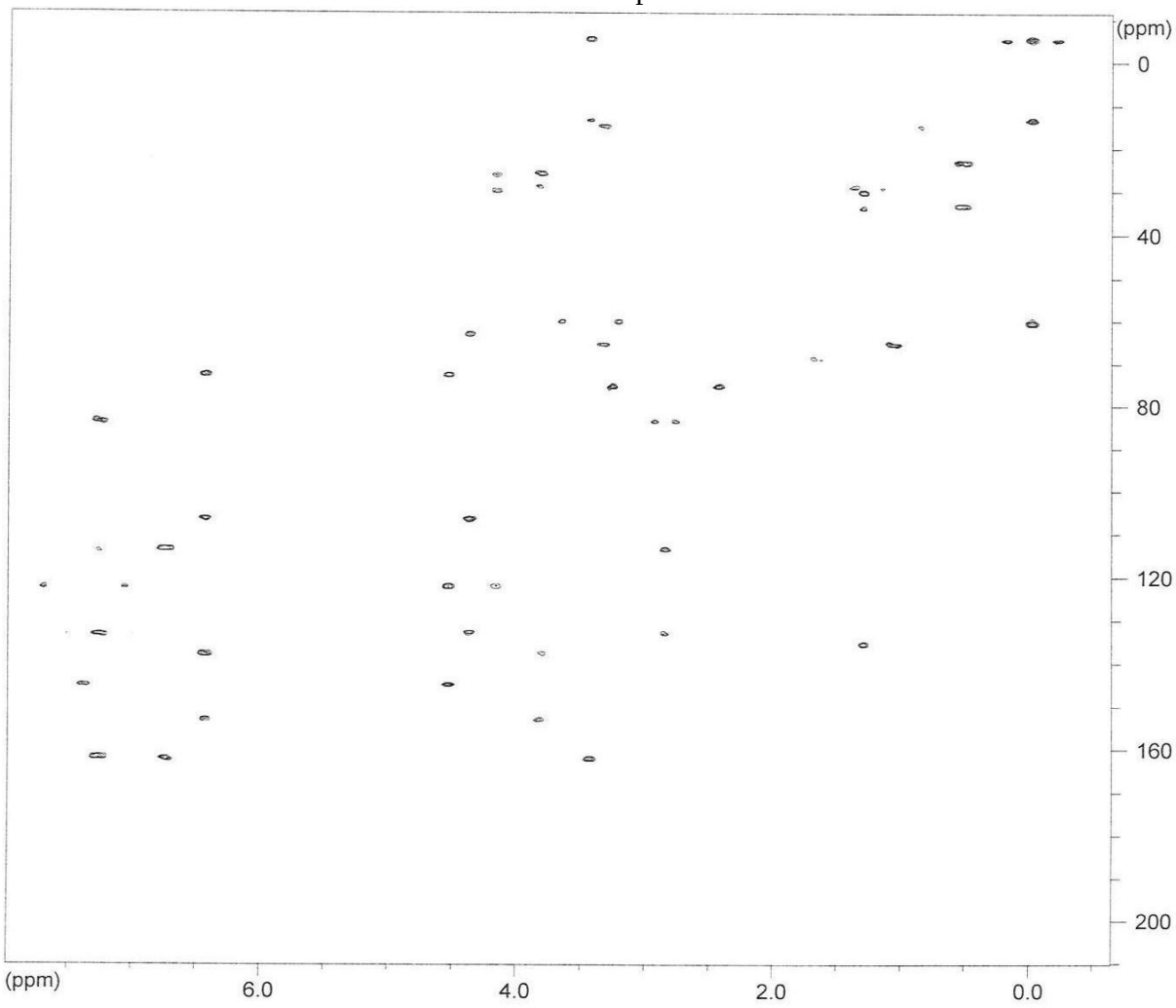
^{13}C NMR spectrum



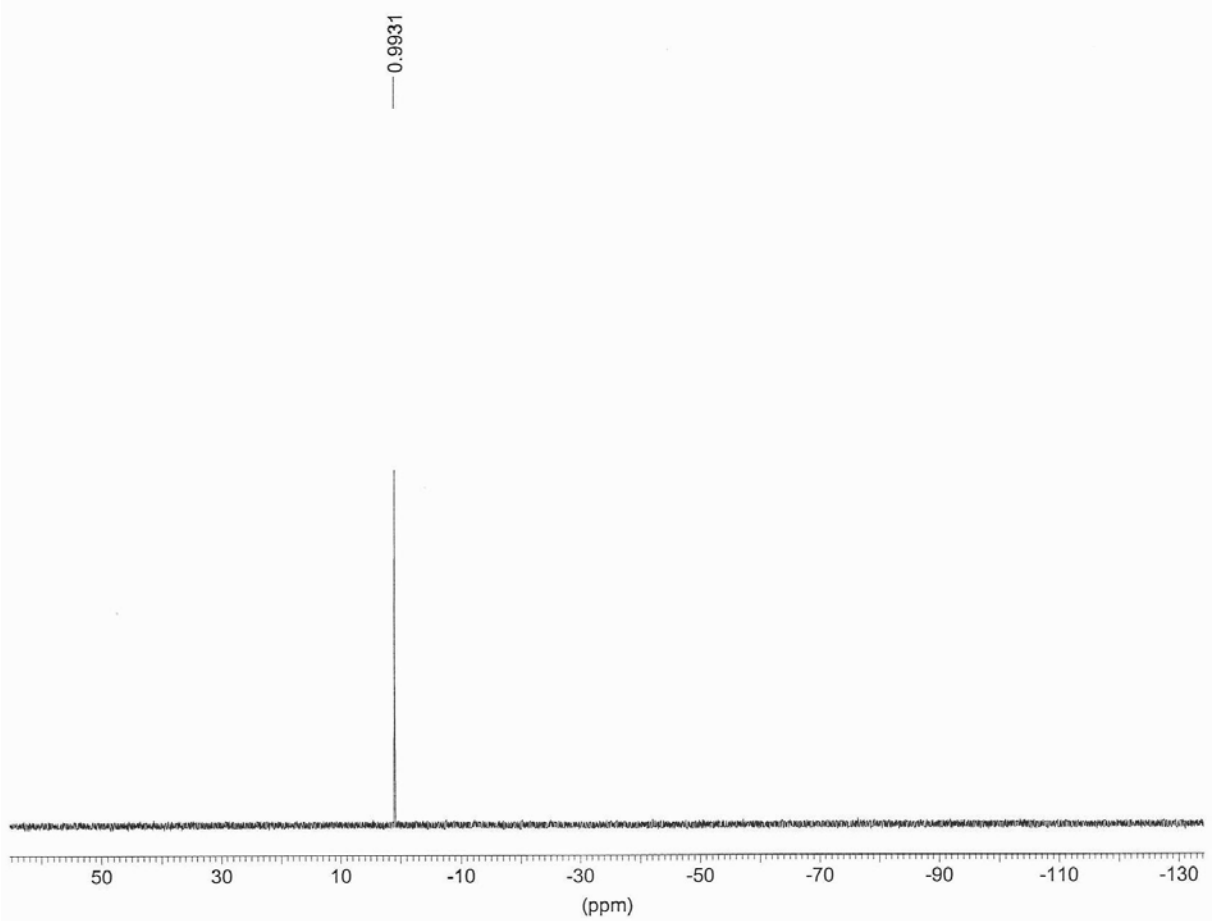
HMQC NMR spectrum



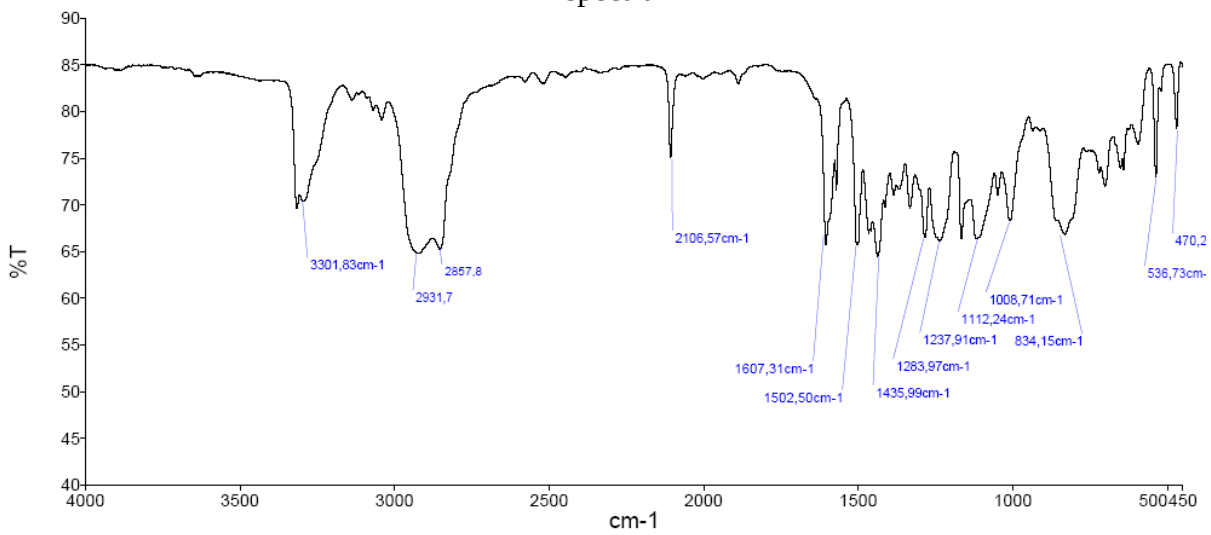
HMBC NMR spectrum



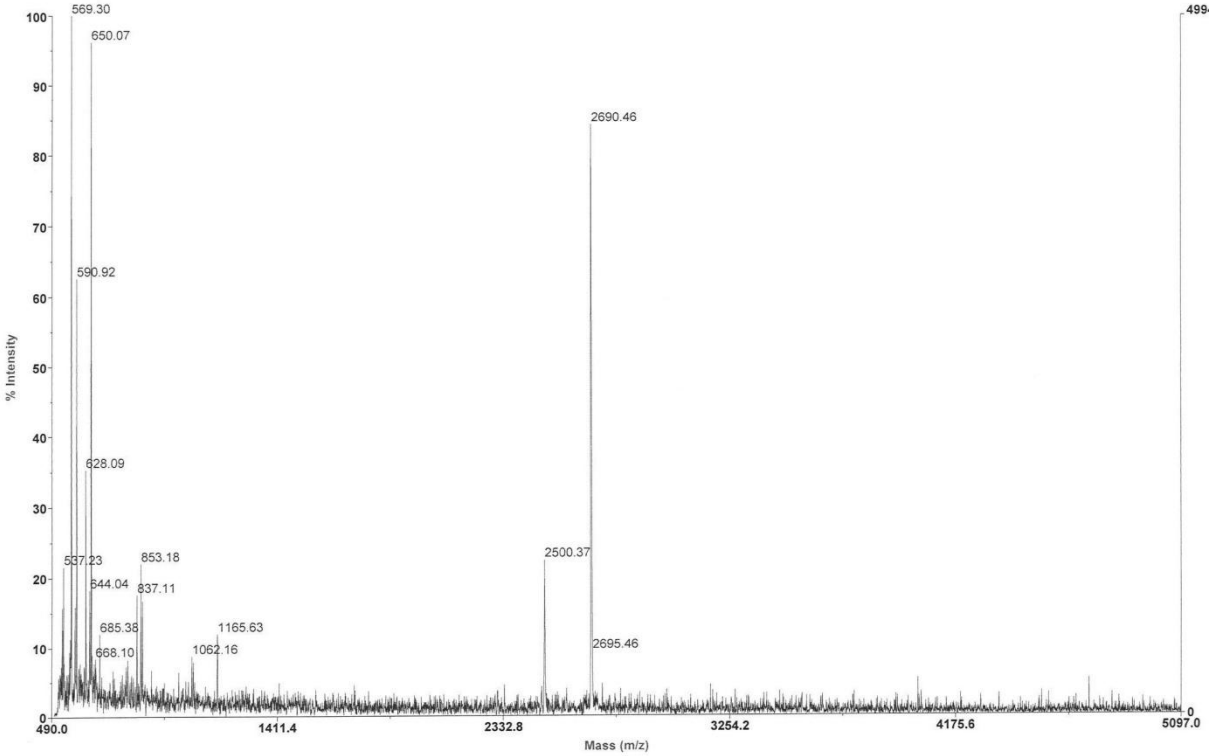
^{29}Si NMR spectrum



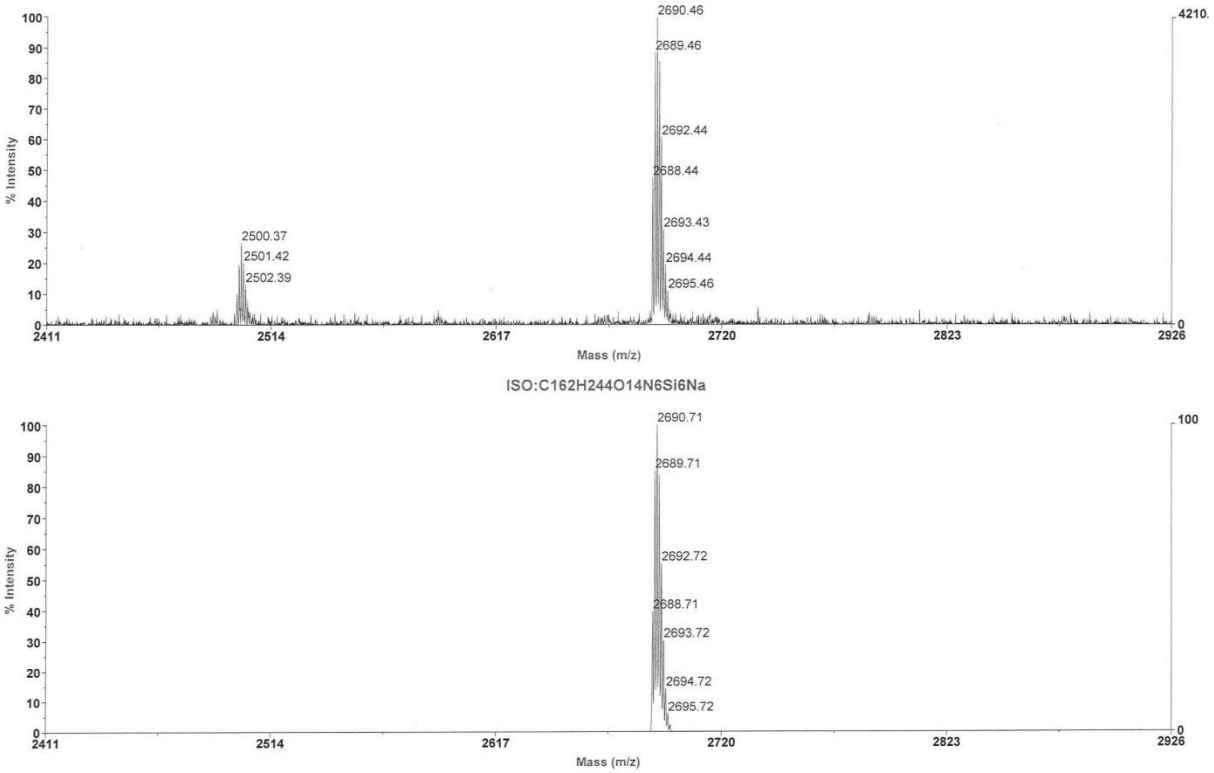
IR spectrum



MALDI-TOF Mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



Sample Details

Sample Name: JC 311
Acquired: 10/05/2010 16:39:40 — lundi 10 mai 2010 17:17
Filename: C:\Cirrus Workbooks\Niko\Niko GPC DMF RI\ism-0010.cgrm
Batch Name: ISM — K of Sample: 14.1000
Injection Volume: 100.0 ul — Alpha of Sample: 0.7000

Workbook Details

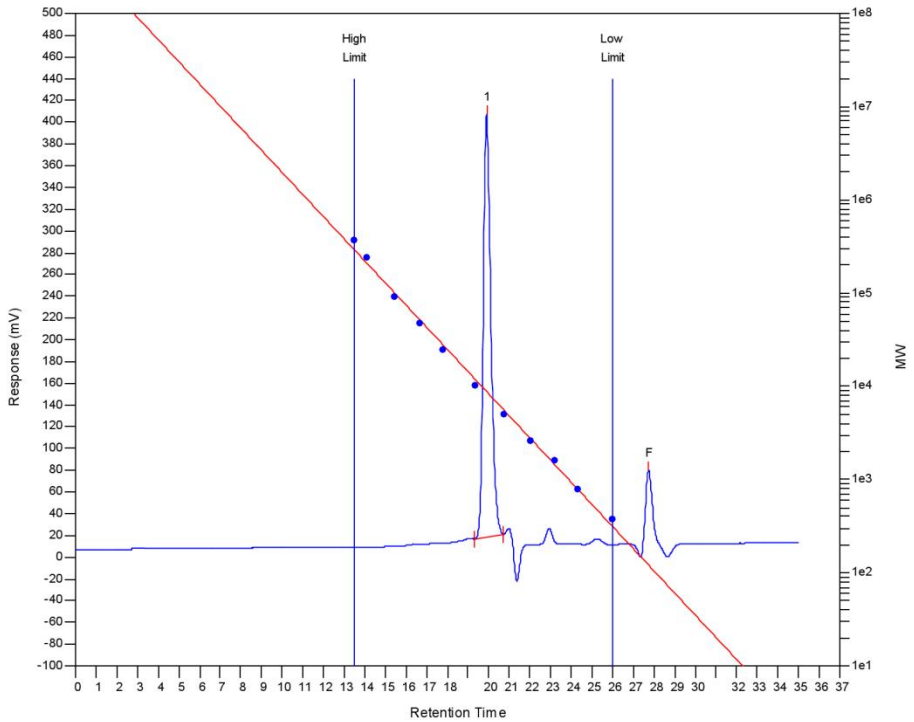
Eluent: DMF LiBr 1g/l — Flow Rate: 1.00 ml/min
Column Set: PLgel 5µm MIXED-D — Column Set Length: 650 mm
Detector: RI — Temperature: 80

Analysis Using Method: Calibration PS-M Easivial 26-04-10

Results File: C:\Cirrus Workbooks\Niko\Niko GPC DMF RI\ism-0010-Repeat (01).rst

Calibration Used: 29/04/2010 18:00:04

Calibration Type: Narrow Standard — Curve Fit Used: 1
Flow Marker RT calibration : 27.77 mins — Flow Marker RT Sample :27.750000



MW Averages

Peak No	Mp	Mn	Mw	Mz	Mz+1	Mv	PD
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2	0	0	0	0	0	0	0

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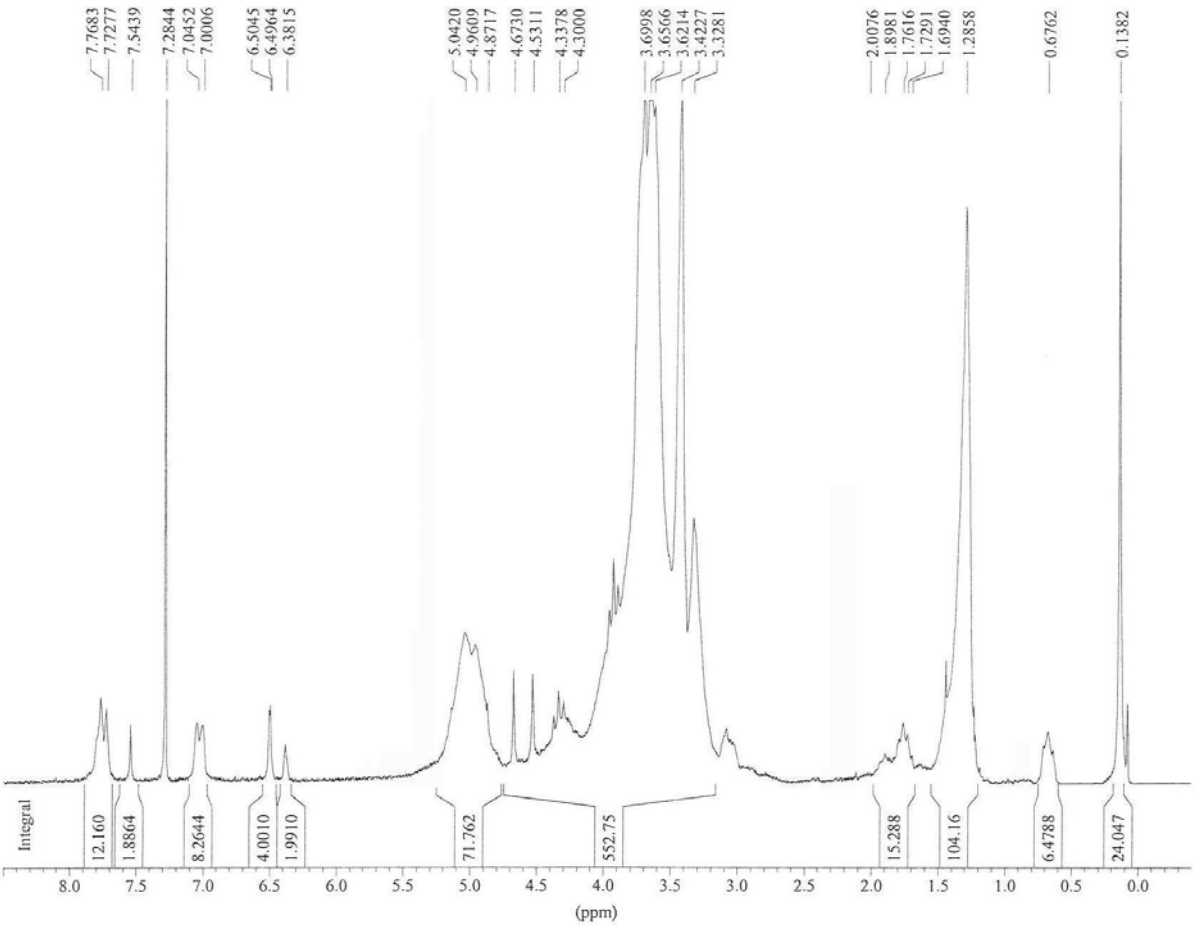
Synthesis of G1-tetra RAME-β-cyclodextrin dendrimer 20

To a solution of G1-tetra alkynyl dendrimer **13** (0.25g, 0.13mmol, 1eq) in dichloromethane was added azido-RAME-β-cyclodextrin (0.89, 0.67mmol, 5.2eq). A solution of $CuSO_4.5H_2O$ (0.52g, 2.1mmol, 16eq) in water was added. The reaction mixture was energically stirred and a solution of sodium ascorbate (0.83g, 4.2mmol, 32eq) in water was then added dropwise. The reaction mixture was stirred at 30°C for 24h under a nitrogen atmosphere. A solution of $CuSO_4.5H_2O$ (0.26g, 1.0mmol, 8eq) in water was added. A solution of sodium ascorbate (0.41g, 2.1mmol, 16eq) in water was then added dropwise. The reaction mixture was stirred for another 24h. Dichloromethane was removed *in vacuo.* Ammonium hydroxide was added and the mixture was stirred for two hours. The reaction mixture was filtered and the solid obtained was washed two times with hot water. The solid was dissolved in dichloromethane, dried over anhydrous sodium sulfate and filtered. The organic layer was concentrated and methanol was added. The organic layer was filtered and evaporated to dryness *in vacuo*. The solid obtained was then lyophilized.
The desired product was obtained as an off-white solid (0.52g, 0.07mmol) in 56% yield.

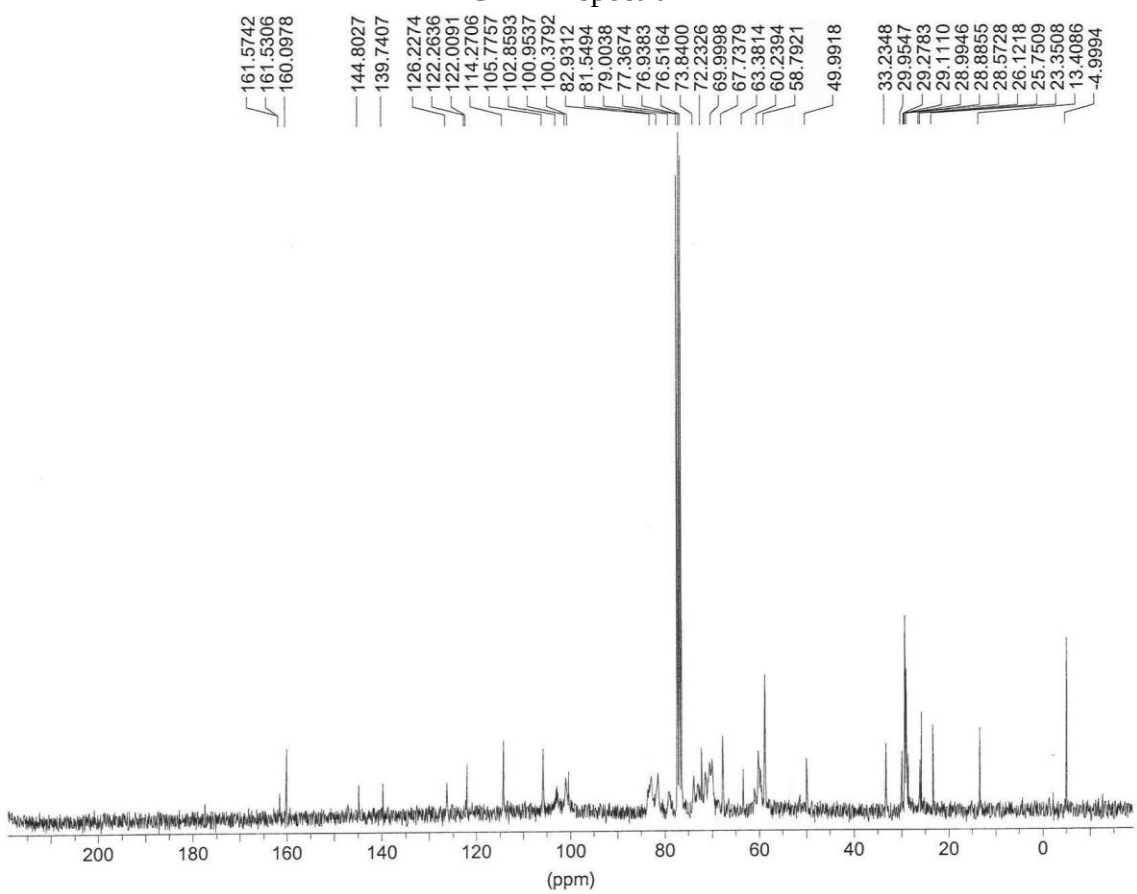
^{1}H NMR ($CDCl_3$ 300MHz): 7.73 ppm (m, external $H_{triazole}$ and H_{ar}, 12H); 7.52 ppm (s, internal $H_{triazole}$, 2H); 7.00 ppm (d, H_{Ar}, 8H) ; 6.48 ppm (d, H_{Ar}, 4H) ; 6.36 ppm (s, H_{Ar}, 2H) ; 4.96 ppm (m, $H_{cyclodextrin}$); 4.65 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.51 ppm (s, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, 4H); 4.30 to 3.00 ppm (m, -CH_2-$N_{triazole}$, meta and para -O-CH_2-CH_2-, Si-CH_2-O and $H_{cyclodextrin}$); 1.82 ppm (m, -CH_2-CH_2-$N_{triazole}$, 4H); 1.69 ppm (m, meta and para -O-CH_2-CH_2-, 8H); 1.50 to 1.20 ppm (br s, -CH_2-, 76H) ; 0.65 ppm (br s, -CH_2-CH_2-Si, 8H) ; 0.12 ppm (s, Si-CH_3, 24H)
^{13}C NMR ($CDCl_3$ 50.3MHz): 161.57, 160.10, 144.80, 139.74, 126.23, 122.27, 122.01, 114.27, 105.78, 102.9-100.3, 83.0-81.5, 79.00, 73.9-69.9, 67.74, 63.38, 60.3-58.7, 49.99, 33.23, 29.95, 29.28, 29.11, 28.99, 28.89, 28.57, 26.12, 25.75, 23.35, 13.41, -5.00 ppm
^{29}Si NMR ($CDCl_3$ 59.6MHz) : only one peak at 0.93 ppm
Maldi-Tof mass spectrometry $[M+Na]^+$ m/z = 7328.2

^{13}C NMR ($CDCl_3$ 50.3MHz): 161.93 and 160.33 ppm (C_{ar}-O); 145.05 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 139.93 (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 133.34 ppm (C_{ar}-H); 122.22 ppm ($C_{triazole}$-H) ; 114.07 ppm (C_{ar}-H); 113.45 (C_{ar}-C≡C-); 106.00 and 100.53 ppm (C_{ar}-H); 83.84 ppm (C_{ar}-C≡C-H); 75.48 ppm (C_{ar}-C≡C-H); 72.48 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 67.96 ppm (-O-CH_2-CH_2-); 63.63 ppm (C_{Ar}-CH_2-O-CH_2-$C_{triazole}$); 60.35 ppm (Si-CH_2-O-) ; 50.23 ppm (-CH_2-$N_{triazole}$); 33.45, 30.22, 29.57, 29.51, 29.35, 29.25, 29.15, 28.83, 26.38, 25.99 and 23.57 ppm (-CH_2-) ; 13.62 (-CH_2-CH_2-Si) ; -4.78 ppm (Si-CH_3)

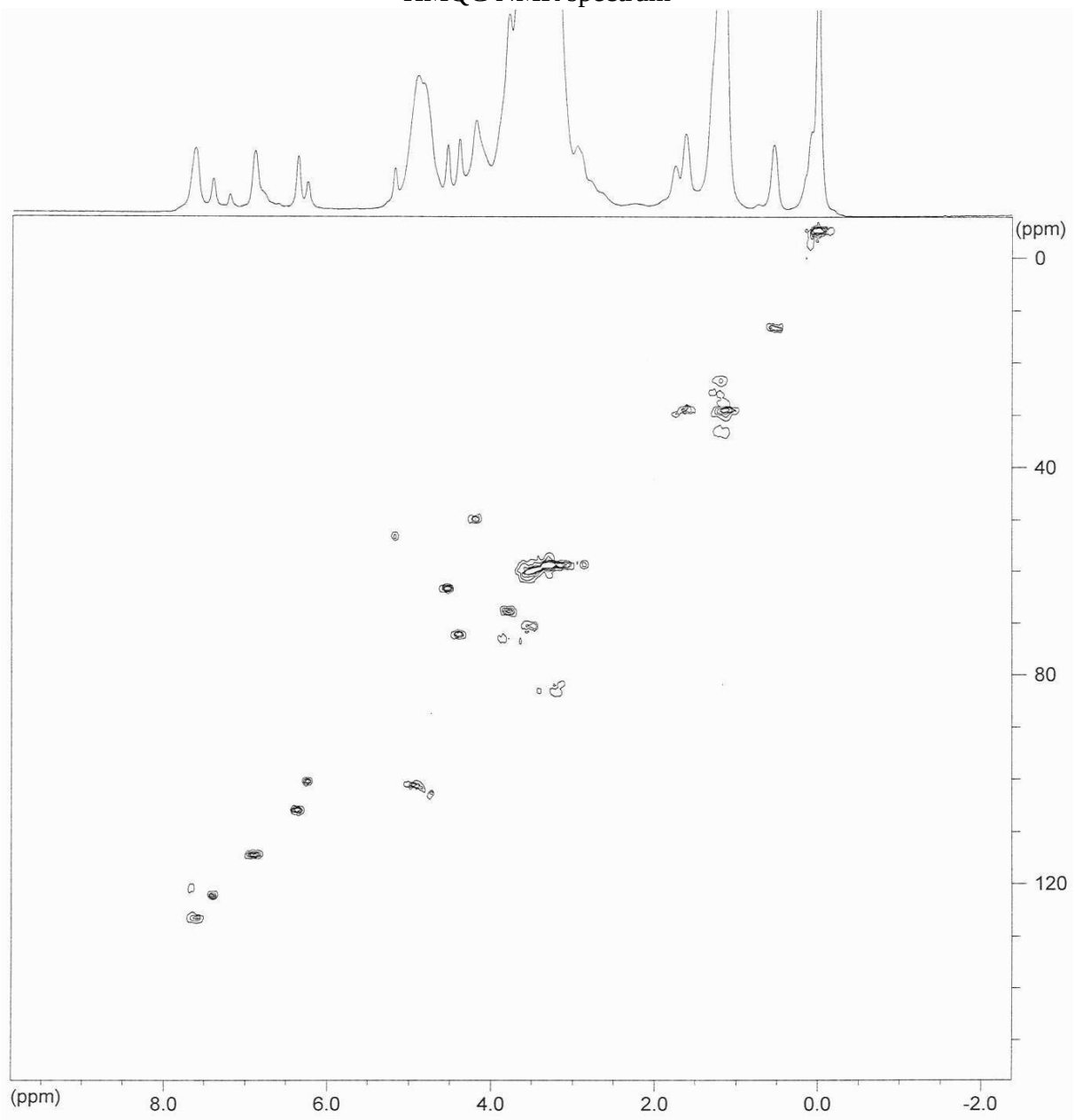
^{1}H NMR spectrum



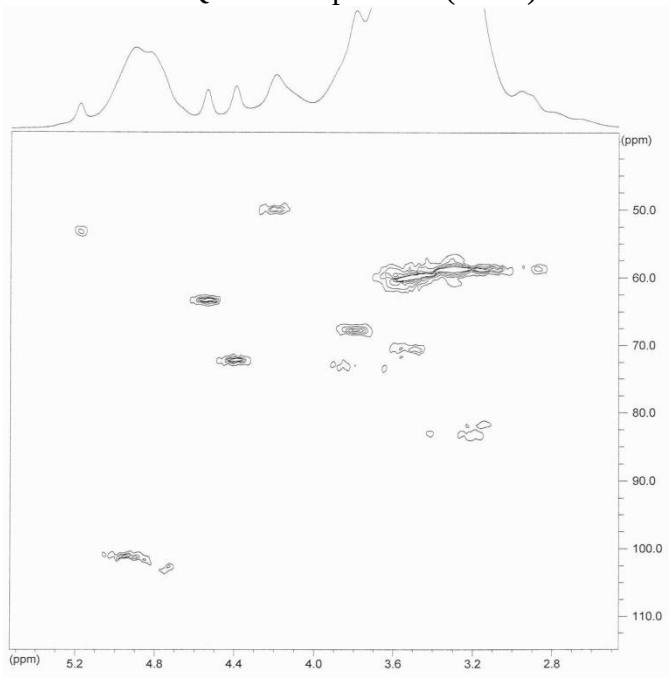
^{13}C NMR spectrum

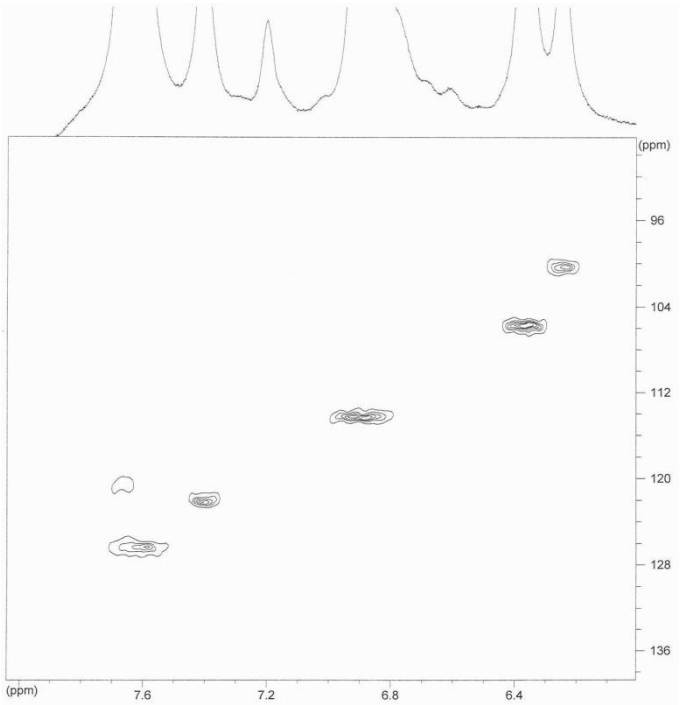


HMQC NMR spectrum

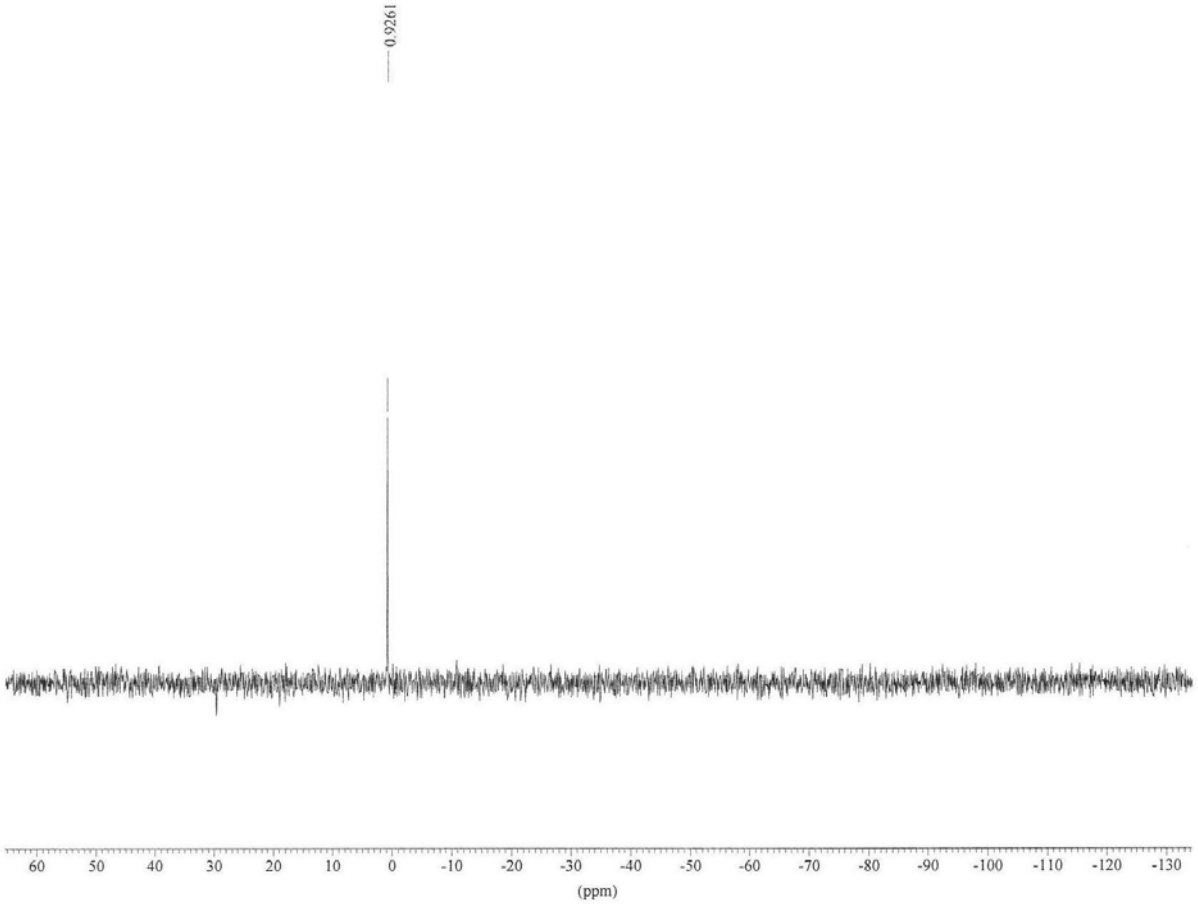


HMQC NMR spectrum (zoom)

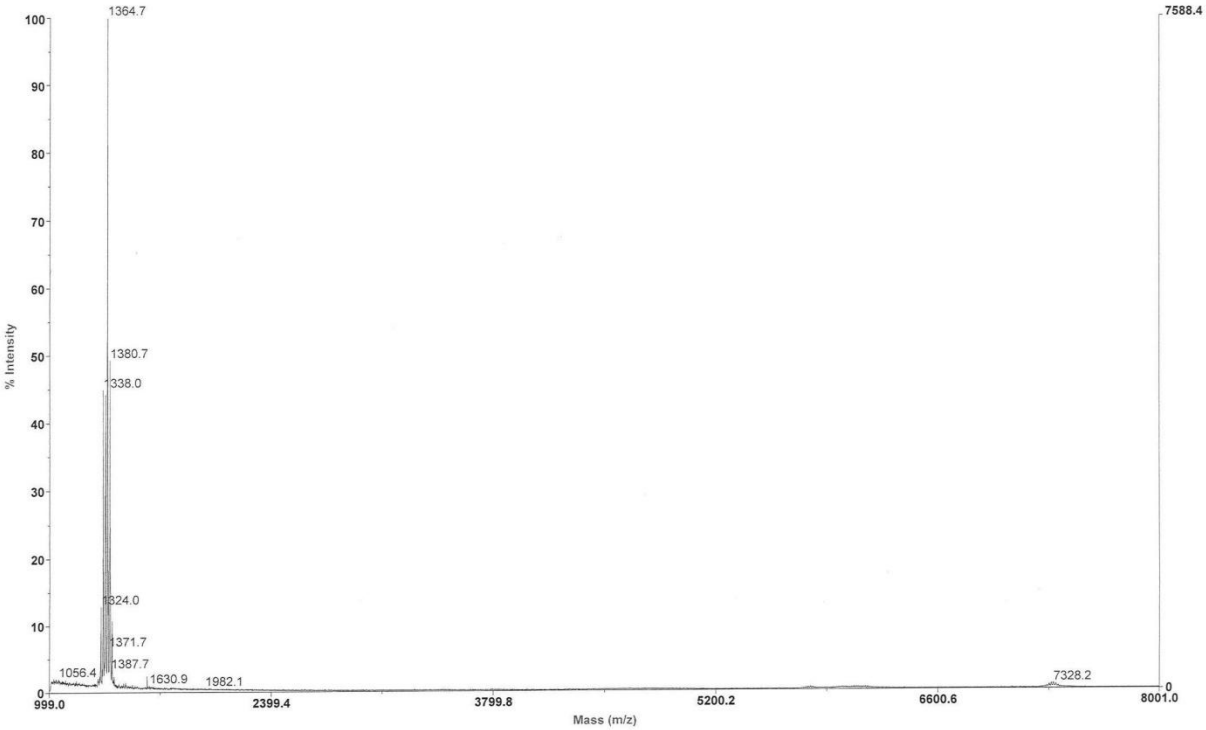




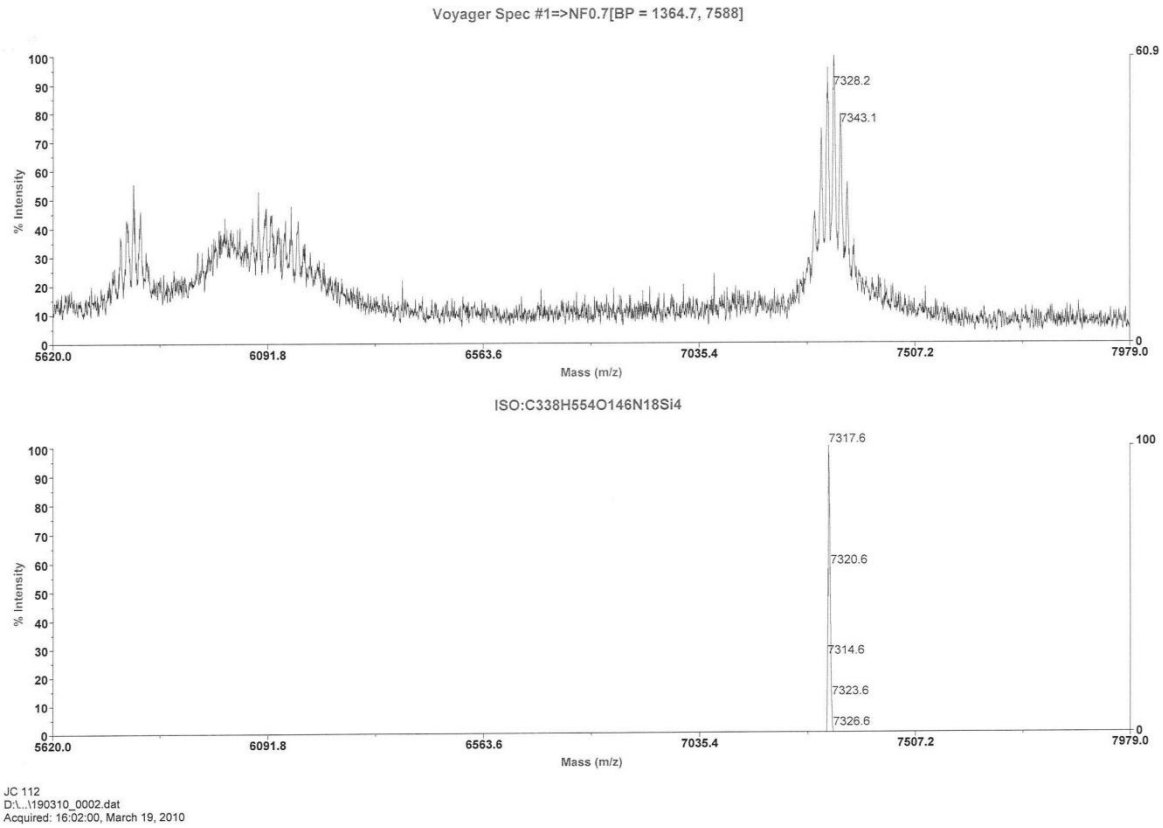
^{29}Si NMR spectrum



MALDI-TOF Mass spectrum (1/2)



MALDI-TOF Mass spectrum (2/2 Molecular ion peak and Simulation)



Sample Details

Sample Name: JC 112
Acquired: 10/05/2010 16:01:48 — lundi 10 mai 2010 16:59
Filename: C:\Cirrus Workbooks\Niko\Niko GPC DMF UV\ism-0009.cgrm
Batch Name: ISM — K of Sample: 14.1000
Injection Volume: 100.0 ul — Alpha of Sample: 0.7000

Workbook Details

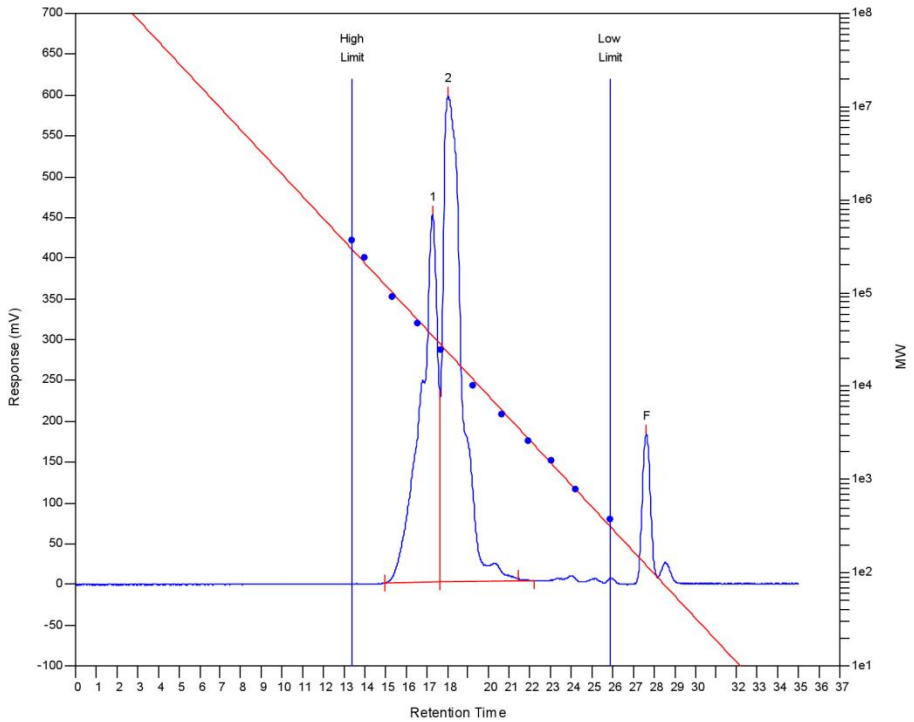
Eluent: DMF LiBr 1g/L — Flow Rate: 1.00 ml/min
Column Set: PLgel 5µm MIXED-D — Column Set Length: 650 mm
Detector: UV — Temperature: 80

Analysis Using Method: Calibration PS-M Easivial 26-04-10

Results File: C:\Cirrus Workbooks\Niko\Niko GPC DMF UV\ism-0009-Repeat (01).rst

Calibration Used: 29/04/2010 18:04:53

Calibration Type: Narrow Standard — Curve Fit Used: 1
Flow Marker RT calibration : 27.68 mins — Flow Marker RT Sample :27.633333



MW Averages

Peak No	Mp	Mn	Mw	Mz	Mz+1	Mv	PD
1	34879	40654	43796	47928	53046	43250	1.07729
2	23126	17769	19631	20887	21813	19415	1.10479
3	0	0	0	0	0	0	0

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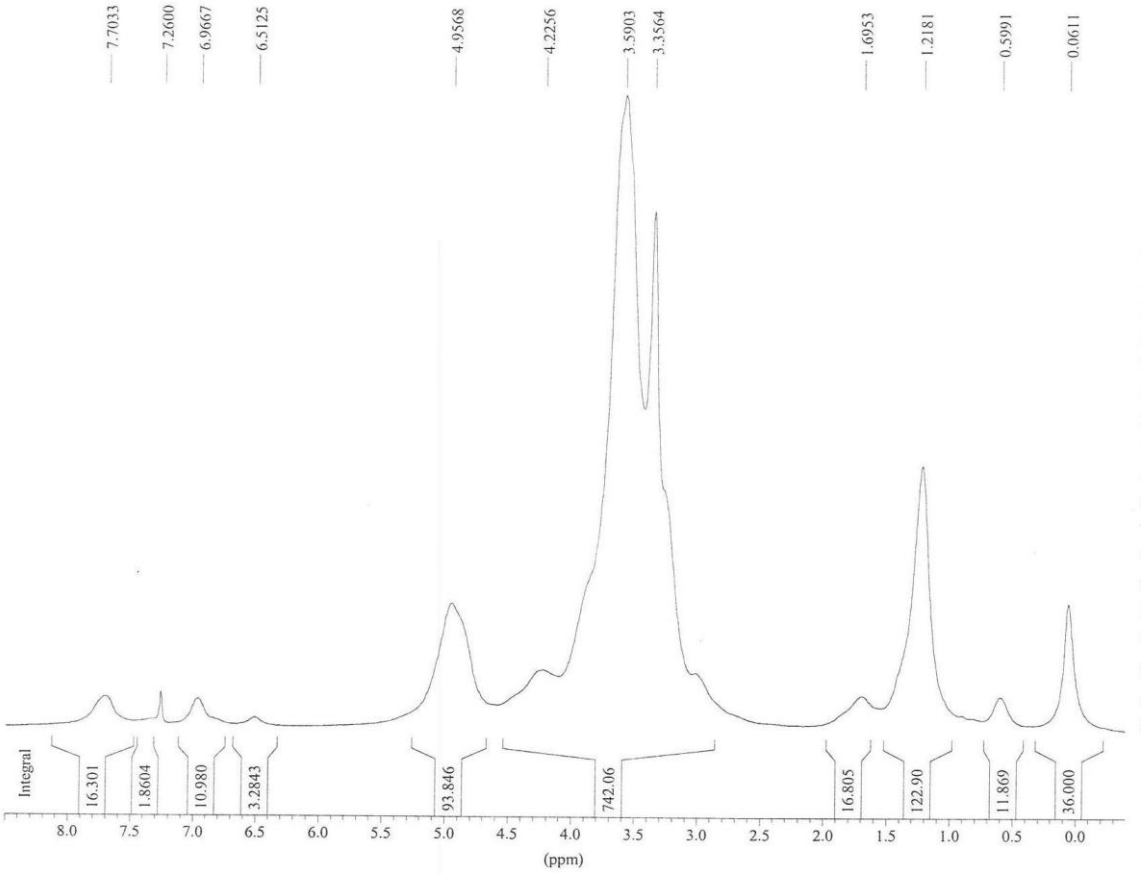
Synthesis of G_1-hexa RAME-β-cyclodextrin dendrimer 21

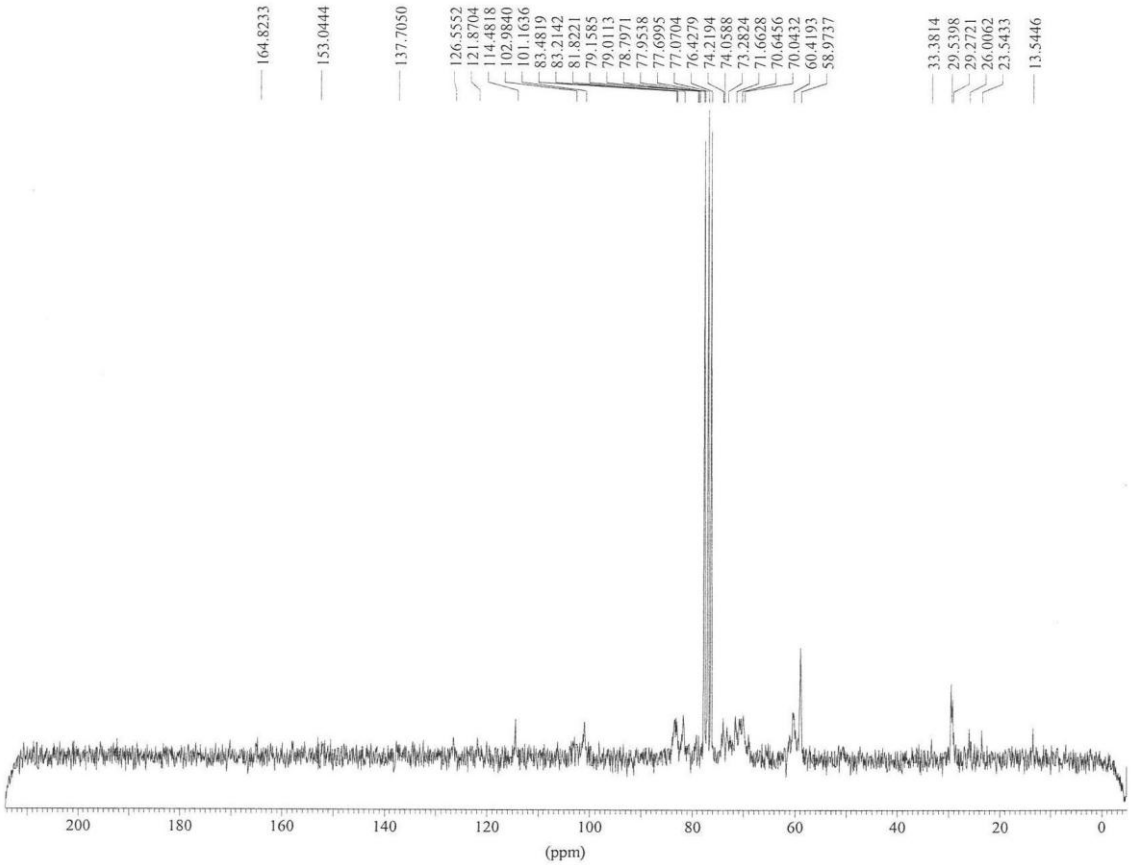
To a solution of G1-hexa alkynyl dendrimer **19** (0.25g, 0.09mmol, 1eq) in dichloromethane was added azido-RAME-β-cyclodextrin (0.98g, 0.73mmol, 7.8eq). A solution of $CuSO_4.5H_2O$ (0.54g, 2.16mmol, 24eq) in water was added. The reaction mixture was energically stirred and a solution of sodium ascorbate (0.86g, 4.32mmol, 48eq) in water was then added dropwise. The reaction mixture was stirred at 30°C for 24h under a nitrogen atmosphere. A solution of $CuSO_4.5H_2O$ (0.27g, 1.08mmol, 12eq) in water was added. A solution of sodium ascorbate (0.43g, 2.16mmol, 24eq) in water was then added dropwise. The reaction mixture was stirred for another 24h. Dichloromethane was removed *in vacuo.* Ammonium hydroxide was added and the mixture was stirred for two hours. The reaction mixture was filtered and the solid obtained was washed two times with hot water. The solid was dissolved in dichloromethane, dried over anhydrous sodium sulfate and filtered. The organic layer was concentrated and methanol was added. The organic layer was filtered and evaporated to dryness *in vacuo*. The solid obtained was then lyophilized.
The desired product was obtained as an slightly yellow solid (0.47g, 0.04mmol) in 47% yield.

^{1}H NMR ($CDCl_3$ 300MHz): 7.69 ppm (br s, $H_{triazole}$ and H_{ar}, 18H); 7.40 ppm (br s, $H_{triazole}$, 2H); 6.97 ppm (br s, H_{Ar}, 12H) ; 6.51 ppm (br s, H_{Ar}, 4H) ; 5.20 to 4.70 ppm (m, $H_{cyclodextrin}$); 4.50 to 4.00 ppm (m, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, C_{Ar}-CH_2-O-CH_2-$C_{triazole}$, , -CH_2-$N_{triazole}$); 4.00 to 3.40 ppm (m, meta and para -O-CH_2-CH_2-, Si-CH_2-O and $H_{cyclodextrin}$); 1.70 ppm (br s, -CH_2-CH_2-$N_{triazole}$ and meta and para -O-CH_2-CH_2-, 4H + 12H); 1.50 to 1.20 ppm (br s, -CH_2-, 108H) ; 0.60 ppm (br s, -CH_2-CH_2-Si, 12H) ; 0.06 ppm (s, Si-CH_3, 36H)

^{1}H NMR spectrum



^{13}C NMR spectrum



Résumé, conclusions et perspectives

Conclusion et perspectives

Durant ce projet de recherche, nous avons tout d'abord développé une nouvelle série dendritique comportant des alcynes périphériques. Cette série s'appuie sur les synthèses dendritiques précédemment réalisées au laboratoire de cœurs polyiodés connus jusqu'à la génération 9 (plus de 100000 branches). Le dendron phénol trialcyne développé par analogie au dendron phenol triallyle classique du laboratoire peut alors être greffé en périphérie. Cette fonctionnalisation est réalisée en utilisant tout le savoir-faire du laboratoire sur les réactions de Williamson en série dendritique afin d'obtenir les dendrimères polyalcynes comportant 27, 81 et 243 branches.

Ainsi, la synthèse utilisée pour obtenir ces dendrimères par ajout d'une génération terminale différente du reste du dendrimère, autorise théoriquement, la synthèse de dendrimères polyalcynes plus gros et ce jusqu'à la génération 9. Il serait donc envisageable de réaliser la synthèse des générations supérieures pour élargir cette famille.

Des ferrocènes ont ensuite été greffés à la périphérie de ces dendrimères en utilisant la chimie « click ». La formation d'un groupement 1,2,3-triazole associé au ferrocène donne à cette architecture des propriétés d'exorécepteur. Ceci nous a permis de réaliser la reconnaissance électrochimique d'oxo-anions d'intérêt biologique dont l'ATP ainsi que de cations métalliques. De plus, nous avons pu mettre en évidence l'interaction entre le cycle 1,2,3-triazole et ces molécules.

L'effet dendritique sur la reconnaissance est relativement faible, comparé à l'effet de tripode ferrocénique. Cependant, les propriétés d'adsorption des dendrimères à la surface des électrodes de platine augmentent fortement avec la génération. Ainsi, nous avons fabriqué des électrodes de platines, modifiées par adsorption de dendrimère, et capables de reconnaitre les mêmes oxo-anions que le dendrimère en solution. Lorsque la génération dendritique augmente, ces électrodes deviennent de plus en plus robustes, ce qui permet leur recyclage.

Il est ainsi envisageable d'utiliser ces molécules pour la synthèse de nanoparticules métalliques comme cela a déjà été réalisé au laboratoire avec d'autres architectures similaires. L'ATP étant un des constituants de l'ADN, il serait intéressant de tester la réponse électrochimique du système en présence d'ADN.

Les cœurs polyalcynes ont ensuite été fonctionnalisés par des dérivés de xylopyranoses. Ceci a été réalisé afin d'obtenir des dendrimères solubles dans l'eau comportant le motif 1,2,3-triazole étudié précédemment. Ces xylopyranoses protégés ont été couplés avec succès sur les cœurs polyalcynes par chimie click pour donner une série de glycodendrimères comportant 27, 81 et 243 xylopyranosides périphériques. Cette série a bien été caractérisée, et différentes techniques de mesure de taille ont été utilisées.

Cependant, le manque de robustesse de ces cœurs polyalcynes a rendu la déprotection impossible, même avec le glycodendrimère le plus petit. En effet, les cassures au niveau du cœur, survenues lors de la déprotection, ont rendu cette réaction impossible à terminer.

Etant donnée l'insolubilité des architectures obtenues en milieu aqueux, et l'impossibilité de réaliser la déprotection, il nous restait deux choix possibles : changer le groupement protecteur du sucre pour une déprotection plus douce, en prenant bien entendu le risque que l'architecture dendritique ne supporte pas les nouvelles conditions de déprotection, ou changer le cœur dendritique pour une architecture plus robuste.

Bien que protégées, les molécules obtenues pourraient tout de même être valorisées par des essais de catalyse en mettant à profit le cycle 1,2,3-triazole, et même en catalyse asymétrique en utilisant l'environnement chiral introduit par les sucres.

Ce projet a ensuite été poursuivi par le greffage d'un xylopyranose protégé sur un cœur dendritique comportant neuf branches azotures, basé sur les architectures classiques du laboratoire. Ces structures plus robustes ont permis le greffage sur l'ensemble des branches puis la déprotection totale des hydroxyles du sucre périphérique. Ceci a permis l'obtention d'un glycodendrimère à 9 branches, soluble dans l'eau.

Des études réalisées par RMN et spectrométrie de masse sur l'interaction de ces molécules avec des cations métalliques (dont le médicament anticancéreux cis platine) sont en cours.

Ces premiers résultats encourageants nous incitent à développer cette famille dendritique. En effet il serait souhaitable de réaliser la synthèse ainsi que les tests d'encapsulation sur des glycodendrimères plus gros. Il est de plus possible de réaliser ces architectures en construisant le cœur dendritique par chimie click et ainsi multiplier d'une part les possibilités d'encapsulation de la structure et d'autre part le nombre de cycles 1,2,3-triazoles présents dans les cavités.

Ce genre d'architectures pourrait faire l'objet de tests pour le transport et l'encapsulation de différentes molécules. Les études concernant l'encapsulation et le relargage de cisplatine par exemple, pourraient être approfondies. La catalyse par transfert de phase, l'encapsulation de catalyseur dans un environnement chiral pour la catalyse asymétrique, l'utilisation comme adjuvant pour la catalyse dans l'eau ou encore comme matrice pour la synthèse et la stabilisation de nanoparticules métalliques sont également des pistes à explorer.

Nous avons ensuite démarré un projet concernant la synthèse de dendrimères polycyclodextrines. Nos premiers essais ont été réalisés sur les cœurs dendritiques polyalcynes comportant 27 branches. Ceci a conduit à un produit insoluble à la fois en milieu aqueux et en milieu organique. Ce résultat reproductible nous a poussé à utiliser une cyclodextrine modifiée chimiquement afin d'augmenter sa solubilité.

La même réaction a donc été réalisée entre le cœur polyalcyne à 27 branches et une cyclodextrine méthylée aléatoirement, l'azido-RAME-β-cyclodextrine. Là encore, nous avons obtenu un produit insoluble, et ce, de façon reproductible.

Pour expliquer ce résultat, un problème de congestion stérique a été avancé. Nous avons donc démarré la synthèse de cœurs dendritiques polyalcynes plus petits afin d'en limiter les effets. Nous avons ainsi obtenu un cœur dendritique comportant neuf branches alcynes et un autre comportant six branches alcynes. Les couplages avec l'azido-RAME-β-cyclodextrine ont alors été réalisés sur ces deux cœurs ainsi que sur un dendron trialcyne. Dans les trois cas, nous avons obtenu uniquement des produits insolubles.

Les architectures dendritiques ont alors dû être repensées, afin d'allonger les branches et ainsi limiter la gêne stérique entre les cyclodextrines.

Nous nous sommes orientés vers la synthèse d'étoiles, comportant de longues branches linéaires autours d'un cœur aromatique, issues de l'allongement de l'hexakis butenylbenzene et de son homologue à 4 branches. L'allongement des branches a été réalisé par le greffage de chaînes polyéthylènes glycol comportant d'un côté une fonction alcyne et de l'autre une fonction phénol.

La fonctionnalisation des deux étoiles par l'azido-RAME-β-cyclodextrine a conduit à des produits parfaitement solubles à la fois dans l'eau et les milieux organiques. Cependant, la fonctionnalisation apparaissait incomplète, et irrégulière. En effet, même les meilleurs lots, qui présentaient un bon taux de greffage par RMN ^{1}H, n'ont jamais donné le signal de l'ion moléculaire en spectrométrie de masse.

De plus, ces cœurs, comportant le motif hydroquinone comme les cœurs polyalcynes, se sont révélés assez instables. Lorsque ces réactions ont été réalisées sur des temps plus long

(une semaine) ou à des températures légèrement plus hautes, des coupures ont été observées. Ainsi, il a été impossible de durcir les conditions pour obtenir les produits totalement substitués.

Il était alors nécessaire de réaliser la synthèse de cœurs dendritiques plus robustes. La solubilité des étoiles nous ayant conforté dans nos choix, ce projet s'est donc poursuivi par la synthèse de petits dendrimères comportant 4 à 6 branches allongées. Cette nouvelle série est construite grâce à la chimie click, la réaction d'hydrosilylation et enfin la réaction de Sonogashira pour obtenir des alcynes terminaux.

Ces synthèses ont été réalisées et optimisées uniquement pour la première génération. Cependant, des tests préliminaires de montée en génération, suivis uniquement par RMN ^{1}H et ^{29}Si, ont été réalisés pour vérifier la faisabilité de la réaction d'hydrosilylation sur le dendrimère de deuxième génération. En effet, la présence de cycles 1,2,3-triazoles internes rend souvent la réaction d'hydrosilylation plus difficile et constitue le facteur limitant de la montée en génération.

Cette série pourra donc être développée sur plusieurs générations. De plus, l'existence de deux dendrons très similaires comportant soit deux branches soit trois branches, permettra également la construction de structures hybrides. Ainsi, pour chaque génération dendritique, soit un dendron soit l'autre pourront être utilisés afin d'adapter plus finement le nombre de branches de l'architecture et donc l'encombrement stérique à la périphérie. Un dendrimère de deuxième génération pourra donc comporter 8 branches (en utilisant le dendron à 2 branches), 18 branches (en utilisant le dendron à 3 branches) ou encore 12 branches (avec une structure hybride) pour une taille similaire.

Les couplages réalisés par chimie click sur ces nouveaux cœurs comportant 4 et 6 branches alcynes ont été fructueux. En effet, le composé comportant 4 RAME-β-cyclodextrines terminales a été identifié en spectrométrie de masse. De plus, il a été caractérisé par RMN ^{1}H, ^{13}C et en RMN 2D.

Les propriétés de solubilité du produit obtenu confirment le greffage. En effet, le produit obtenu est insoluble dans l'eau, là où l'azido-RAME-β-cyclodextrine a une solubilité de plus de $500 g.L^{-1}$. Le produit final ne possède pas les propriétés de solubilité dans l'eau désirées, cependant, la stratégie d'allongement des branches semble encore être efficace, car la solubilité du dendrimère final reste bonne en milieu organique.

Ainsi, ces structures pourraient être valorisées en réalisant des essais de catalyse en milieu organique. De plus, la catalyse biphasique prévue initialement pourrait être testée en ajoutant un co-solvant comme le méthanol dans la phase aqueuse.

Enfin, il conviendra de synthétiser de nouvelles architectures, tout en conservant les aspects positifs comme le nombre de branches, leur allongement, la structure dendritique ou la robustesse de la molécule. Cependant, l'hydrophobicité du cœur devra être revue à la baisse en remplaçant par exemple les chaînes aliphatiques par des chaînes polyéthylènes glycol, ce critère étant sans doute ici limitant pour la solubilisation dans l'eau des molécules finales.

Résumé

Un nouveau dendron phénol trialcyne a été développé par analogie avec le dendron phénol triallyle déjà connu. En nous appuyant sur les cœurs dendritiques polyiodés du laboratoire, nous avons obtenu une famille de dendrimères polyalcynes comportant 27, 81 et 243 branches.

Des ferrocènes ont ensuite été greffés par chimie « click » à la périphérie de ces dendrimères. La série obtenue permet la reconnaissance électrochimique d'oxo-anions d'intérêt biologique, comme l'ATP, et de cations métalliques. Grâce aux propriétés d'adsorption des grand dendrimères, nous avons obtenu des électrodes de platine modifiées, robustes et recyclables, permettant de réaliser cette reconnaissance.

Une série de glycodendrimères comportant 27, 81 et 243 xylopyranosides terminaux a également été synthétisée. Les méthodes de caractérisation de nanoobjets ont été investiguées, et en particulier, les techniques permettant d'obtenir la taille des molécules en solution comme la RMN DOSY et la diffusion dynamique de la lumière (DLS).

Enfin, une série de dendrimères robustes comportant 4 à 6 branches alcynes très longues a été développée. Le greffage périphérique par chimie « click » de β-cyclodextrines méthylées aléatoirement est également rapporté.

Abstract

A new easily accessible trialkyne phenol dendron has been developed mimicking the already known triallyl phenol dendron. A family of polyalkynyl containing dendrimers with 27, 81 and 243 terminal branches was obtained starting from the classical polyiodo dendritic cores of the laboratory.

Ferrocenes were then grafted using “click” chemistry. The dendrimers obtained allowed electrochemical sensing of both biologically interesting oxo-anions like ATP and metallic cations. Robust and recyclable modified platinum electrodes were obtained thank to the adsorption properties of large dendrimers. These electrodes are able to recognize the same ions as the dendrimer in solution.

A novel series of glycodendrimers with 27, 81 and 243 modified xylopyranosides termini was synthesized too. The characterization methods for such nanoobjects were investigated, and particularly technics that allow to obtain the size of the molecules like dynamic light scattering (DLS) and DOSY NMR.

Finally, a family of robust polyalkynyl containing dendrimers with 4 to 6 enlarged branches was developed. The functionalization with randomly methylated β-cyclodextrins using “click” chemistry is also reported.

Résumé : Synthèse de nanoarchitectures à vocation biochimique

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Mots-clés : Dendrimères, Ferrocènes, Electrochimie, Reconnaissance, ATP, Xylose, Glycodendrimère, Cyclodextrine, Chimie click

Abstract : Synthesis of nanoarchitectures for biochemical role

A new easily accessible trialkyne phenol dendron has been developed mimicking the already known triallyl phenol dendron. A family of polyalkynyl containing dendrimers with 27, 81 and 243 terminal branches was obtained starting from the classical polyiodo dendritic cores of the laboratory.

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Keywords : Dendrimers, Ferrocenes, Electrochemistry, Sensing, ATP, Xylose, Glycodendrimer, Cyclodextrin, Click chemistry