Chem. Rev. **1999,** *99,* 3199–3246

o-Quinodimethanes: Efficient Intermediates in Organic Synthesis

José L. Segura and Nazario Martín*

Departamento de Química Orgánica, Facultad de Química, Universidad Complutense, E-28040 Madrid, Spain

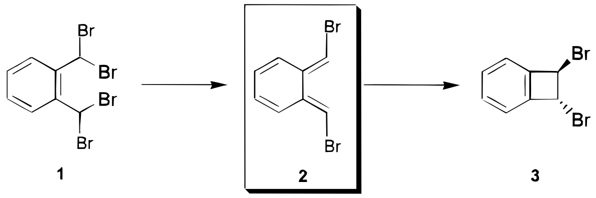
Received February 11, 1999 (Revised Manuscript Received April 16, 1999)

Contents

I. Introduction

The elusive intermediate *o*-quinodimethane (oQDM), also named *o*-xylylene, has attracted much attention of both theoretical and synthetic chemists over the past 30 years. As *cis*-dienes, oQDMs have a remarkable Diels–Alder reactivity and are often used as building blocks in the syntheses of cyclic organic compounds by inter- or intramolecular [4 + 2] trapping. In 1957, Cava and co-workers first suggested the participation of an *o*-quinodimethane **2** as a reaction intermediate in the conversion of $\alpha,\alpha,\alpha',\alpha'$-tetrabromo-*o*-xylene (**1**) to *trans*-1,2-dibromobenzocyclobutene **3** (Scheme 1),[1] and this was later proven by trapping experiments with a number of cyclic dienophiles.

Scheme 1



Since then, many methods for the generation of oQDM[2] and oQDM heteroanalogues[3] have been developed and their characterization, structure, and chemical reactivity have been thoroughly studied. Thus, during the past decade an explosive amount of activity in the area of the *o*-quinodimethane chemistry has been developed from their interest in a variety of fields ranging from the syntheses of steroids and other natural products,[4] their applica-

10.1021/cr990011e CCC: $35.00

José L. Segura received his education in chemistry at the Universidad Complutense de Madrid, where he obtained his Diploma in 1989 and his Ph.D. in 1994 under Professor N. Martin and Professor C. Seoane. In 1993 he visited the group of Professor W. Daily (University of Pennsylvania) where he worked in the area of strained-ring organic syntheses. After postdoctoral stays in the group of Professor M. Hanack (University of Tübingen) working in the syntheses of electroluminescent conjugated polymers and in the group of Professor F. Wudl (University of California at Santa Barbara) working in the functionalization of C_{60} fullerene, Dr. Segura joined the faculty in the Department of Organic Chemistry at the Universidad Complutense de Madrid.

Nazario Martin was born in Madrid in 1956. He studied chemistry at the Universidad Complutense de Madrid (UCM), where he obtained his Doctorate on the synthesis of 4*H*-pyrans at the Department of Organic Chemistry under Professor C. Seoane in 1984. After spending a year working on X-ray contrast agents in a pharmaceutical company, he worked as a postdoctoral fellow (1987–1988) at the Institut für Organische Chemie der Universität Tübingen under Professor M. Hanack on electrically conducting organic materials. In 1994, he was a Visiting Professor at the Institute for Polymers and Organic Solids (IPOS) at the University of California, Santa Barbara (UCSB), working with Professor F. Wudl on modified fullerenes. Since 1989, he has been Associate Professor of Organic Chemistry at the Complutense University. His research interests range over the chemistry of fullerenes, electroactive molecules with emphasis on the electrical and optical properties, and, in particular, the design and synthesis of electroactive organofullerenes. He is also active in the chemistry of *o*-quinodimethanes as well as in the asymmetric synthesis of heterocyclic systems.

tion in the emerging fullerene chemistry,[5,6] their employment as the first nitric oxide cheletropic trap,[7] their use as building blocks in the syntheses of polymeric materials[8] or in materials science,[9] and their implications in different electrochemical[10] and physical[11] studies.

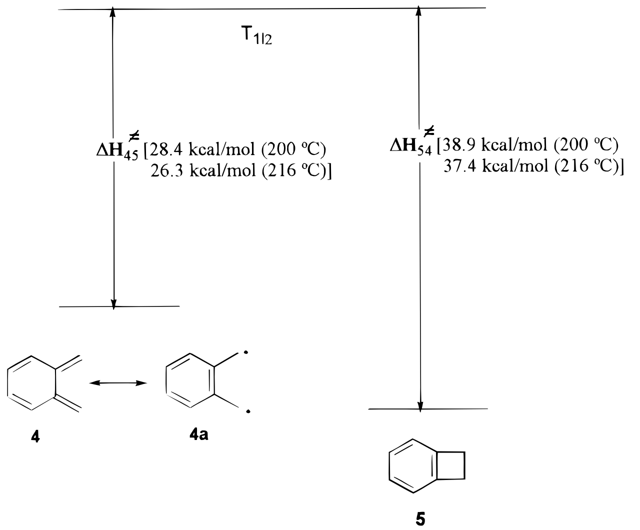


Figure 1. Enthalpy of activation values determined for the 4 $\rightleftharpoons$ 5 system.

The increasing interest of oQDMs in organic synthesis prompted us to prepare a renewed and up-date review of this important organic intermediate with implications in many different areas of the organic chemistry.

The main purpose of this article is 2-fold: (a) to publicize recent developments in the generation of oQDMs and new oQDM heteroanalogues and (b) to emphasize with recent examples the pronounced increase in the use of oQDMs as intermediates in organic synthesis and their applications in different research fields.

II. Structure and Properties of o-Quinodimethanes

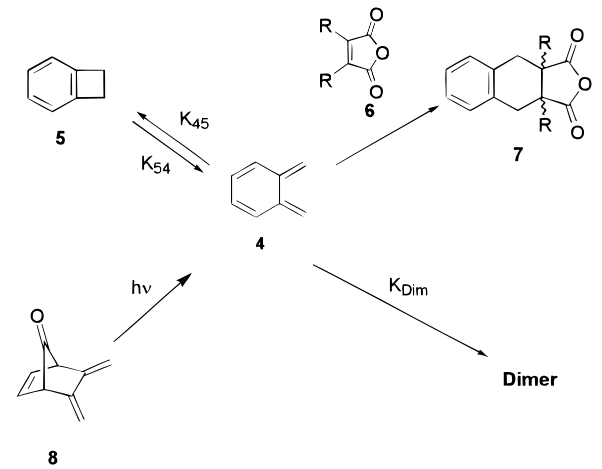
The parent *o*-quinodimethane (**4**) is a reactive intermediate that dimerizes at −150 °C.[12] The thermodynamics and kinetics of the equilibrium gas-phase reaction of oQDM (**4**) and its bicyclic valence tautomer benzocyclobutene (**5**) have been the subject of detailed studies.[13]

o-Quinodimethanes can be also represented as the resonance structure **4a** (Figure 1) as a highly stabilized biradical. With the aim to study the role of biradicals on the reaction coordinates, Roth and coworkers have studied the energy profile of the cyclization of oQDM (**4**) to form the benzocyclobutene system (**5**) (Figure 1).[13a]

The enthalpy of formation of benzocyclobutene was measured by combustion calorimetry to be ΔH°_{f} (g) = 199.4 kJ/mol (47.7 kcal/mol), and from the kinetics of the reaction of **5** with maleic anhydride (**6**, R = H) (Scheme 2), the activation parameter for the oQDM formation **5** → **4** was obtained [$E_a = 166.9$ kJ/mol (39.9 kcal/mol), $A = 2.8 \times 10^{14}$ s^{-1}]. The corresponding value for the back reaction **4** → **5** was determined from the dimerization rate of oQDM, obtained by flash photolysis of 5,6-diethylbicyclo[2.2.1]hept-2-en-7-one (**8**), and from the dimerization of benzocyclobutene, yielding $E_a = 122.7$ kJ/mol (29.3 kcal/mol), $A = 2.2 \times 10^{13}$ s^{-1}.[13a]

Shortly after these measurements, Roth and coworkers studied by Shock tube technique the kinetics of the decomposition of ketone **8** to yield oQDM (**4**) [$E_a = 107.0$ kJ/mol (25.6 kcal/mol); $A = 3.1 \times 10^{13}$ s^{-1}] and its cyclization to benzocyclobutene (**5**) [$E_a = 112.4$ kJ/mol (26.9 kcal/mol); $A = 2.1 \times 10^{12}$ s^{-1}].

Scheme 2



From the temperature dependence of the equilibrium **4** ⇌ **5** which was studied by the same method, the enthalpy of formation of oQDM (**4**) was established to be ΔH_T (g) = 254.1 kJ/mol (60.8 kcal/mol).[13b]

The observed data suggest that **4** can exist together with **5** either in a high-temperature equilibrium [equilibrium constants $K_{581} = 20.8$ (measured)[13] and $K_{800} \approx 4$ (estimated)[14a]] or much more efficiently at low temperatures as an intermediate after the decomposition of a suitable starting compound.

Houk and co-workers have predicted the transition structures for a wide variety of pericyclic reactions by ab initio quantum mechanics.[14b] The electrocyclic ring opening of benzocyclobutene was calculated to be endothermic by 62.7 kJ/mol (15.0 kcal/mol); compound **4** is thus not thermodynamically favored in the equilibrium **4** ⇌ **5**. Interestingly, theoretical calculations predict a nonplanar geometry for oQDM (**4**) with the exocyclic double bonds twisted (82° and 137°) out of planarity.[14b] By trapping experiments with oxygen and by determining the temperature dependence of the equilibrium **4** ⇌ **5**, the activation parameters for the mutual interconversion of **4** and **5** have been determined and compared with previous literature values.[15]

Commonly asked questions about the electronic structure of oQDMs involve the relative importance of contributions from structures such as **4a**−**c** (Figure 2) in various electronic states, spacing and even ordering of these states on the energy scale, in particular of the lowest and first excited singlet, S_0 and S_1, and triplet T_1, preferred geometry, and reaction modes of each state.[12,16]

Questions of particular interest have to cope with the possible presence of a low-lying doubly excited singlet state and with possible differences in the preferred geometry in the S_1 as opposed to T_1 states.[17] By preparing oQDM by irradiation of six different precursors at −196 °C, Flynn and Michl achieved for the first time direct observation of oQDM and concluded that oQDM appeared to be a ground-state singlet which is indefinitely stable in rigid media but dimerizes fast as soon as the medium is softened. The spectral data observed were well accounted for by semiempirical π-electron calculations, which also predict the existence of a low-lying partly doubly excited state. Configuration interaction (CI) wave functions of the low-lying state of oQDM were analyzed in terms of both delocalized and localized frontier orbitals as well as natural orbital occupation numbers to bring out the characteristics of *biradicaloid species*, the term biradicaloid being applied to those molecular geometries at which a simple MO picture shows two approximately nonbonding molecular orbitals containing a total of two electrons in the ground state.[16a] Thus, although the reactivity of oQDM parallels that of a highly reactive diene, it may also be represented as a biradicaloid hydrocarbon.[16a,18−20]

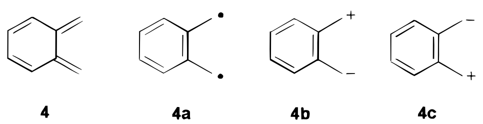


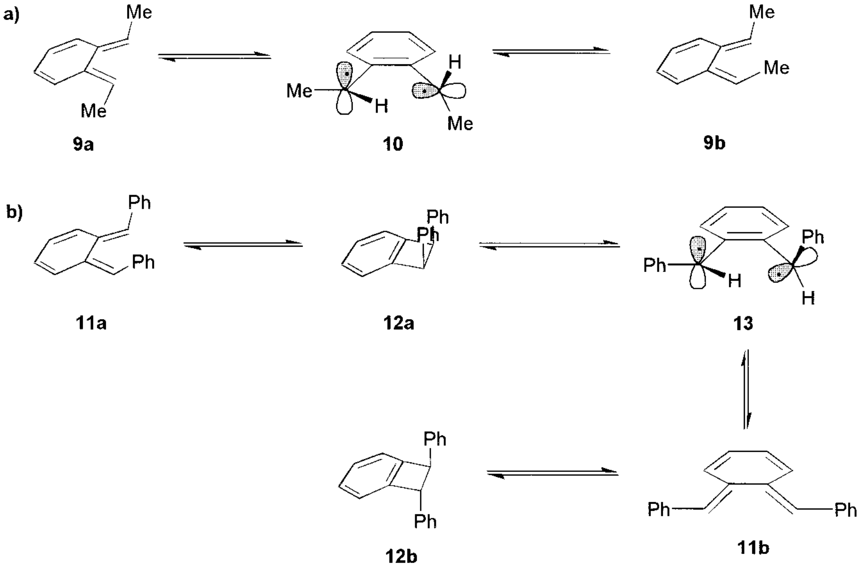
Figure 2. Different structures contributing to oQDM.

In an attempt to determine the reaction mechanism of the Diels−Alder cycloaddition of benzocyclobutene with dienophiles, Kametani et al. have calculated the stabilities for the alternative structures of the intermediate by using MINDO/3, STO-3G, and 4-31G methods.[21] They concluded that the Diels−Alder reaction of benzocyclobutene proceeds via a biradical intermediate by a stepwise cycloaddition, which is in agreement with the results reported by Trahanovsky[22] who suggested that oQDM dimerizes via a stepwise mechanism involving a biradical intermediate preferring a non-endo approach.

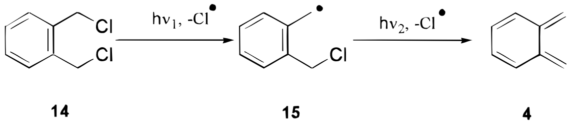
In 1988, cyclobutane derivatives, which are severely restrained from generating noninteractive 1,4-diradicals, were examined thermochemically to provide quantitative evidence to support a “forbidden” concerted, antiaromatic mechanism for their [2 + 2] cycloreversion.[23] This work was followed, in 1996, by study of the energy profiles for the con- and disrotatory opening of benzocyclobutene by NO and oxygen trapping. The enthalpy for the transition states for the “forbidden”-concerted, antiaromatic cycloreversion was identical with the heat of formation of the orthogonal biradicals derived by geometrical isomerization of the diene formed in this reaction.[24] As proof of the proposed stepwise biradical(oid) pathway instead of the concerted “forbidden” electrocyclic disrotatory ring opening, a comparison between dimethylbenzocyclobutene and the diphenyl analogue was carried out. In Scheme 3 is depicted the proposed mechanism for the geometric isomerization of (a) α,α′-dimethyl-*o*-quinodimethane (**9**) and (b) α,α′-diphenyl-*o*-quinodimethane (**11**). As a consequence of the higher stabilization of **13** (benzyl stabilization) in comparison with **10**, the difference in the enthalpy for the con- and disrotative ring opening in the diphenyl isomer should be smaller. This prediction was further corroborated experimentally. While a difference of 20.5 kJ/mol (4.9 kcal/mol) was found for the dimethyl isomer (**9**), a difference of only 4.2 kJ/mol (1.0 kcal/mol) was observed for the diphenyl isomer (**11**).

Korth, Sustmann, and co-workers have studied very recently, for the first time, a *meso*/*rac* isomer-

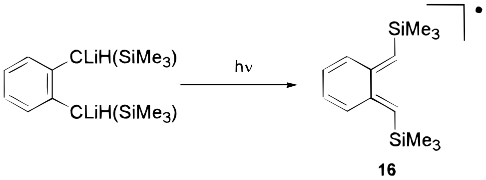
Scheme 3



Scheme 4



Scheme 5



ization process for substituted benzocyclobutenes at room temperature.[25] In agreement with the above-mentioned drop in the difference between the activation barriers for the “forbidden” and conrotatory isomerization when going from the dimethyl-substituted *o*-quinodimethane **9** to the diphenyl analogue **11**, they assume that for a diphenyl dimethoxy analogue, the energy difference between both processes should be of the same order or probably even more in favor of the “forbidden” one due to the additional stabilizing effect of the methoxy groups. Thus, the energetic difference between the “allowed” and the “forbidden” reaction pathways might have virtually vanished, thus explaining the facile *meso*/*rac* isomerization observed for the diphenyl dimethoxy substituted benzocyclobutenes at room temperature.

Mechanistic studies on the photogeneration of oQDM have been recently carried out.[11,26] Fujiwara, Tanimoto, and co-workers have studied the photochemical formation of oQDM by two-pulse fluorescence and transient absorption spectroscopy. They found that formation of oQDM from dissociation of both C−Cl bonds in α,α′-dichloro-*o*-xylene (**14**) proceeds via a 266-nm two-photon process, and a question arises about an intermediate species that absorbs the second 266-nm photon.[11] Three possibilities have been considered: the S_1 and T_1 states of **4** and the *o*-(chloromethyl)benzyl radical **15** (Scheme 4).

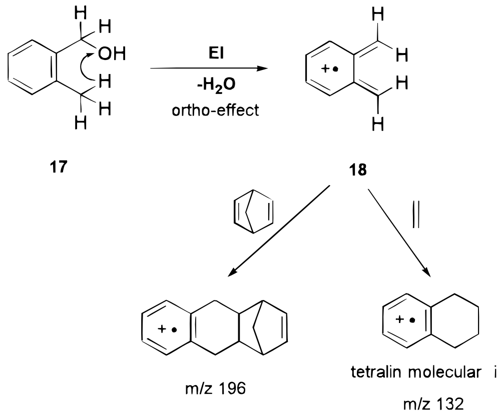
Miranda et al. have further explored the photochemistry of the benzyl radical **15** produced after dissociation of one C−Cl bond of **14** by using two-laser two-color techniques to obtain new data to support or reject the intermediacy of **15** in the formation of oQDM.[26] Thus, 266 nm laser pulses (20 mJ/pulse) were used to photolyze **14**, and a 308 nm excimer laser (90 mJ/pulse) was used to irradiate **15**. They have demonstrated that benzyl radical **15** is the key light-absorbing transient in the two-photon generation of oQDM **4** from the corresponding dichloroxylene by comparing the spectra obtained upon irradiation with the first and second laser, and therefore, the mechanism for the photogeneration of oQDM from α,α′-dichloro-*o*-xylene (**14**) is that depicted in Scheme 4.

Prior to these fluorescence experiments, other spectroscopic investigations on oQDM have given direct evidence for its existence. The absorption,[16a,17,19,27,28] fluorescence,[13,16a−19,27] IR,[19,28] and Raman[19] spectra of oQDM have been observed in low-temperature matrixes, and the absorption spectrum of oQDM has been obtained in solution by flash photolysis[13a,29] and stopped flow[22b] techniques.

Despite the great amount of research focused on the 8π-electron oQDM system, the 9π-electron quinodimethane radical anion and its derivatives have remained elusive. Although resonance-energy calculations suggest that the oQDM radical anion should be well stabilized,[30] it has eluded unequivocal experimental observation.[19,31] It has been only recently that the oQDM radical anion of α,α′-bis(trimethylsilyl)-*o*-quinodimethane (**16**) was prepared by photolysis of a suitable precursor (Scheme 5) at −120 °C with a high-pressure mercury lamp (500 W), which leads to a strong ESR signal ($g = 2.0029$) showing hyperfine splittings of 0.698 (2H) and 0.192 mT (4H).[32]

On the other hand, oQDM radical cations can be generated in the gas phase under carefully controlled conditions as stable, noninterconverting species. These species are particularly interesting provided that [4 + 2] cycloadditions of the Diels−Alder type

Scheme 6



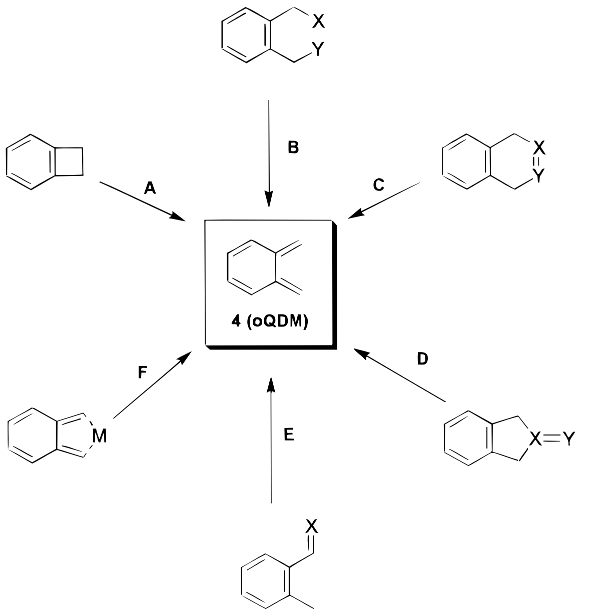
are accelerated dramatically by the oxidation of one of the reactants to the radical cation.[33] Thus, reactions of oQDM radical cations (**18**) with alkenes are particularly well suited for the study of $[3\pi + 2\pi]$ radical cation-mediated reactions considering that the ionization energy (IE) of oQDM (7.70 eV[34]) is sufficiently well below the IE of alkenes to prevent charge exchange from competing radical cation-mediated reactions. Grützmacher and Barkow have studied ion−molecule reactions of oQDM$^{+\bullet}$ ions (from EI-induced loss of water from 2-methylbenzyl alcohol, **17**) and different alkenes by using FT-ICR[35] (Fourier transform-ion cyclotron resonance) spectrometry (Scheme 6).[33] All fragmentation products from the reaction of oQDM radical cations are derived from the [4 + 2] cycloadduct, suggesting either a concerted process or a fast two-step process.

III. Generation of o-Quinodimethanes

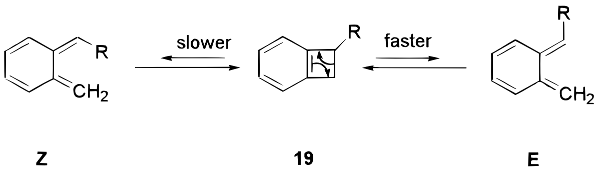
In connection with the utility of oQDMs as synthetic intermediates, the development of efficient methods for the generation of these reactive species under mild conditions and with control of the stereochemistry of the cycloaddition reactions to dienophiles has received considerable attention. Numerous methods for the generation of oQDM intermediate from the corresponding precursors using various types of promoters have been collected in different review articles.[2,36,37]

In our last account of 1991,[2] we classified and reviewed the most general generation methods of oQDM in five main groups according to the different precursors used: thermolysis of benzocyclobutenes (path A), 1,4-elimination of α,α′-substituted *o*-xylenes (path B), from benzo-fused heterocyclic compounds (reverse Diels−Alder reaction; path C and D), from *o*-methylbenzaldehydes or *o*-methylstyrenes (photoenolization and photorearrangement, respectively; path E), and from *o*-xylylene−metal complexes (path F) (Scheme 7).

Scheme 7



Scheme 8



An exhaustive overview of the generation methods for oQDM is out of the scope of the present review and would be somehow repetitive provided that the main reactions paths outlined above[2] have continued being the preferred synthetic routes in recent oQDM syntheses. We will focus now on the most important modifications carried out on previously described methods which have contributed to the development of the oQDM use in organic syntheses. Reactions will be classified into three main types according to the different conditions used for the generation of the oQDM: (i) thermal reactions; (ii) photochemical reactions; and (iii) electrochemical reactions.

A. Thermal Generation of Substituted Carbocyclic o-Quinodimethanes

1. Thermolysis of Benzocyclobutenes

Reversible conrotatory opening of the cyclobutene ring in benzocyclobutenes (**19**) has been a widely used procedure for the generation of oQDM derivatives.[2,36,37,38,39] Derivatives bearing a substituent on the cyclobutene ring undergo a thermally allowed conrotatory ring opening preferentially outward to give the sterically less hindered *E*-diene[36] (Scheme 8).

The ease of ring opening varies widely with the nature of the substituent on the cyclobutene ring;[40] therefore, recent developments on this reaction involve the preparation of differently substituted benzocyclobutenes. Sammes and co-workers demonstrated that the thermal conversion of α-methoxycyclobutenes to α-methoxy-*o*-xylylene occurs with exclusive formation of the *E*-isomer.[41] The methoxy group leads to a lowering of ca. 9 kcal/mol in the activation energy for the ring-opening reaction. This lowering of the energy barriers toward oQDM formation has been observed when other electron-donating substituents are present at sp^3 carbons of the benzocyclobutene ring. Thus, the ease of ring opening parallels the availability of the electron pair when the substituent on the cyclobutene ring is capable of donating an electron pair, and temperatures even below 0 °C have been reported for the ring opening of electron-donating-substituted benzocylobutenes.[42] For **19a** (R = NH_2) the ring opens at 25 °C, **19b** (R = OH) at 80 °C, **19c** (R = NHCOR′) at 110 °C, and **19d** (R = Alk) at 180 °C.[36] An extraordinary accelerating power on the conrotatory opening has been observed for the arylsulfoxy (R = Ar−SO−) and sulfonyl (R = Ar−SO_2−) groups which lower the reaction temperature for the ring opening to as low as −30 °C.[43]

Not only electron-donating-substituted benzocyclobutenes have been used to generate substituted oQDM. 1-Benzocyclobutenecarbonitrile (**19e**, R = CN)[44] and different ketone-substituted benzocyclobutenes[12] have been used as precursors of the corresponding α-cyano- or α-keto-substituted oQDMs which have been used as intermediates in different organic syntheses. In this case, as a consequence of the electron-accepting ability of these groups, the thermal conversion has to be carried out in a high boiling point solvent provided that temperatures above 160 °C are required to afford the reactive diene.

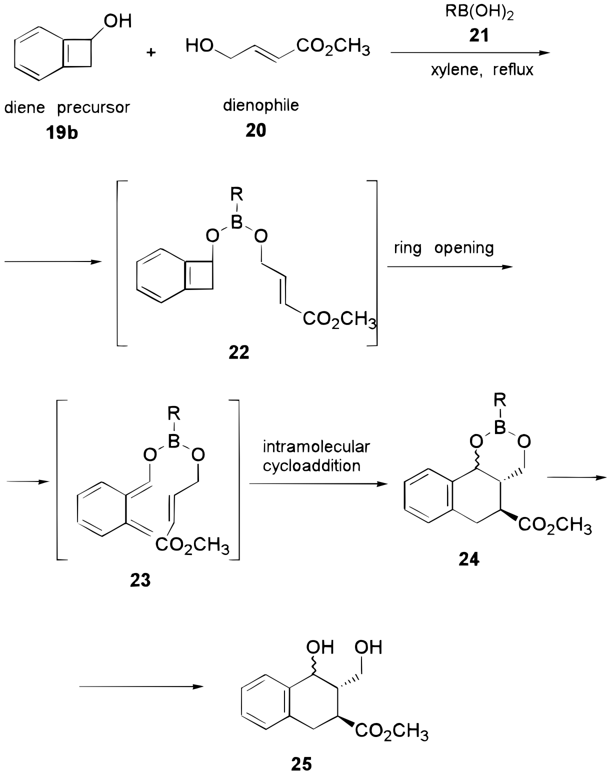
Different studies have been reported on the preference of the less hindered conrotatory ring opening of the benzocyclobutene system.[24,41,45] Steric effects are only partially responsible for the preferred outward rotation of substituents in the ring opening of benzocyclobutenes. To the best of our knowledge, in the most recent reports on this subject, Roth and coworkers[24] and Korth, Sustmann, and co-workers[25] have studied the con- and disrotatory opening of benzocyclobutenes taking into account the orbital symmetry of the transition state.

However, the most studied feature of benzocyclobutenes as precursors of oQDM has been their use as intermediates in organic synthesis.[39] Recently, boron compounds have proved to be efficient as trapping reagents of α-hydroxy oQDM when generated by thermolysis of 1,2-dihydrobenzocyclobuten-1-ol (**19b**) (Scheme 9). Thus, when a boron compound could both trap an α-hydroxy oQDM and a dienophile as a mixed boronate (**22**), oQDM (**23**) could be prevented from dimerization or isomerization and the Diels−Alder reaction proceeds regioselectively in an intramolecular manner.[46]

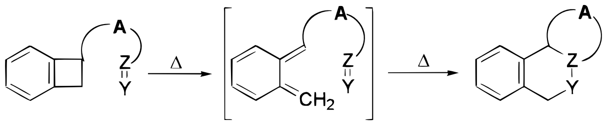
Special attention has been devoted to the generation of oQDM by thermolysis of substituted benzocyclobutenes which are involved in further intramolecular reactions[4,36,39] (Scheme 10).

We will return later to the generation of this type of oQDM derivatives when discussing the use of oQDM as a synthetic intermediate in the preparation of natural products as well as in its use as a building block for the preparation of polymeric materials.

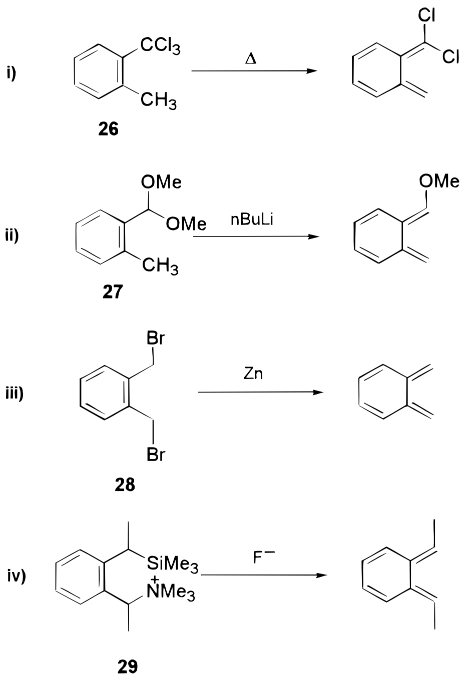
Scheme 9



Scheme 10



Scheme 11

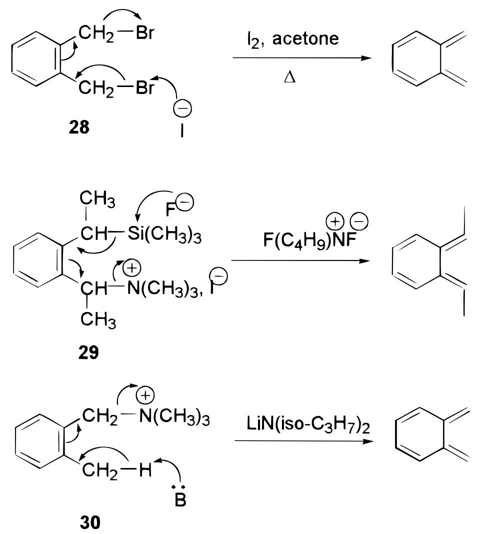


2. 1,4-Elimination of α,α′-Substituted o-Xylenes

One of the most important methods for the generation of oQDM is the 1,4-elimination from *o*-xylene derivatives because of the ready availability of the starting materials. The 1,4-elimination process to generate oQDM may involve (i) thermal eliminations, (ii) base-catalyzed eliminations, (iii) reductive eliminations, and (iv) ion-catalyzed eliminations (Scheme 11).[2,37]

Flash vacuum thermolysis of *o*-methylbenzyl chlorides **26** has proved to be a convenient method for

Scheme 12



the generation of oQDM through 1,4-dehydrohalogenation.[12] By using this method, good yields of benzocyclobutenes are obtained while dimerization of the intermediate oQDM is minimized.[47]

1,4-Methanol elimination from derivatives **27** induced by a strong base has also been used to generate oQDM.[48] The process has been used as an efficient route to polycycles by intramolecular trapping of the intermediate oQDM formed.[49]

Reductive 1,4-dehalogenation using zinc has been used to generate oQDM from *o*-xylylene dibromides **28**.[50] The use of ultrasound has been recommended to improve the efficiency of these reactions.[51]

Hofmann elimination from (*o*-methylbenzyl)trimethylammonium hydroxide (**30**), induced iodide debromination of *o*-xylylene dibromides (**28**),[1,52] and elimination from *o*-(trimethylsilyl)methylammonium salts (**29**), triggered by fluoride ion,[53] have been also used to generate oQDM (Scheme 12).

During the past years, much attention has been focused on the use of different leaving groups in these types of 1,4-elimination reactions of α,α′-substituted *o*-xylenes in the search for milder generation methods for oQDMs. Thus, the high leaving ability of the tributylstannyl cation[54] has allowed the formation in high yields of substituted oQDM by base-induced destannylation of [(tributylstannyl)methyl]benzylammonium salts (**31**),[55] by electrophile addition to *o*-vinyl benzyltributylstannane (**32**) in the presence of $ZnBr_2$,[56a,b] or by elimination of the tributylstannyl radical triggered by one-electron reduction of stannylaldehydes (**33**)[56c] (Scheme 13).

Alternatively, Lenihan and Shechter have developed a methodology to obtain substituted oQDM by 1,4-elimination of α,α-disubstituted silyl sulfones (**34**) with tetrabutylammonium fluoride (TBAF, Scheme 14).[57] It has proved to be a mild and efficient method for generating substituted oQDM. Of note is that α-alkyl-α-bromosulfones (**34:** R^1= Alkyl; R^2= Br) react with TBAF to give stable benzocyclobutenes (**36**) by ring closure of intermediate oQDMs (**35**) while producing vinyl sulfones (**38**) by 1,5-sigmatropic rearrangement of hydrogen in oQDM intermediate **37**.

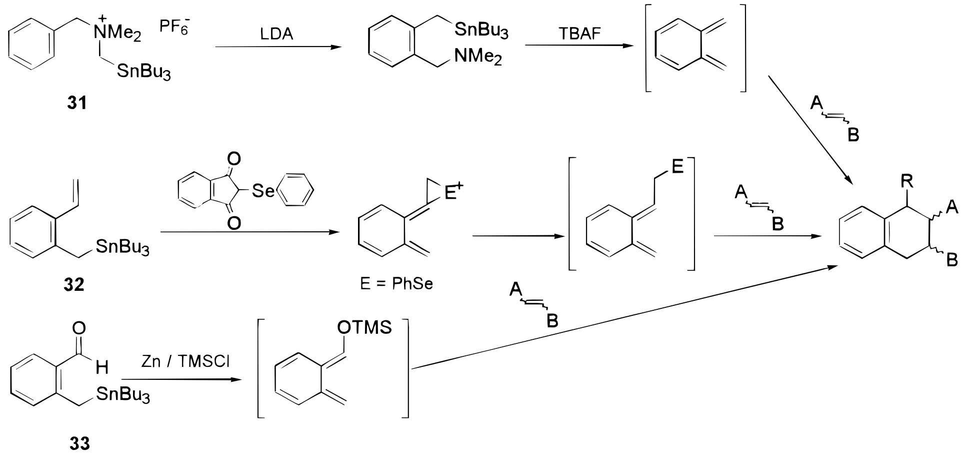
Finally, a synthesis of bis(alkylthio)-*o*-quinodimethanes (**41**) has been recently reported.[58] By *S*-methylation of *o*-alkyl-substituted dithiobenzoates (**39**) with trimethyloxonium tetrafluoroborate, the corresponding bis(alkylthio)arylmethylium tetrafluoroborate (**40**) is obtained and upon treatment with lithium hexamethyldisilazane (LiHMDS) is attacked almost exclusively at the *o*-methyl group to afford the bis(alkylthio)-*o*-quinodimethane (**41**) which dimerizes in a [4 + 4] cycloaddition to yield a dibenzo[*a*,*e*]cyclooctene (**42**) (Scheme 15).

3. From Benzo-Fused Heterocyclic Compounds

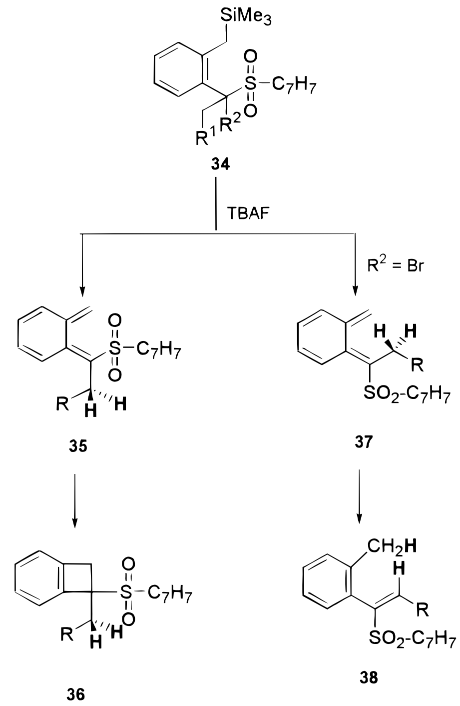
Different strategies toward the generation of oQDM from benzo-fused heterocyclic compounds have been employed including (i) reverse Diels−Alder reaction in which a small molecule like nitrogen[20,59] or carbon dioxide[60−62] is lost from compounds of type **43** and **44**, respectively, and (ii) by thermal cheletropic extrusion of sulfur dioxide from sulfinates (**45**) and sulfones (**46**) (Scheme 16).[2,20,37]

Loss of nitrogen from 1,4-dihydrophthalazine (**43**) through a Diels−Alder cycloreversion process has been used to generate oQDM either thermally[59] or photochemically.[19,20] Oxidative loss of nitrogen from *N*-aminoisoindolenines (**47**) can be performed by mercuric oxide or through reaction with *p*-toluensulfonyl chloride in pyridine to give diphenylcyclobutene

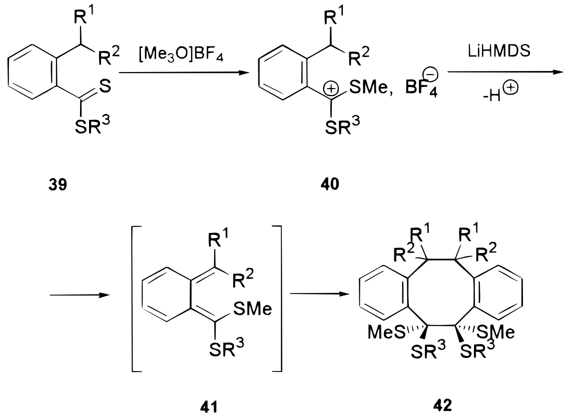
Scheme 13



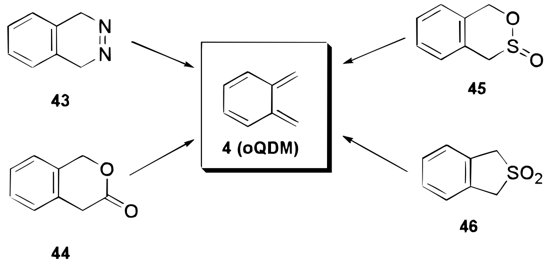
Scheme 14



Scheme 15



Scheme 16

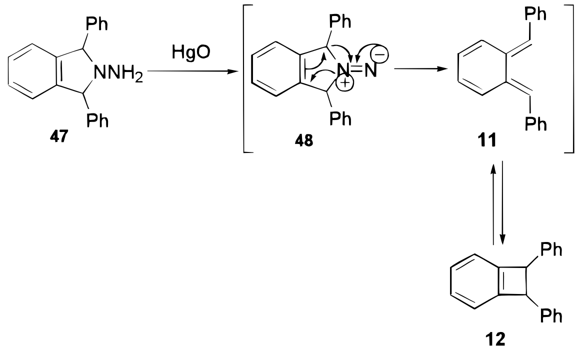


(**12**) by fragmentation of the intermediate amino–nitrene (**48**)[63] (Scheme 17).

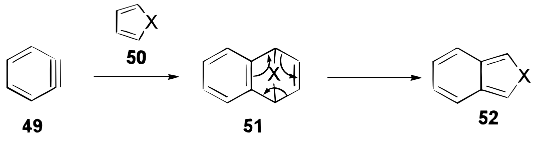
Another type of Diels–Alder cycloreversion process is the thermal decarboxylation of isochromanones **44** which takes place by flash vacuum thermolysis at temperatures close to 500 °C and which has been used as a convenient route to certain benzocyclobutenes.[64]

Fragmentation involving reverse Diels–Alder reactions has been extensively used to generate oQDMs of the type **52** from the adducts **51** which are readily available by addition of benzyne (**49**) to different dienes **50**[12,65] (Scheme 18).

Scheme 17



Scheme 18



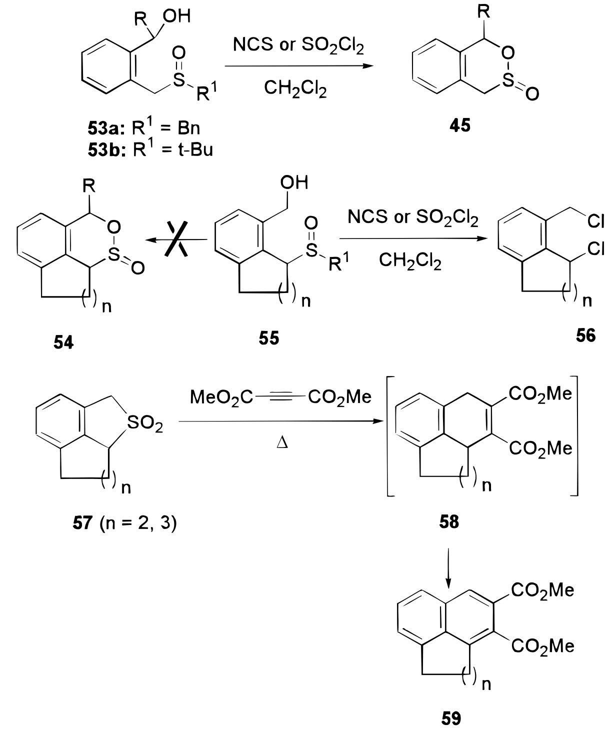
X= O, NR, C=CMe$_2$

Cheletropic elimination of sulfur dioxide from sulfones (**46**) was first reported by Cava in 1959,[66] the literature on this reaction being reviewed by Oppolzer.[60] Since then, other papers concerning this type of oQDM generation method have appeared.[37] However, most of the recent work involving the use of sulfones is devoted to the syntheses of oQDM heteroanalogues which will be later studied.

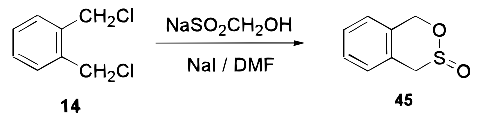
The route which has attracted more attention during the last years has been the oQDM generation via sultines, which were first synthesized by Durst and co-workers.[67] Generation of oQDM from sultine (**45**, 4,5-benzo-3,6-dihydro-1,2-oxathiin-2-oxide) has advantages over methods involving metals and dihalide, which cannot be used in the presence of reducible groups, or the fluoride ion catalyzed decomposition of {*o*-[(trimethylsilyl)methyl]benzyl}-trimethylammonium bromide, because enolization can take place in the quinone adducts.[68] On the other hand, while sulfone **46** is stable and requires temperatures around 300 °C to generate oQDM,[67] sultines are known to require lower thermolysis temperature for the cheletropic elimination of SO$_2$. Thus, oQDM can be obtained from sultines at temperatures as low as 80 °C.[69]

The disadvantage of this method was the multistep process involved in the synthesis of the starting sultine.[67,70] Connolly and Durst have recently reexamined[71] the original synthesis of sultines from δ-hydroxysulfoxides (**53**)[67] with the purpose of extending this synthetic route to obtain bicyclic sultines. As depicted in Scheme 19, *S*-benzyl- (**53a**) and *S*-*tert*-butyl- (**53b**) δ-hydroxysulfoxides, when treated with chlorinating agents, undergo an intramolecular cyclization–fragmentation sequence to afford sultines **45** in high yields (Scheme 19). However, reaction of the bicyclic system **55** with *N*-chlorosuccinimide (NCS) or SO$_2$Cl$_2$ did not provide the desired sultines (**54**); instead, the dichloroxylenes **56** were isolated. Therefore, they have concluded that this type of

Scheme 19



Scheme 20



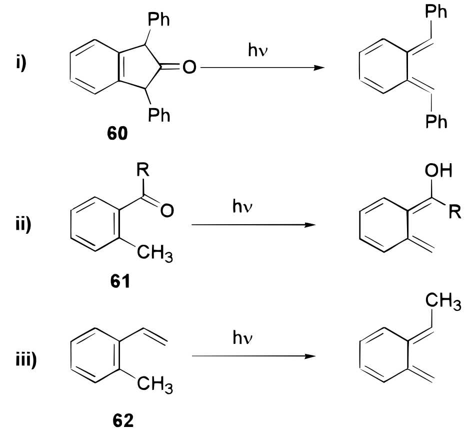
reaction is not as general as that previously described provided that a cyclic intermediate oxo−sulfonium salt is formed and may react via a number of pathways to afford γ-chlorosulfones and α,α′-dichloroxylenes.

Bicyclic oQDM could be finally prepared from the tricyclic sulfones **57**.[72] However, the mild reaction conditions used for the generation of oQDM from sultines could not be used, and reactions have to be carried out by heating the sulfones with an excess amount of dimethylacetylene dicarboxylate in the absence of solvent at 250−320 °C to afford the corresponding cycloadduct **59**.

There have been several recent advances in the use and synthesis of sultines[73] since they can be versatile synthetic intermediates[74] and, in addition to the ring-opening reactions, they undergo alkylation and oxidation reactions at the sulfur atom to give sulfones,[75] and reductive desulfurization. Dittmer has developed a straightforward and versatile high-yield method for the synthesis of sultines (**45**) by treatment of α,α′-dihaloxylenes (**14**) with rongalite (sodium hydroxymethanesulfinate) and sodium iodide in DMF (Scheme 20).[69,76] Formation of sultine could occur by simple displacement of one of the halogen atoms to produce the sulfinate, which reacts intramolecularly.

Microwave irradiation can be employed to accelerate organic reactions, increasing both product purity and yields.[77] We have recently applied this methodology for the generation of oQDMs from the corresponding sultines.[78,79] Thus, reaction of C_{60} with oQDM, formed from sultine under microwave irradiation for 20 min, affords the corresponding 1:1 cycloadduct in higher yield (39%) in comparison with conventional thermal conditions (30% after 18 h, refluxing). By using other substituted sultines,[78] higher yields in shorter times have been also observed for the cycloaddition reactions, therefore, the accelerating microwave effect in the generation of oQDM from sultines seems to be quite general (see below).

Scheme 21



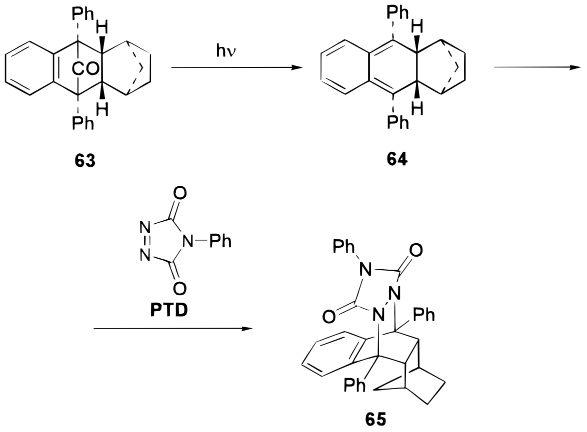
Finally, it is worth mentioning that during the last few years, the preparation and study of the reactivity of heterocycle-fused sultines have also been the subject of intensive research in order to obtain heteroanalogues of oQDM.[80] Therefore, we will come back to this route when studying the methods for the generation of heteroanalogues of oQDM.

B. Photochemical Generation of Substituted Carbocyclic *o*-Quinodimethanes

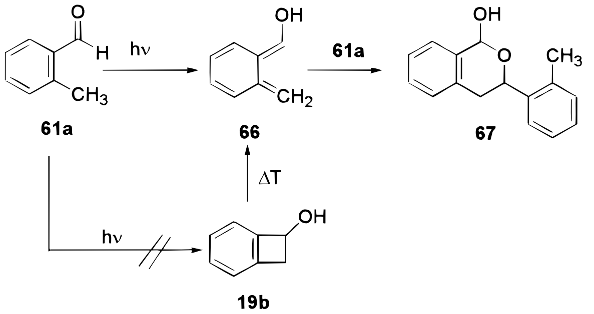
There are a number of synthetically useful transformations leading to the preparation of oQDMs that can only be carried out, or can be best carried out, under irradiation of light. Photochemical formation of reactive intermediates presents some advantages in comparison with thermal conditions, since they can often be generated under conditions (e.g., temperature) and concentrations (e.g., by flash photolysis) not possible from ground-state reactions.[20] Among them, the photochemical extrusion of carbon monoxide from substituted 2-indanones (**60**),[20,81] the photoenolization of *o*-alkylbenzaldehydes and *o*-alkylbenzophenones (**61**), and the photochemical 1,5-hydrogen shift of *o*-alkylstyrenes (**62**) (Scheme 21) have deserved special attention.

Quinkert and co-workers have employed the photodecarbonylation of 2-indanones (**60**) to prepare a number of aryl-substituted oQDMs and have shown that the loss of carbon monoxide occurs from the same singlet excited state, which is consistent with a stepwise, noncheletropic carbon monoxide elimination.[82] Following the report of Starr and Eastman[83] on the photodecarbonylation of 1,1,3,3-tetramethylindan-2-one, McCullough and co-workers prepared a series of methylated 2-indanones[20] by flash photolysis to study their photodecarbonylation as a route to oQDM intermediates.

Scheme 22



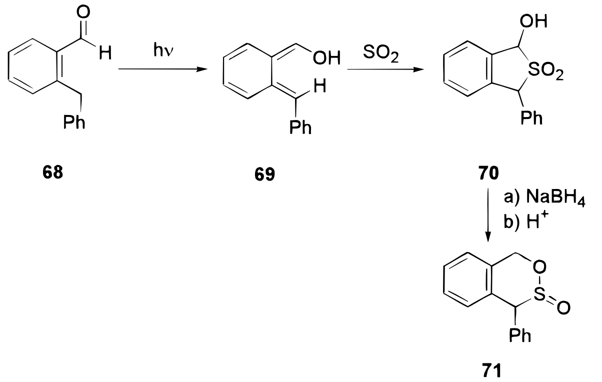
Scheme 23



This route has also been used to prepare isolable oQDMs by inclusion of the normally reactive diene system of oQDM in a six-membered ring which prevents conrotatory ring closure to the benzocyclobutene, although it retains high *o*-quinodimethane reactivity. Thus, by photolysis of **63**, a deep orange solution of the oQDM **64** is formed (Scheme 22) which crystallized from the reaction mixture and could be further recrystallized under N_2 atmosphere. Reaction of **64** with phenyltriazolinedione (PTD) and other dienophiles all occur at the less hindered face of the diene system, terminating at the α,α′-positions of the oQDM.[84]

An effective route to α-hydroxy-oQDMs is the well established[37,85,86] photoenolization of *o*-alkylbenzaldehydes and related carbonyl compounds (**61**) by a photochemical 1,5-hydrogen shift. The mechanism of this photoenolization is now very well understood, and many of the generated intermediates have been observed and characterized via time-resolved spectroscopy.[87] The process involves excitation to an $n\pi^*$ triplet state followed by intramolecular hydrogen abstraction to give a triplet 1,4-diradical. Thus, 2-methylbenzaldehyde (**61a**, R = H) serves as a source for the parent (*Z*)- and (*E*)-ω-hydroxy-oQDM (**66**) generated photochemically via two triplet states ($\tau_T = 1.1$ and 95 ns[88]) and subsequently a common triplet 1,4-diradical ($\tau_B = 310$ ns[89]). (*E*)-**66** could be trapped with a variety of dienophiles such as dimethyl butynedioate, maleic anhydride, tetracyanoethylene, and even with triplet oxygen. In the absence of trapping reagents, the photolysis of **61a** leads to a dimerization product (hemiacetal, **67**) besides a photoreduction product (1,2-ditolylglycol) (Scheme 23).[90] The dimerization product **67** was not observed when (*E*)-ω-hydroxy-oQDM (**66**) was generated by thermolysis of the benzocyclobutanol **19b**. The explanation given in the literature is the assumption of a two-photon process for the photochemical reaction, i.e., the reaction of triplet excited 2-methylbenzaldehyde (**61a***) with the photochemically generated oQDM **66**.[91] Griesbeck and Stadtmüller have recently reported the first example of a photochemically generated hydroxy-oQDM trapped by a ketone[90] and propose that a rather low bimolecular reaction rate constant for dimerization and not the previously proposed photochemical formation must be responsible for the exclusive formation of **67** during thermolysis of cyclobutanol **19b**.

Scheme 24



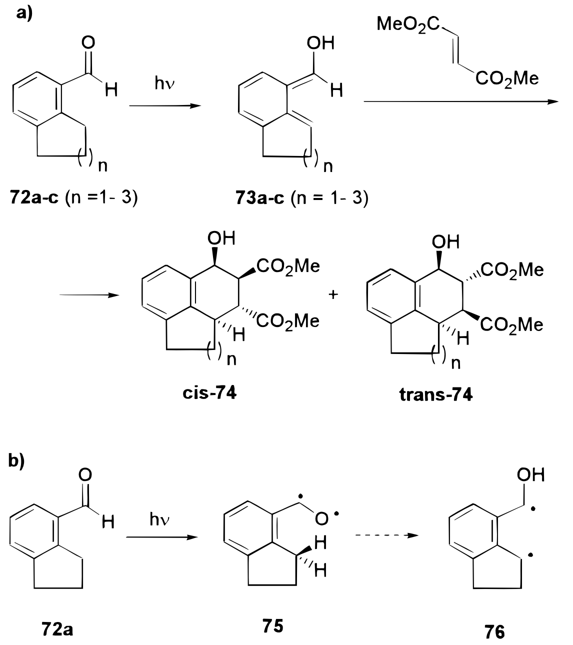
An application of the photoenolization of *o*-benzylbenzaldehyde (**68**) involved trapping the photoenol formed upon irradiation (**69**) with sulfur dioxide to give the sulfone (**70**). Reduction of **70** with $NaBH_4$ and acid treatment led to the sultine **71**, which was useful for the generation of 1-phenyl-oQDM (Scheme 24).[92,12]

As mentioned above, Durst and Connolly had previously reported on bicyclic oQDMs. As an efficient alternative to the thermal route previously described (Scheme 19),[72] they prepared a series of carbonyl compounds (**72**) that afforded an *E*-photoenol (**73**) when irradiated (Scheme 25a).[93] The reaction conditions are now milder, being conducted at room temperature rather than in the 250−300 °C range found necessary for expulsion of SO_2 from tricyclic sulfones.

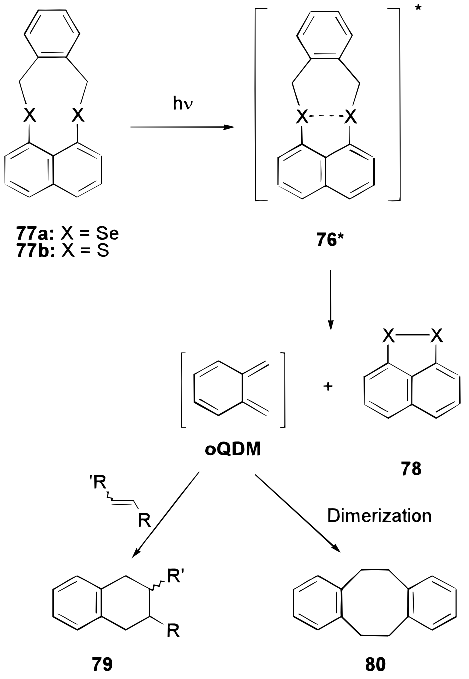
Interestingly, contrary to the observed high reactivity of **72b** and **72c**, aldehyde **72a** reacts only with very reactive dienophiles and even then only sparingly. One possible explanation for this behavior is the geometry limitation imposed by the five-membered ring. If the triplet **75** (Scheme 25b) cannot attain the correct geometry to abstract a γ-hydrogen, then conversion to biradical **76**, which is the triplet state of the photoenol, will not occur.

The all-carbon analogue of the photoenolization reaction has also been studied. The reaction involves the photolysis of *o*-alkylstyrenes (**62**) to produce oQDMs via a [1,5]sigmatropic shift (Scheme 21).[20,94] This route has not been exploited much and presumably occurs because the 1,5-hydrogen shift can be antarafacial and photochemically allowed in the open-chain system. Thus, the closed system analogue, isoindene, could not be generated in a similar fashion.[20,95]

Scheme 25

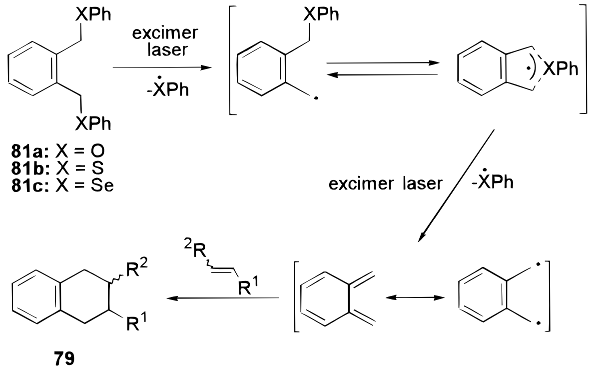


Scheme 26



Other less general photochemical generation methods of oQDM have also been used. Furukawa reported not long ago on the generation of oQDM by photolysis of 8,13-dihydrobenzo[*g*]naphtho[1,8-bc]-[1,5]diselenonin (**77a**) and 8,13-dihydro-benzo[*g*]-naphtho[1,8-bc][1,5]dithionin (**77b**) (Scheme 26). The decomposition of **77a**,**b** takes place quantitatively when exposed to sunlight in the presence of air to give an oQDM dimer (**80**) and naphtho[1,8-*c*,*d*]-1,2-diselenole (**78**).[96] In the presence of a dienophile, upon UV irradiation, the corresponding tetrahydronaphthalene (**79**) derivatives can be isolated in high yields, together with 100% recovery of **78**.[97]

Scheme 27



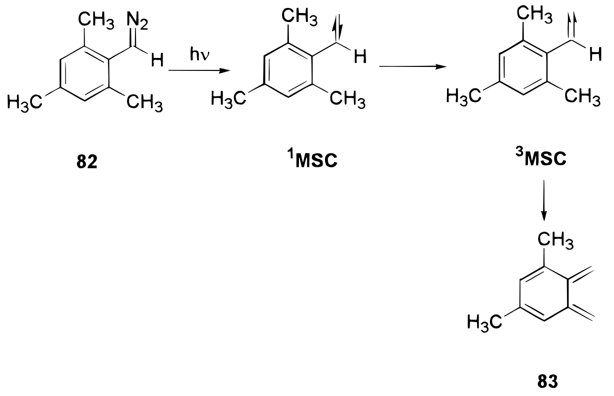
Recent developments on the application of lasers to organic photochemistry have revealed the occurrence of many reactions which only proceed by the use of lasers.[98] The use of lasers can provide more precise control over the reaction of intermediates and/or excited states which are involved in the photochemical process.[99] Thus, Ouchi and co-workers recently reported on an efficient double-homolytic C−X (X = O, S, Se) bond cleavage of 1,8-bis(substituted-methyl)naphthalenes by the use of excimer lasers, which proceeds through a two-photon process.[100] This efficient reaction has been applied to the generation of oQDM by the laser photolysis of 1,2-bis(phenoxymethyl)benzene (**81a**), 1,2-bis[(phenylthio)methyl]benzene (**81b**), and 1,2-bis[(phenylseleno)-methyl]benzene (**81c**) (Scheme 27).[97] oQDM precursors **81** can be easily prepared by a one-step procedure from commercially available 1,2-bis(bromomethyl)-benzene (**28**) and, within a pulse of an excimer laser, generate oQDM, which can be trapped with various dienophiles. The phenylseleno group was found to be the best among the three heteroatoms tested, and the maximum yield of the cycloadduct (48%) was obtained by the use of a KrF laser.

Laser flash photolysis (LFP) has been extensively used for the study of aryl and diaryl carbenes.[101] These studies have been recently extended among others to mesitylcarbene, observing the formation of dimethyl-substituted oQDM.[102] Thus, short photolysis (six photolysis cycles, 10 s) of mesityldiazomethane (**82**) in rare gas matrixes (argon or nitrogen) at 11 K with the full arc of a 200 W high-pressure mercury lamp releases mesitylcarbene (**MSC**). Utilization of the full arc of the photolyzing light leads to the formation of a dimethyl-substituted-*o*-quinodimethane which may be the result of secondary photolysis of carbene (Scheme 28). Triplet mesitylcarbene (^{3}**MSC**) is thermally unstable even at 11 K and isomerizes to the dimethyl-substituted-oQDM (**83**). The thermal conversion can be easily monitored by UV−Vis spectroscopy.

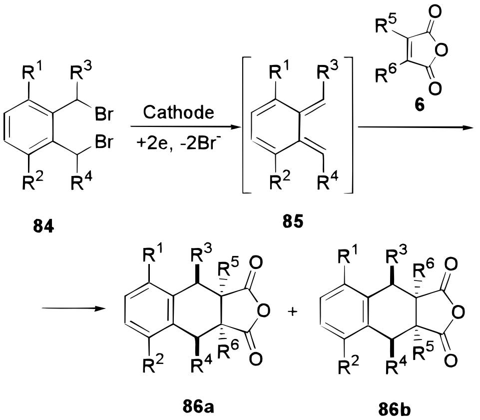
C. Electrochemical Generation of Substituted Carbocyclic *o*-Quinodimethanes

The cathodic generation of oQDMs from 1,2-bis-(halomethyl)arenes was first reported by Covitz,[103] and electrochemistry has recently proved to be a very convenient method for the generation of a variety of oQDMs. Since the electrochemical method avoids the production of potentially harmful inorganic residues, it has gained attention during the last years, and

Scheme 28



Scheme 29



very recently the redox chemistry of quinodimethanes has been reviewed.[10] In 1993, Utley and co-workers described the preparation of Diels–Alder adducts (**86a,b**) of oQDMs **85** by the cathodic reduction of dibromides **84** in the presence of substituted maleic anhydrides[104] (Scheme 29).

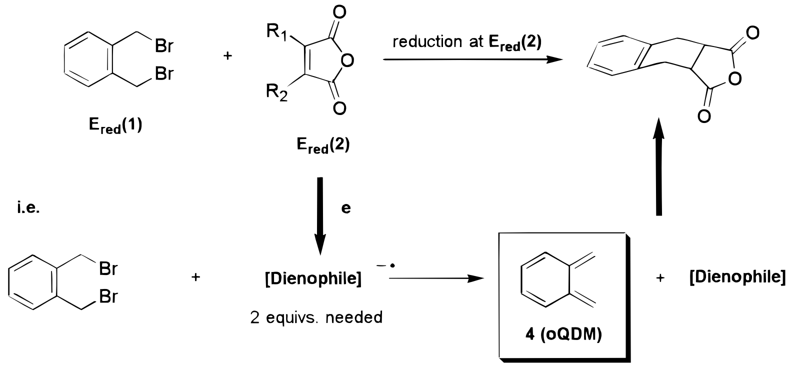
The mechanism and scope of this reaction has been further studied by Utley's group.[10,105] They have observed that the reduction potential of the maleic anhydride (**6**) is higher (less cathodic) by several hundreds of millivolts than that required for direct reduction of 1,2-bis(bromomethyl)benzene **84**. They have also observed by cyclic voltammetry that the dienophile was reversibly reduced at relatively low scan rates, and the addition of the less easily reduced α,α′-dibromo-*o*-xylene caused reduction to become irreversible with a considerable rise in the cathodic peak current. Utley points out that this behavior is characteristic of redox catalysis and can be considered as evidence of the dual role of the dienophile as a mediator in the formation of the oQDM and as a reactant with it.[10] An alternative mechanism proposed for this type of reaction involves cycloadditions between the dienophile radical anions (SOMO) and the neutral *o*-quinodimethane (LUMO) in the propagating step. However, the most commonly accepted mechanism is the first one. In Scheme 30 is depicted the redox-catalyzed electrogeneration of oQDM combined with cycloaddition.

Other dienophiles, including quinones and other maleic anhydride derivatives, have been used in the preparative-scale reductions and associated Diels–Alder reactions with α,α′-dibromo-*o*-xylene, obtaining, in most cases, the respective cycloadducts in high yields (48–98%).[105] The products and their stereochemistry are as expected, and when comparison is possible, they are identical with those obtained by zinc-induced formation of the oQDM.[10]

D. Generation of *o*-Quinodimethane Heteroanalogues

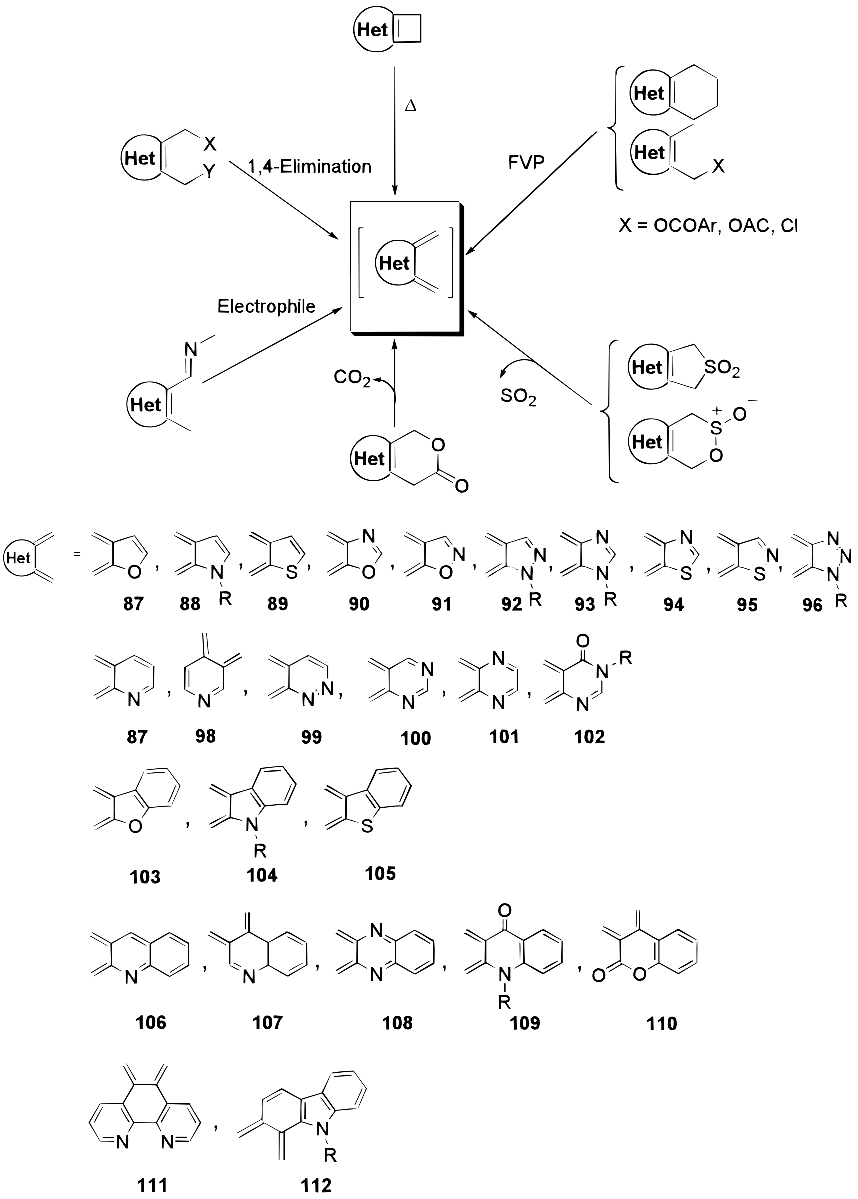
From a synthetic point of view, heterocyclic oQDMs are very interesting because of the wide range of heterocyclic systems which can be incorporated. Inter- or intramolecular cycloaddition reactions involving heterocyclic oQDMs provide an attractive route to heteropolycyclic compounds,[60] and an increasing number of examples of such processes are to be found in recent review articles where the literature of the generation of heterocyclic oQDMs until 1993 is thoroughly reviewed.[3] Thus, during the past decade a great deal of effort has been devoted to the syntheses of heteroanalogues of oQDM and furan (**87**),[106–109] pyrrole (**88**),[110] thiophene (**89**),[111,112] oxazole (**90**),[113] isoxazole (**91**),[114,115] pyrazole (**92**),[116,117] imidazole (**93**),[116c] thiazole (**94**),[118,119] isothiazole (**95**),[120] triazole (**96**),[121] pyridine (**97** and **98**),[122,123] pyridazine (**99**),[124] pyrimidine (**100**),[125,126] pyrazine (**101**),[127] pyrimidinone (**102**),[128] benzofurano (**103**),[129,130] indolo (**104**),[131] benzothieno (**105**),[132] quinoline (**106** and **107**),[133] quinoxaline (**108**),[134,135] quinolinone (**109**),[136] coumarin (**110**),[137] phenanthroline (**111**),[138] and carbazole (**112**)[139] based oQDMs (Scheme 31).[140,141]

Scheme 30



N.B. $E_{red}(2)$ is less cathodic than $E_{red}(1)$

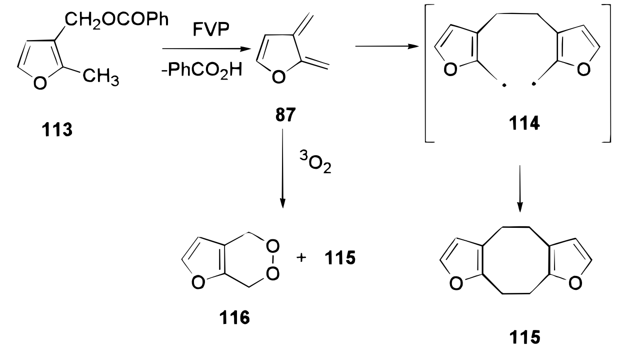
Scheme 31



As noted above, Chou reviewed the generation methods of heteroanalogues of oQDM until 1993, and therefore, we will mainly focus on the most recent developments in the field.

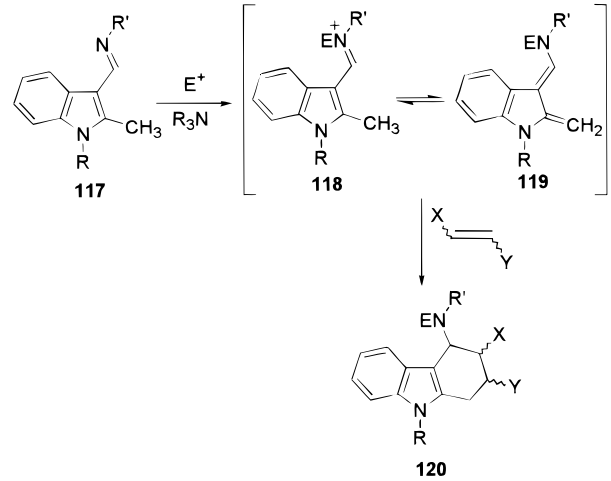
Flash vacuum pyrolysis (FVP) of cyclohexene-fused heterocycles,[142] suitable esters, or chloromethyl derivatives[107] usually needs very harsh conditions (temperatures may vary from 600 to 900 °C).[3] Trahanovsky and co-workers have studied extensively during the past decade the dimerization mechanism of furan-based oQDMs generated by FVP of (2-methyl-3-furyl)methyl benzoate (**113**), which occurs readily in solution at temperatures above −30 °C and proceeds by a stepwise mechanism via the diradical intermediate (**114**) to yield mainly the head to head [4 + 4] dimer **115** (Scheme 32).[107a] On the basis of a secondary deuterium kinetic isotope effect study, it was concluded that the cyclization involves rate-determining formation of the diradical **114**, followed by rapid closure of the diradical to give the dimer.[22a] The same authors have also reported that furan-based oQDMs when in contact with triplet oxygen give rise to the corresponding cyclic peroxide **116** in addition to the [4 + 4] dimer **115**.[107b]

Scheme 32

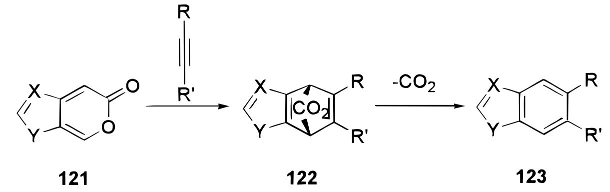


Tautomerism of imino derivatives bearing a methyl group in an *ortho* position (**117**) offers another method for the generation of five-membered heterocyclic oQDMs (Scheme 33).[143] Trapping such intermediates (**119**) with dienophiles by an intramolecular

Scheme 33



Scheme 34



[4 + 2] cycloaddition has constituted an efficient strategy toward the total synthesis of indole alkaloids (**120**).[3]

One stable version of heteroaromatic *o*-quinodimethanes are the pyranones **121**, which undergo smooth Diels–Alder reactions with, for example, alkynes or alkyne equivalents to yield adducts **122**; subsequent loss of carbon dioxide from **122** results in the generation of a benzene ring (**123**) (Scheme 34).[144]

1,4-Exocyclic eliminations are also largely employed to generate oQDMs since they are carried out under very mild conditions. Indeed, oQDM heteroanalogues have been synthesized (i) by fluoride-induced expulsion of the silicon and leaving groups (L = OAc or NR_3^+) from substrates **124**,[130,145] based on the original Ito–Saegusa idea for the generation of *o*-quinodimethanes from the corresponding benzenoid derivatives, (ii) by treatment of a tributylstannylfuryl derivatives (**125**) with boron trifluoride–diethyl ether,[109] or (iii) by the well-known reductive debromination of vicinal halomethyl derivatives **126** (Figure 3).[109b,115,117,119,131a,132a,146]

A general strategy toward the generation of these reactive intermediates involves cheletropic extrusion of sulfur dioxide from heteroaromatic-fused-3-sulfolenes.[147] As Chou points out,[129a] there are several advantages to this approach: (a) removal of SO_2 from 3-sulfolenes requires moderate temperatures, normally between 100 and 180 °C, and neutral conditions so that the oQDM heteroanalogues generated in situ can be trapped in good yield, (b) derivatives of 3-sulfolenes are easily prepared and handled, and (c) heteroaromatic-fused-3-sulfolenes of similar structure can be synthesized from a common intermediate. To date, furan,[106] pyrrole,[110] thiophene,[111] oxazole,[113] isoxazole,[114] pyrazole,[116] thiazole,[148] isothiazole,[120] pyridine,[122] pyrimidine,[125] pyrazine,[127] pyrimidone,[128] benzofurano,[129] indolo,[131] benzothieno,[132] quinoline,[133] quinoxaline,[134] and quinolinone[136] 3-sulfolenes have been synthesized.

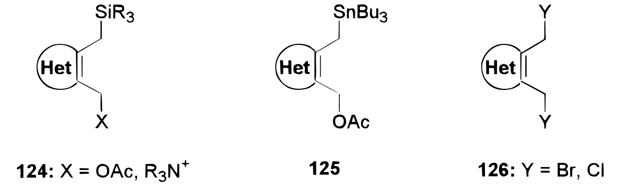
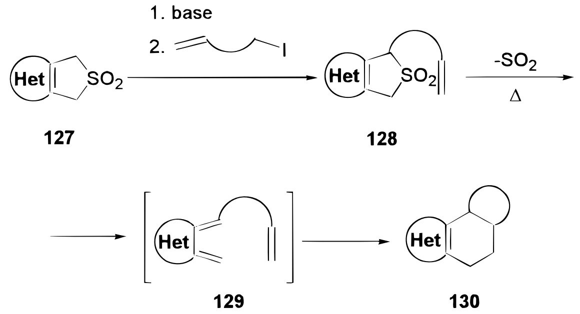


Figure 3. Precursors of oQDM heteroanalogues by 1,4-exocyclic elimination.

Scheme 35

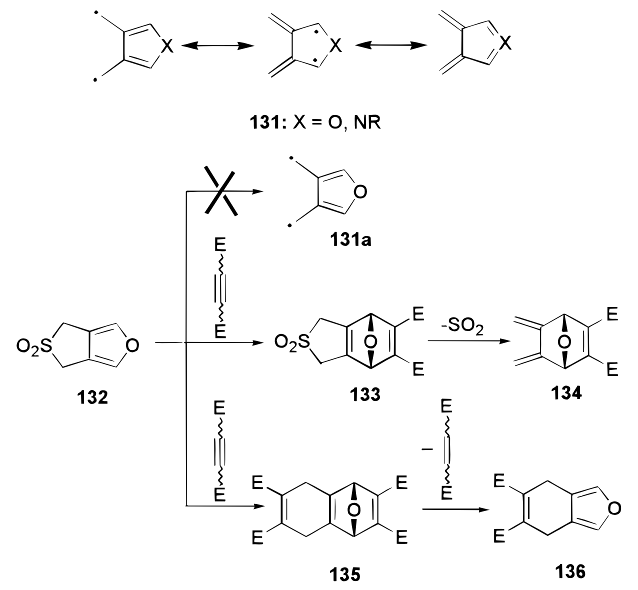


The ease of introducing substituents at the α-position of the sulfolene group,[147] leading to various functionalities, has been applied in the syntheses of compounds **128** of which the thermal extrusion of sulfur dioxide and subsequent intramolecular Diels–Alder reaction of intermediate **129** produce a multicyclic heteroaromatic system **130**[136] (Scheme 35).

It is worth mentioning the special reactivity presented by heteroaromatic-fused 3-sulfolenes at 3,4-positions. 3,4-Dimethylene heteroaromatics (**131**) are π-conjugated non-Kekulé molecules for which full valence structures can be written only by expansion of heteroatom octet and, therefore, are classified as *nonclassical o*-quinodimethanes.[3] They have been generated from the corresponding diazenes[149] or postulated as transient intermediates in base-catalyzed rearrangement of the bis-allenyl compounds.[150] Although the furan- and pyrrole-fused sulfolenes at 3,4-positions have been synthesized and seem to be ideal precursors of 3,4-dimethylenefuran and pyrrole, it has not been possible to generate them under the usual conditions.[147c] However, these compounds have been shown to be useful building blocks. Since both furan and 3-sulfolene moieties can be used as the diene component in Diels–Alder reactions, **132** could sequentially react with two types of dienophiles [first on the furan moiety (**133**) and then on the diene moiety (**135**), resulting from cheletropic desulfonylation] and offer a rapid elaboration of multicyclic systems (**136**) (Scheme 36).[151]

Other precursors of heterocyclic oQDMs are the sultine derivatives. One of the advantages of using sultines over sulfones is the lower thermolysis temperature required for the cheletropic elimination of SO_2. However, despite the extensive use of sultines as precursors of carbocyclic oQDM derivatives, the use of sultines in heteroaromatic analogues is still rare. Chung and co-workers have reported on the syntheses of furan-, thiophene- and pyrrole sultines

Scheme 36



as precursors for nonclassical heteroaromatic oQDMs, and their application in the Diels–Alder reactions. In the absence of a dienophile, sultines **137** undergo thermolysis to give the sulfolene **140** in good yields. Heating the sultines in the presence of dienophiles at 180 °C gave both the isomerized sulfolenes **140** and fused adducts **138**. No adducts were formed when the thiophene-fused sulfolene **140** was heated in the presence of a dienophile at the same reaction temperature. Possible reaction pathways proposed by Chung are depicted in Scheme 37.

Sultines can be generated in good yields following the general method of Dittmer[69,76] by treatment of the corresponding heterocyclic bis(chloromethyl)-derivative with rongalite (sodium hydroxymethanesulfinate) and tetrabutylammonium bromide (TBAB) in dimethylformamide. A recent example of this synthesis has been the preparation of quinoxaline-fused sultines (**145**) by Chung and Liu (Scheme 38).[134] They have been used as precursors for quinoxalino-*o*-quinodimethanes (**108**) in Diels–Alder reactions. In the absence of a dienophile, quinoxaline-fused sultine undergoes thermal extrusion of SO_2 to form the corresponding cyclobuta[1,2-*b*]quinoxaline (**146**) almost quantitatively. Diels–Alder adducts were also formed in excellent yield when the cyclobutene **146** was heated in the presence of dienophiles at 200 °C, indicating that this cyclobutene is also a good precursor of oQDM **108**.

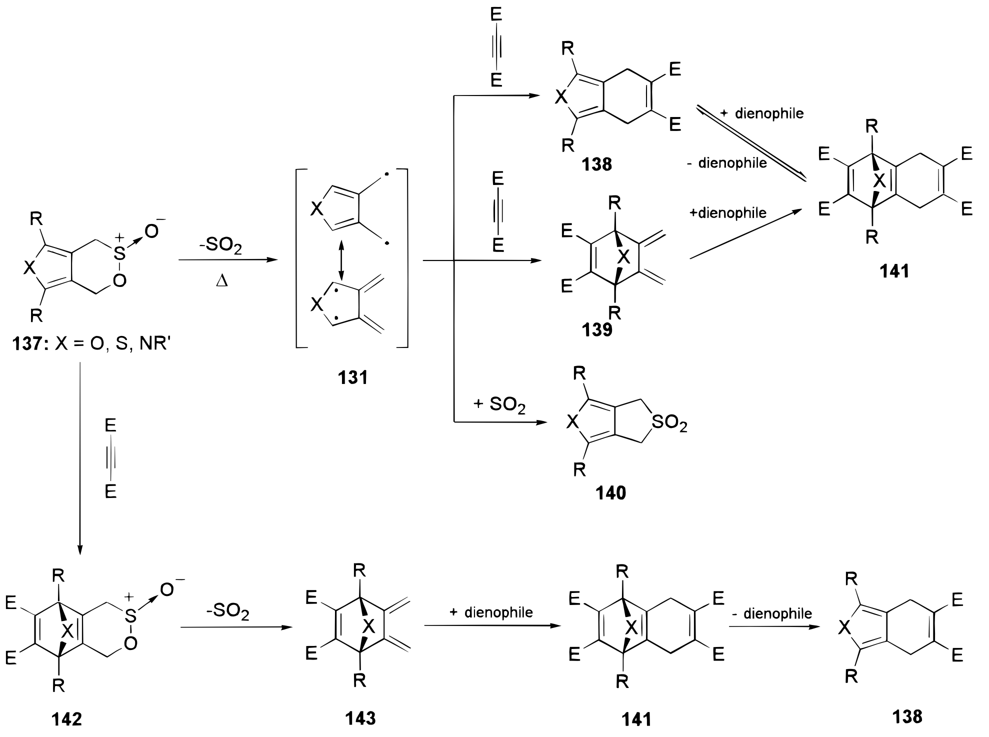
The use of cyclobutene-fused heterocycles as precursors of oQDM heteroanalogues has remained practically unexplored. Thus, we have recently reported, to the best of our knowledge, the first synthesis of oQDM heteroanalogues from the corresponding cyclobutene-fused heterocycles.[126a,b] Cyclobutapyrimidines (**149**)[126c] have proved to be excellent precursors for the in situ generation of the reactive substituted pyrimidine oQDM analogue (**150**), which can be trapped as 1:1 adducts (**151**) when heated in *o*-dichlorobenzene (ODCB) at 180 °C in the presence of different dienophiles. 2,4-Disubstituted alkyl or aryl cyclobutene-fused pyrimidines (**149**) can be directly obtained in one step by reaction of cyclobutanone (**147**) with nitriles (**148**) (Scheme 39).

IV. *o*-Quinodimethanes as Synthetic Intermediates

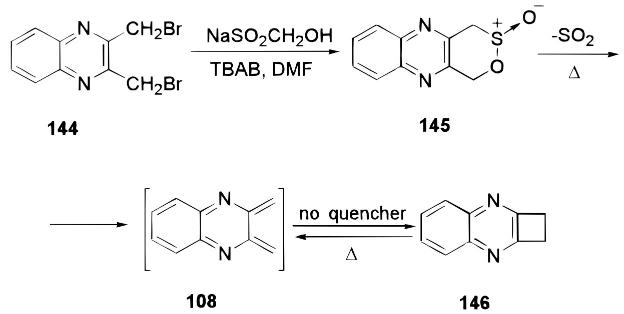
A. *o*-Quinodimethanes Reactivity

oQDMs are highly reactive intermediates which in many cases cannot be isolated as a consequence of various decay modes (Scheme 40) including electro-

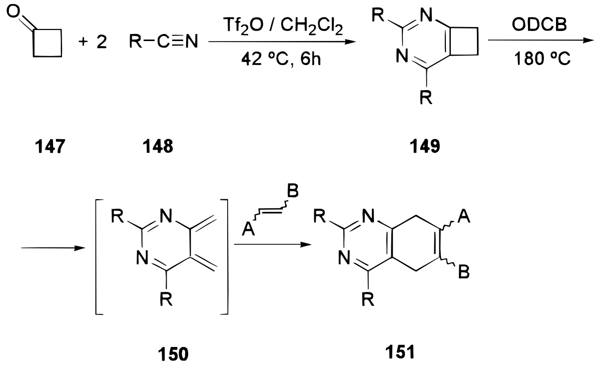
Scheme 37



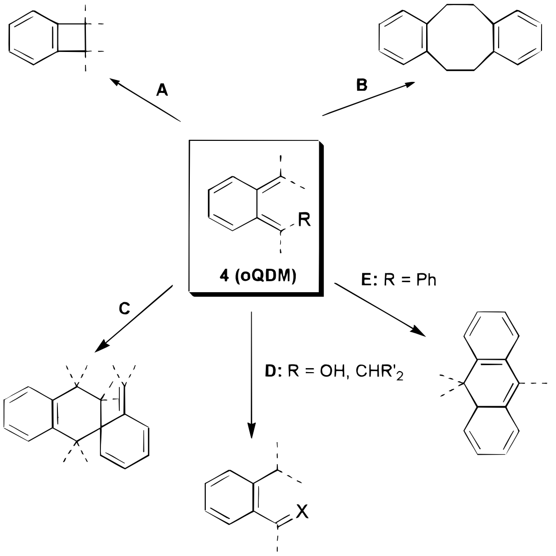
Scheme 38



Scheme 39



Scheme 40



cyclic ring closure to substituted benzocyclobutenes (path A), [4 + 4] cycloaddition to give dibenzocyclooctadienes (path B), formation of spiro compounds via [4 + 2] cycloadditions (Diels−Alder reaction; path C), 1,5-hydrogen shift if suitable hydrogen-donating substituents (alkyl, hydroxyl) are present (path D), and electrocyclic ring closure to 4a,10-dihydroanthracene derivatives in the case of R = phenyl (path E).[12]

Taking advantage of the ability of oQDMs to undergo Diels−Alder cycloadditions, they have been used (a) to test fundamental aspects of the Diels−Alder reaction and mainly (b) as efficient intermediates in organic synthesis. On the other hand, as a consequence of their high reactivity, oQDMs have also found practical use as “traps” to intercept species such as nitric oxide.

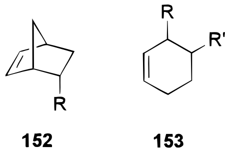
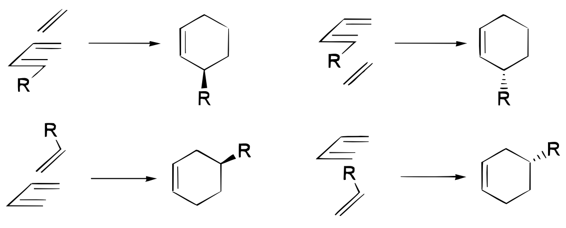


Figure 4. Preferred stereoselectivity (endo) and regioselectivity (1,2-disubstituted) in Diels−Alder reactions.

Scheme 41



B. *o*-Quinodimethane as a Diene in Diels−Alder Reactions

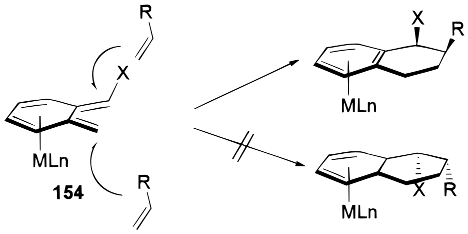
Diels−Alder reaction occupies a position of particular prominence in the arsenal of the synthetic organic chemist provided that it offers the possibility to generate six-membered rings with high regio- and stereoselectivity, leading to the creation of four continuous stereogenic centers in one synthetic operation.[152] Although its mechanism remained obscure for a long time,[153] now the regio- and stereochemistry of these reactions are well understood[154] and several generalizations can be made.[37] Although Diels−Alder reactions are considered to be concerted (pericyclic) with bonds being broken and formed simultaneously, depending on the electronic properties of the diene and dienophile, stepwise mechanisms are also known.[154e] The reaction is stereospecifically syn (suprafacial) for both the diene and dienophile, *endo* products (**152**) are stereoselectively preferred over *exo* isomers and 1,2-disubstituted products (**153**) are regioselectively preferred over 1,3-disubstituted isomers (Figure 4).[37]

oQDMs are constituted by two diene units, one endocyclic and the other exocyclic, and theoretically both units can take part in a Diels−Alder reaction. However, the exocyclic diene unit is known to react preferably over the other, and it has also been verified from the frontier orbitals of oQDM that the exocyclic diene unit forms the HOMO.[154c]

In 1987, Charlton and Alauddin reviewed[37] the regio- and stereochemical course of the Diels−Alder addition of differently substituted oQDMs, hinting at the asymmetric induction in Diels−Alder reactions of oQDMs which can occur if the reaction can be induced to take place preferentially on one face of the diene or dienophile[155] (Scheme 41).

Among the many ways to obtain good facial selectivity, linking the diene[156] or the dienophile[157] to a chiral auxiliary, chelating the dienophile with a chiral Lewis acid[158] or incorporating an allylic stereogenic center[152] have been the subject of different studies. Numerous reports have also appeared concerning the role of heteroatom substitution at the allylic position and the use of protecting groups of allylic alcohols as a means of controlling π-facial selectively.[152] Efficient asymmetric control (>90% de)

Scheme 42



in Diels–Alder reaction of oQDMs has been demonstrated in intra- and intermolecular reactions between achiral oQDMs and chiral dienophiles.[155] Only moderate asymmetric inductions (30–60% de) were found, however, in the few examples where the chiral auxiliary was fixed on the oQDM rather than on the dienophile.[159] By using the ability of oQDMs to form transition metal π-complexes,[160] Kündig and Leresche have recently generated (*o*-quinodimethane)Cr(CO)$_3$ complexes (**154**) and studied their reactions with dienophiles and the stereochemical control of the chiral centers in the cycloadducts.[160] They observe that the Cr(CO)$_3$ complexes of in situ generated oQDMs undergo cycloaddition reactions exclusively to the face opposite the metal center (Scheme 42). High inductions (ca. 90% ee) can be achieved by this method. However, to expand the scope of this strategy for synthetic applications, a more efficient access to enantiopure (*o*-quinodimethane)Cr(CO)$_3$ would be required.

During the last two decades, it has become increasingly clear that the intramolecular [$4\pi + 2\pi$] reaction, where the diene and the dienophile are constrained in the same molecule, can be used effectively to synthesize a variety of interesting polycyclic species. In properly designed systems, added advantages result in terms of ease of reaction and regio- and stereoselectivity.[161]

Indicative of the worldwide activity is the number of reviews on this field which have appeared in the past:[161,162] Special attention has been devoted to the in situ generation of oQDMs which can be trapped intramolecularly by a dienophile to give fused ring systems which have been successfully applied, among others, to the total synthesis of natural products. In the next sections we will focus on the applications of *o*-quinodimethanes as intermediates in the synthesis of natural products as well as in materials science, among others.

V. Synthesis of Natural Products from o-Quinodimethanes

The utilization of oQDM intermediates and their respective derivative enophiles for the regio- and stereocontrolled annulation of aromatic systems is of practical importance and has been successfully applied in efficient synthesis of alkaloids, steroids, terpenes, anthracyclines, and lignanes among other natural products. In fact, the literature is so extensive that an exhaustive survey would be impractical. The reader is referred to several review articles for complete coverage of the field.[36,60,143d,161,162d,163,164]

In the following, we will discuss some selected and representative examples of the literature to illustrate the usefulness of oQDMs in the preparation of biologically active compounds.

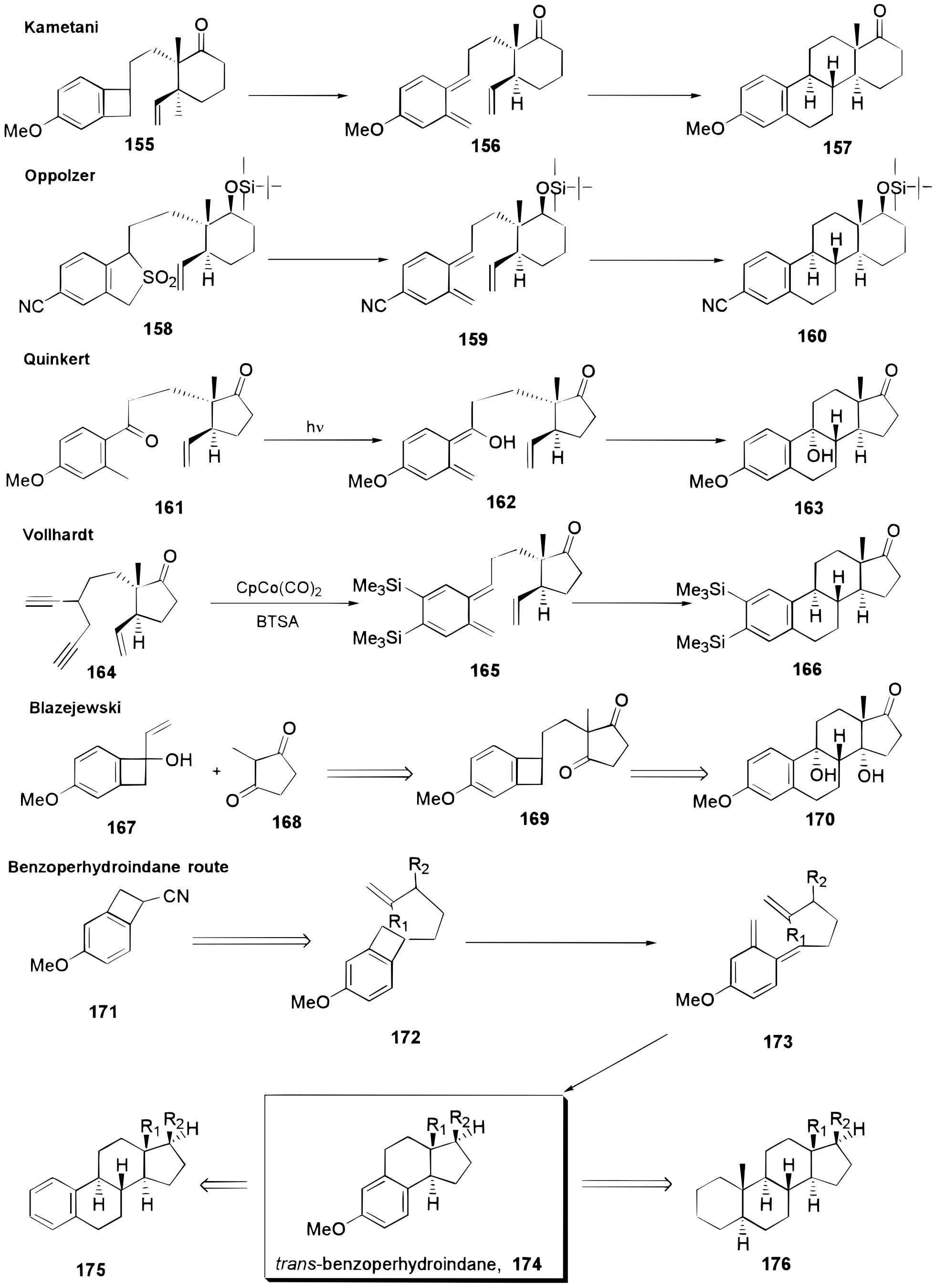
The syntheses of steroids via oQDM[165] has been recently reviewed by Nemoto and Fukumoto.[4] Several groups independently and almost simultaneously realized that intramolecular oQDM cycloadditions could provide a convenient approach to the aromatic steroid skeleton. Some examples are depicted in Scheme 43. The total synthesis of D-homoestrone methyl ether (**157**) through cycloaddition of in situ generated oQDMs by thermolysis of benzocyclobutene (**155**) was carried out by Kametani and co-workers in 1977.[166]

Oppolzer and co-workers carried out the synthesis of (+)-stradiol from the polycyclic compound (**160**) which could be obtained by thermolysis of the monosubstituted sulfone (**158**).[167] Quinkert and co-workers developed photochemical reactions toward the synthesis of natural products.[164c] One example is the photoenolization of *o*-toluketone **161** to yield the 9α-hydroxyestrone methyl ether **163** via oQDM **162**.[168] One synthetic drawback of the above procedure lies in the relative difficulty of synthesizing appropriately substituted benzocyclobutenes. Vollhardt and co-workers developed a synthetic strategy toward the preparation of substituted benzocyclobutenes from hexa-1,5-diynes (as well as other α,ω-diynes) by co-cyclization with substituted acetylenes in the presence of a cobalt(I) catalyst (η^5-cyclopentadienyldicarbonylcobalt).[163] In Scheme 43 is shown how the cobalt-mediated co-cyclization of the diyne **164** with bis(trimethylsilyl)acetylene (BTSA) generates the oQDM derivative **165** to give the corresponding polycyclic product **166**, which was finally converted to (±)-estrone.[169] Recently, the synthesis by Kametani, Nemoto, and co-workers of 14α-hydroxyestrone methyl ether (**170**)[170] was improved by Blazejewski and co-workers by using the Torgov reaction of the benzocyclobutanol **167** and the cyclopentadione **168** followed by catalytic hydrogenation to afford the intermediate **169**[171] used in the original synthetic route.

Since all these routes are only useful for preparing aromatic steroids, during the last 10 years more flexible and efficient routes to both aromatic and nonaromatic steroids have been developed. Kametani and co-workers have used benzoperhydroindanes (**174**, Scheme 43) as key intermediates for the preparation of either A-trienic or nonaromatic steroids (**175** or **176** respectively). **174** can be prepared out of benzocyclobutene **171** by chemical transformation to **172** and further ring opening to afford **173**, which finally undergoes an intramolecular cycloaddition. The versatility of this route has been proved through the total syntheses of various types of biologically important steroids such as 19-norspironolactone, 19-nordeoxycorticosterone, aldosterone analogues, 11-oxoprogesterone, adrenosterone, cortisone, and vitamin D$_3$ and related compounds.[4]

However, the synthetic utility of oQDMs is not restricted to steroids, and they have also been used in the syntheses of other interesting natural products. As an example, in Scheme 44 is depicted the thermal reaction of benzocyclobutene **177** as the key

Scheme 43



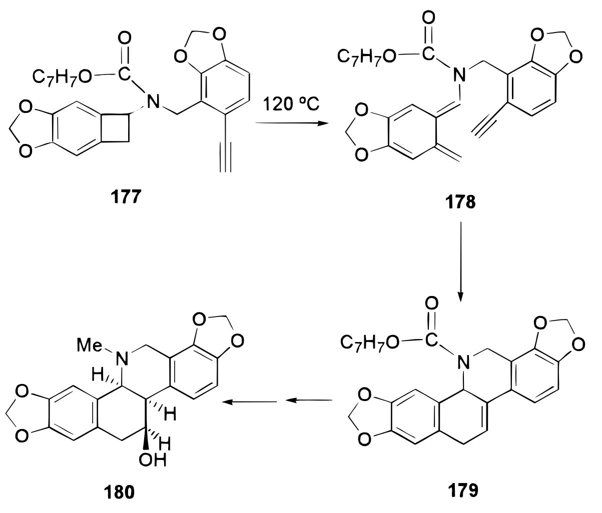
step in the total synthesis of the alkaloid chelidonine (**180**).[172]

Magnus and co-workers developed a route to indole alkaloids **183** from an indole-2,3-quinodimethane intermediate **182** through imine tautomerization and subsequent intramolecular trapping[143d] (Scheme 45).

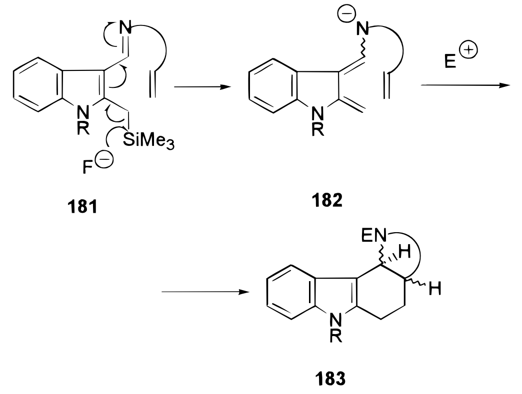
Intermolecular Diels–Alder reactions have also proved to be synthetically valuable for the preparation of natural products. Thus, intermolecular cycloaddition between oQDMs and dienophiles has allowed the synthesis of naturally occurring lignans with biological activities including some optically active podophyllotoxin analogues[173] with antitumor properties. This application of oQDM chemistry is studied in detail in the review article of Charlton and Alauddin,[37] and therefore, we will only present some representative examples. Reaction of sulfones **184** with different dienophiles afforded the corresponding cycloadducts **185**–**188** with a high degree of stereoselectivity and regioselectivity (Scheme 46). Further transformation of these cycloadducts offers a flexible approach to the preparation of 1-aryl lignans. For example, the diester **186** may be reduced to give isodeoxypicrophyllotoxin while reduction of diester **187** to the corresponding diol and subsequent treatment with methyl iodide and sodium hydride in dimethyl sulfoxide afforded (±)phenyltetralin.[174]

Saá and co-workers reported the use of *cis*-2-arylbenzocyclobutenol methyl ethers (**191**) for the synthesis of lignans (Scheme 47). Irradiation of some highly congested, phenolic 2-(methoxymethyl)benzophenones (**189**) provides a rapid, efficient, and

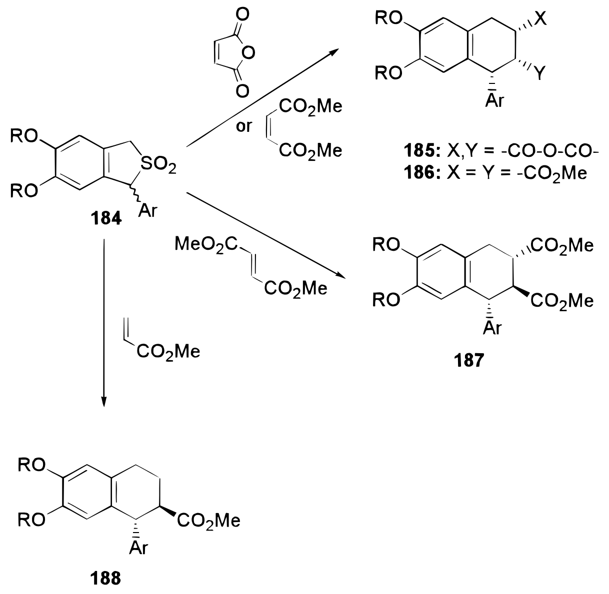
Scheme 44



Scheme 45



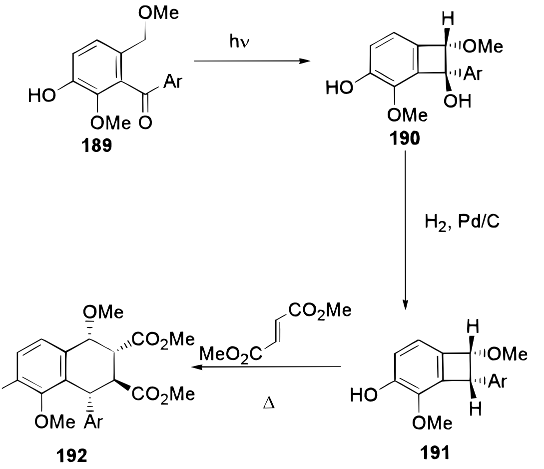
Scheme 46



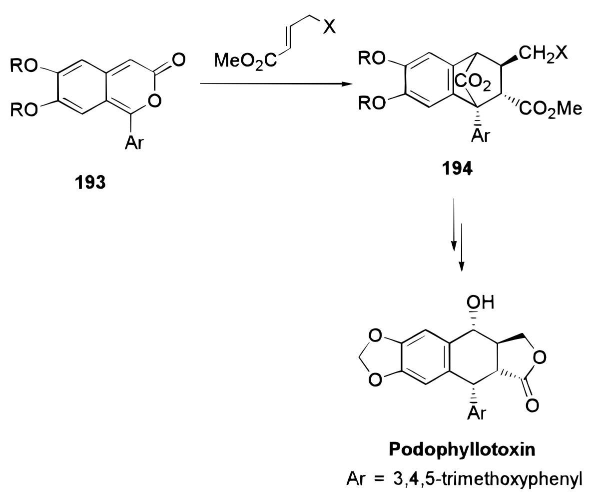
stereoselective entry to the corresponding 1-aryl-1-hydroxy-2-methoxybenzocyclobutenes (**190**) which may be used for the synthesis of lignanes via the intermolecular Diels–Alder approach.[175]

Jones and co-workers carried out model experiments toward the synthesis of podophyllotoxin by using Diels–Alder additions of the oQDM derivative 1-phenyl-2-benzopyran-3-one (**193**) with different dienophiles to yield the cycloadducts **194**[176] (Scheme 48).

Scheme 47



Scheme 48



VI. *o*-Quinodimethanes in Materials Chemistry

During the past decades the chemistry of new molecular and polymeric organic materials exhibiting different optoelectronic and magnetic properties has experienced huge development. oQDMs have somehow contributed to this development provided that they were extensively used as the intermediate in the syntheses of π-extended systems including new donor and acceptor molecules as precursors of electrically conducting or semiconducting charge-transfer complexes, they were employed as the monomeric unit in the preparation of different polymeric materials with different solid-state properties, and they were used as dienes in combination with the exceptional molecule of [60]fullerene leading to a great amount of thermally stable cycloadducts which preserve the properties of the parent C_{60}.

A. *o*-Quinodimethanes as Precursors of π-Extended Systems

1. Synthesis of Polyacene Derivatives

The synthesis of ladder conjugated polymers as a mean of reaching low band gap polymers was con-

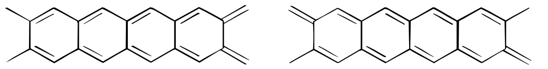


Figure 5. Polyacene systems as examples of low-dimensional ladder conjugated polymers.

sidered in early works.[177,178] Such polymers, which can be considered as one-dimensional graphite ribbons, represent a possible strategy for increasing the dimensionality of low-dimensional π-conjugated polymers.[179] Polyacene (Figure 5) is probably the most famous member of this class of materials.

It can be viewed as a combination of two parallel chains of trans $(CH)_x$ fastened together, and due to its unique structure, this polymer has been the focus of much theoretical interest.[179]

Miller and co-workers have developed a method for the synthesis of linear, multiring, polyquinoidal polyacenes which are of theoretical and practical interest because of their electronic properties.[180,181] Considered in the context of polyacene hydrocarbons, like hexacene, quinoidal derivatives have interesting properties for substantially varying the electronic structure of a large molecular framework, and by appropriately choosing quinone, semiquinone, and hydroquinone type moieties the reactivity and the optical, magnetic, and electrical properties may be controlled. The synthetic route used for the synthesis of the polyacenequinoid derivatives involves the use of appropriate bisdienes and quinones. Among them, bis-*o*-quinodimethanes proved to be useful bisdienes for the generation of these polyacenequinoid systems. When tetrakis(bromomethyl)benzene derivatives **195** are allowed to react in DMF with iodide and 2,3-dimethylbenzoquinone (**196**), the corresponding bis-oQDM is formed and the Diels–Alder reaction, including dehydrogenation, takes place successfully giving the polyacene quinoid **197** (Scheme 49a).

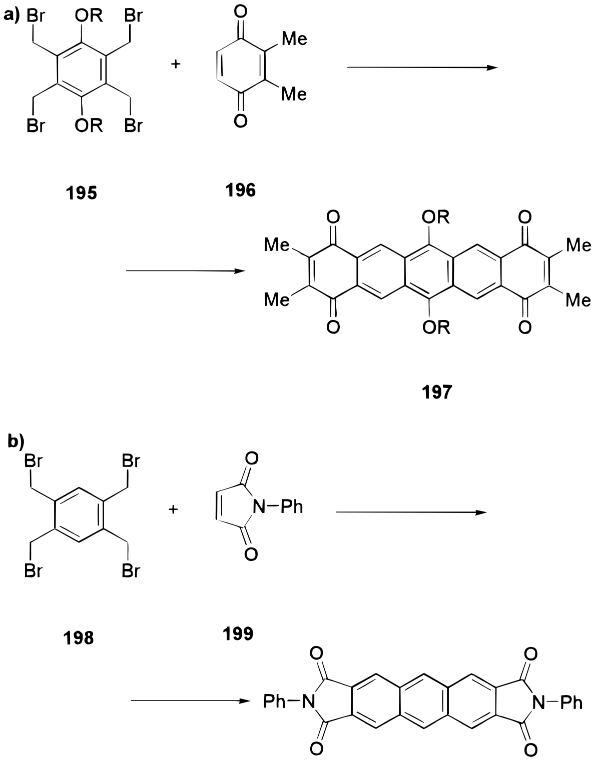
Further reduction conversion of quinone units to solubilizing ionic or bulky groups increases the solubility of the final materials, thus allowing their structural identification and different spectroscopic studies.[182,183]

McLaughlin recently reported the application of this approach to the synthesis of other linear aromatic systems. As a representative example, in Scheme 49b is depicted how tetrakis(dibromomethyl)-benzene can be used as a precursor of the corresponding bis-*o*-quinodimethane, which undergoes cycloaddition with 2 equiv of maleimide (**199**) to generate the corresponding anthracene derivative (**200**) in good yield.[184]

2. π-Extended Electron-Donor and Electron-Acceptor Systems

The synthesis of the highly conducting charge-transfer (CT) complex formed by tetracyano-*p*-quinodimethane (TCNQ) and tetrathiafulvalene (TTF), as electron-acceptor and electron-donor components, respectively (Figure 6), opened up the field of molecular organic conductors.[185] Since then, a large number of different CT complexes have been prepared in the search for electric properties. The synthesis of the so-called 'organic metals' or 'synthetic metals' has mainly focused on modification of the donor fragment,

Scheme 49



and much less synthetic effort has been devoted to the preparation of novel acceptors.[186−188]

One of the most interesting aspects in the synthesis of tetracyano-*p*-quinodimethanes other than TCNQ is to increase the π-extension of the electron acceptor in order to lower the intramolecular Coulombic repulsion in the anion of the acceptors, resulting in more stable radical anions and hence in highly conducting CT complexes.[187] Thus, we have recently used oQDM in the syntheses of new benzo-fused tetracyano-*p*-quinodimethane (TCNQ)[189−191] and dicyano-*p*-quinonediimine (DCNQI)[191−193] derivatives as new π-extended electron-acceptor systems.

The synthesis of novel π-extended TCNQ (**204**, **209**) and DCNQI (**205**, **210**) derivatives was carried out from the corresponding 1,4-anthraquinone (**203**) and 6,13-pentacenedione (**208**) by reaction with malononitrile and bis(trimethylsilyl)carbodiimide (BTC), respectively, in the presence of titanium tetrachloride (Scheme 50). 1,4-Anthraquinone derivatives (**203**) could be obtained by reaction of substituted *p*-benzoquinones (**201**) with oQDMs generated favorably from either sultine (**45**) or α,α,α′,α′-tetrabromo-*o*-xylene (**1**). The intermediate Diels–Alder adduct

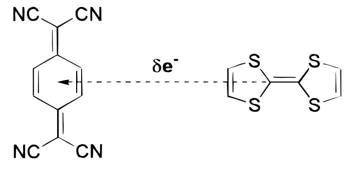
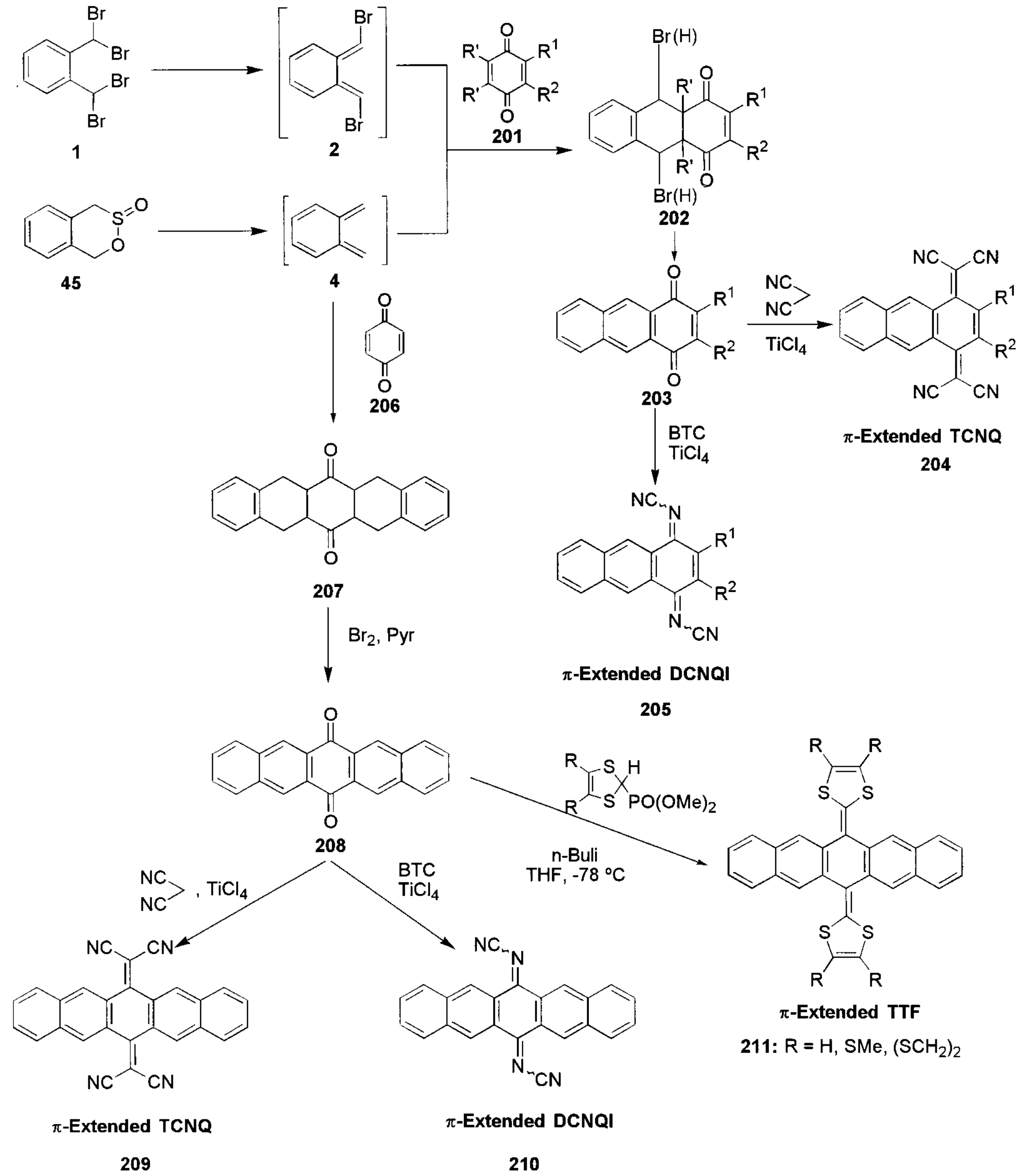


Figure 6. CT-Complex TTF-TCNQ with $\sigma_{RT} = 500\ S\ cm^{-1}$ opened up the field of "synthetic metals".

Scheme 50



(**202**) easily undergoes oxidation to the fully aromatized quinones (**203**) (Scheme 50).

More π-extended TCNQ and DCNQI derivatives were also obtained starting with reaction of oQDM with unsubstituted *p*-benzoquinone (**206**). The 5,5a,6a,7,12,12a,13a,14-octahydro-6,13-pentacenedione (**207**) obtained after the bis-cycloaddition can be easily oxidized by bromine/pyridine in DMF to form 6,13-pentacenedione (**208**). In the presence of titanium tetrachloride, reaction of this quinone with malononitrile or BTC yields the corresponding π-extended TCNQ (**209**) and DCNQI (**210**), respectively. Cyclic voltammetry measurements reveal that the increase in benzannulation results in a shift of the reduction potentials toward more negative values (weaker electron acceptors), following the same trend as both TCNQ and DCNQI derivatives.

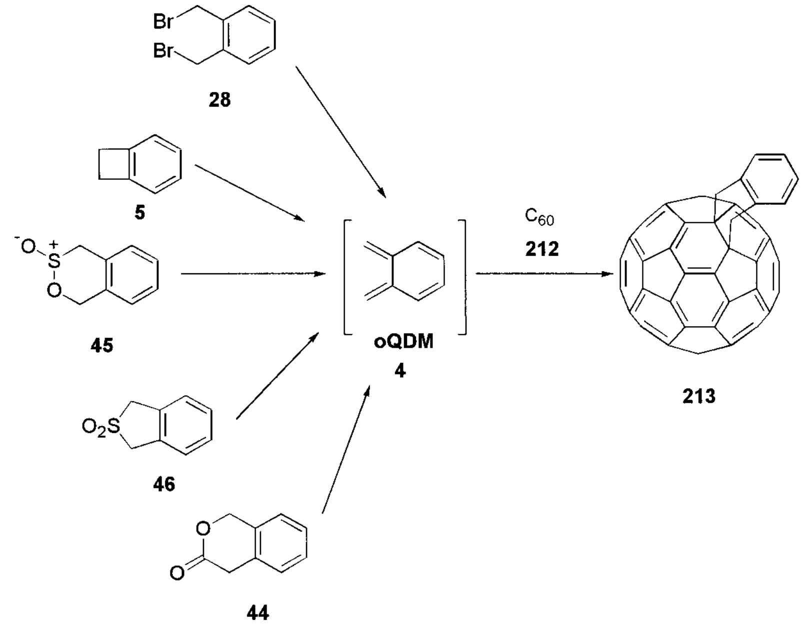
These π-extended TCNQ derivatives have recently been used as acceptors in composite films together with conjugated semiconducting polymers which act as donors.[194] The composite films of these D/A couples give rise to long-lived charge-separated states upon photoexcitation and, therefore, have been tested as suitable materials for the preparation of photovoltaic cells.

Not only acceptor molecules have been synthesized from the previously described π-extended quinones obtained from oQDMs. We have also recently reported the synthesis of largely π-extended *p*-quinodimethane analogues of TTF (**211**) (Scheme 50). The synthesis of these compounds is carried out by Wittig–Horner reaction of a phosphonate with the corresponding quinonic system.[195]

B. Cycloadditions of *o*-Quinodimethane to Fullerenes: A Versatile Approach to Stable Modified Fullerenes

In the more recent years, one of the most outstanding applications of oQDMs has been the formation of novel cycloadducts with fullerene C_{60} (**212**). Since the preparation of Krätschmer et al. of macroscopic

Scheme 51



quantities of fullerenes,[196] the chemistry of these new carbon allotropes has been efficiently and rapidly developed. The wide variety of novel organofullerenes reported has led to an understanding of the basic chemical reactivity of fullerene C_{60}, which is already well-established.[197]

Compared to C_{60}, the lower symmetry of the known higher fullerenes results in the formation of a large number of possible structural isomers which are difficult to separate. As a consequence, in addition to their low abundance in the original soot, the chemistry of higher fullerenes has been mainly focused on C_{70} and much less on the larger spheres.[198]

Among the different methods reported in the literature for the functionalization of [60]fullerene, cycloadditions and, particularly, Diels–Alder reactions play a very important role.[199] C_{60} has a low-lying LUMO which is a clear advantage for Diels–Alder and other cycloaddition reactions. It behaves as a dienophile, reacting in [4 + 2] cycloadditions by a 6–6 double bond, thus avoiding the unfavorable 5–6 double bonds within the fullerene framework.

The Diels–Alder reaction of C_{60} with oQDMs has been carried out from different precursors for the in situ generation of the reactive intermediates as shown in Scheme 51. The experimental conditions for the generation of the reactive diene are highly dependent on the starting material used as the precursor.

It is important to note that some of the cycloadducts prepared by reaction of C_{60} with dienes undergo facile cycloreversion to the starting materials as a consequence of their thermal instability. Thus, as a typical example, cycloadducts resulting from cyclopentadiene are unstable and can be stabilized by selective hydrogenation of the resulting double bond or by transforming it into a different functional group by a further chemical reaction.[200]

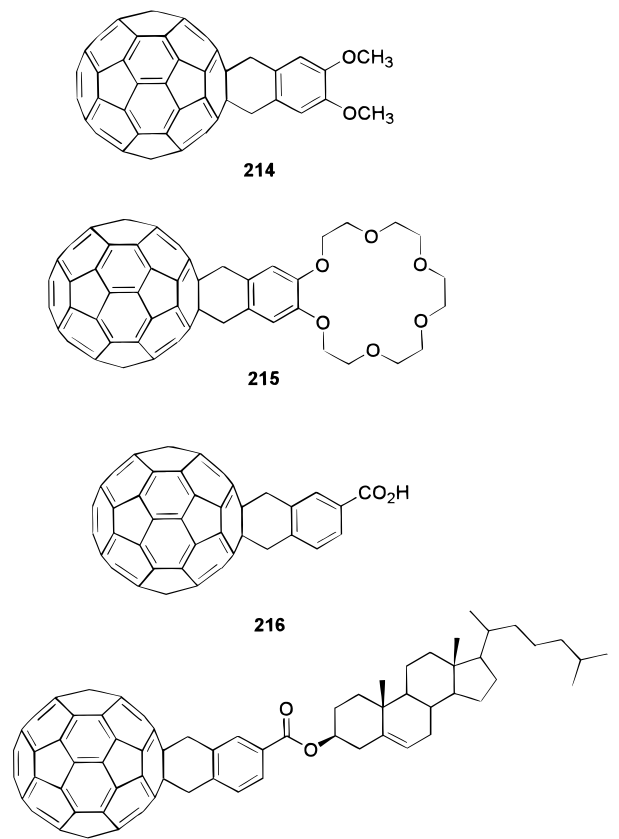
In contrast, adducts obtained from oQDMs as dienes are thermally stable due to the additional stabilization provided by the aromatic system formed. In addition, oQDMs can be used as a vehicle for the introduction of a wide variety of reactive functional groups useful for further chemical modification.

In general, [4 + 2] cycloadditions of C_{60} proceed reasonably well with formation of the [60]fullerene-based monocycloadducts in moderate yields. Addition of a second oQDM leads to the formation of regioisomeric mixtures which are difficult to separate. Thus, cycloadditions to [60]fullerene have been mainly directed (see below) to the preparation of the respective monoadducts which can be easily characterized.

The [4 + 2] cycloaddition of unsubstituted oQDM (**4**) to C_{60} was first reported by Müllen in 1993.[201] In this case, the reactive diene was generated by iodine-induced 1,4-elimination of 1,2-bis(bromomethyl)benzene (**28**) in boiling toluene and using 18-crown-6 as the phase-transfer catalyst. Simultaneously and using differently substituted 1,2-bis(bromomethyl)benzenes as precursors of the oQDM, Diederich *et al.* reported the synthesis and X-ray analysis of the dimethoxy-substituted cycloadduct (**214**) as well as the benzo-18-crown-6 derivative (**215**).[202a] Cycloadduct **217** was obtained from **216** by further chemical reaction (Figure 7).[202b]

Since then, many other C_{60}-based cycloadducts have been prepared by generation of the oQDM intermediate from other starting materials (Scheme 51). Although one of the most widely used methods is based on the 1,4-elimination of halogen from α,α′-dihalo-*o*-xylenes,[202] thermolysis of benzocyclobutenes (**5**) carried out in high boiling point solvents to promote the ring opening[203,204] or extrusion of CO_2 from isochromanone (**44**) derivatives[205] has also been used for the generation of oQDM and further trapping by C_{60}.

In Scheme 52 some examples of cycloadducts obtained by thermally allowed conrotatory [$\sigma^2 + \pi^2$] electrocyclic ring opening of benzocyclobutene derivatives **19b,f** together with other cycloadducts (**219**–**222**) prepared by a further chemical transformation are shown.[206]



214

215

216

217

Figure 7. Some representative C_{60}-based cycloadducts obtained from substituted oQDM.

Organofullerenes **218** were prepared in refluxing toluene due to the presence of the alkoxy substituent on the cyclobutene ring which, as it was already mentioned, produces a lowering of the activation energy in the generation of the alkoxy-*o*-quinodimethane, which can be thus generated under smooth conditions.

The cycloadducts obtained exist as two interconverting boat conformers at room temperature, showing an interesting dynamic behavior because of the rigidity of the C_{60} backbone and the peri-interactions of the α-substituent.[206] Thus, the NMR experiments and observed NOEs on **218f** allowed the configurational assignment in which the less stable isomer has a pseudoequatorial alkoxy group (Figure 8).

Interestingly, some substituted benzocyclobutenes react with C_{60} to afford novel cycloadducts bearing different functional groups. Thus, thermolysis of benzocyclobutenone in dichlorobenzene in the presence of [60]fullerene affords the [4 + 2] cycloadduct **223**.[207a]

Cycloadduct **224** was prepared from 3-phenylbenzocyclobutenol in refluxing toluene.[207b] A [60]fullerene adduct **225** endowed with a reactive triethoxysilyl functional group has been recently synthesized.[208] The high solubility of this adduct in polar solvents enables its covalent incorporation into sol−gel silica matrix (Scheme 53).

Benzocyclobutene homologues containing polyaromatic hydrocarbons also undergo ring opening.[203] The activation barriers to the oQDM are not reduced as much as when some functional group is linked at the benzyl position. An activation free energy of the ring opening of $\Delta G^{\ddagger} = 142$ kJ/mol at 200 °C was reported for the oQDM used for the preparation of **226**.

Table 1. Comparative Results in Cycloadditions Using Classical and Microwave Procedures

ratio 45a:C_{60}	microwave[a] (time/min)	yield 230 (%)	classical heating T (°C)	time (h)	yield 230 (%)
5:1	25	10 (12)[b]	reflux[c]	1.5	10 (10)[b]
2:1	20	39 (44)[b]	reflux[c]	1	22 (31)[b]
2:1	45	30 (44)[b]	reflux[c]	1	24 (40)[b]
1:1.1	20	23 (28)[b]	reflux[c]	18	30 (47)[b]

[a] Power 800 W. [b] On the basis of recovered C_{60}. [c] Solvent: benzene.

oQDMs can also be efficiently generated from sulfolenes **46** as well as from sultines **45** by SO_2 extrusion. Thus, Gügel and Müllen reported the generation of an amino-substituted oQDM from 1,3-dihydro-5-amino-isobenzothiophene-2,2-dioxide **227** by sulfur dioxide extrusion at about 200 °C.

The good solubility of the obtained cycloadduct (**228**) in chloroform allowed its further chemical derivatization to yield novel substituted organofullerenes **229a**−**e**[209] (Scheme 54).

As already pointed out, sultines (**45**) are ideal precursors for the generation of oQDMs because they decompose at around 80 °C and do not produce organic or inorganic byproducts except for the cheletropic extrusion of SO_2. Thus, we have reported the first example of a C_{60}-based cycloadduct (**230**) obtained from 4,5-benzo-3,6-dihydro-1,2-oxathiin-2-oxide (**45a**, sultine) (Scheme 55).[78] The starting sultine can be now favorably generated in situ in a one-step procedure from α,α′-dibromo-*o*-xylene (**28**) and sodium hydroxymethanesulfinate (“rongalite”) in high yield.[76]

Application of microwaves to fullerene's chemistry was first studied in the [4 + 2] cycloaddition of the parent oQDM generated from sultine.[78,79] It is well-known that microwave irradiation can be employed to accelerate organic reactions, increasing product purity and yields.[77] In Table 1 are shown the comparative results in the cycloaddition of sultine and C_{60} using classical and microwave procedures.

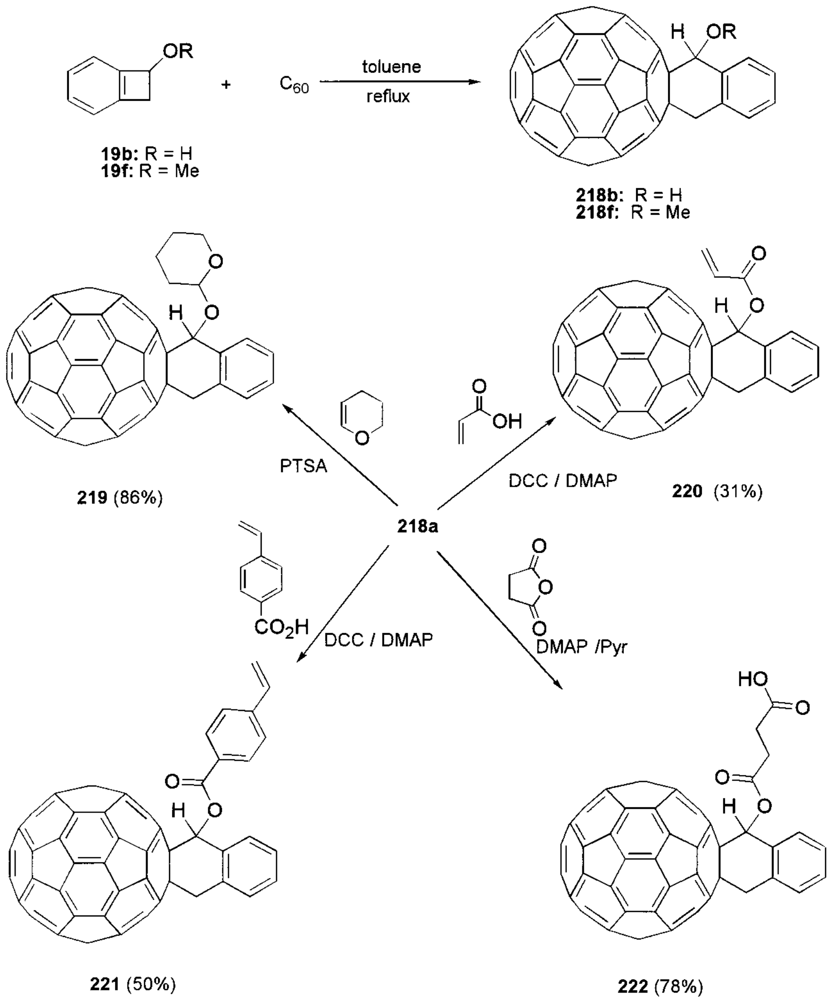
Higher yields in shorter times were obtained under microwave irradiation. This quick functionalization of C_{60} can be particularly useful to prepare adducts which decompose under long heating periods of time.

1. Cycloadditions of Masked oQDMs and Related Structures to C_{60}

[60]Fullerene functionalization from oQDMs has been intensively investigated since highly stable [4 + 2] adducts are obtained in relatively high yields. This behavior is in contrast to that of cyclopentadiene which forms cycloaddition products which are not energetically stabilized.

An interesting case has been recently reported by [4 + 2] cycloaddition of isoindene (**232**), generated in situ from indene (**231**) to afford cycloadduct **233**

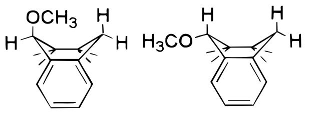
Scheme 52



as an alternative procedure for the derivatization of fullerenes[210] (Scheme 56).

To prove the reactivity of C_{60} with benzylic-substituted oQDMs, 6b,10b-dihydrobenzo[*j*]cyclobuta[a]acenaphthylene (**234**) was reacted with C_{60} in 1,2,4-trichlorobenzene to afford the novel cycloadduct **236** from the substituted intermediate **235** in 57% yield.[211]

Very recently, Echegoyen has reported the reaction of C_{60} with 1,8-bis(bromomethyl)naphthalene (**237**) in the presence of KI/18-crown-6 to form a cycloadduct with a seven-membered ring fused to a 6−6 junction.[212] A naphthoquinodimethane intermediate (**238**), formed from a very unstable three-membered ring containing intermediate, has been suggested as a mechanistic explanation of the formation of cycloadduct **239** (Scheme 56). Theoretical calculations reveal that cycloadduct **239** has a lower binding energy than other oQDM fullerene adducts by ~16.7 kJ/mol (4.0 kcal/mol).



218f (major) **218f** (minor)

Figure 8. Conformational isomers for cycloadduct **218f**. The major conformer has the methoxy group on a flagpole position.

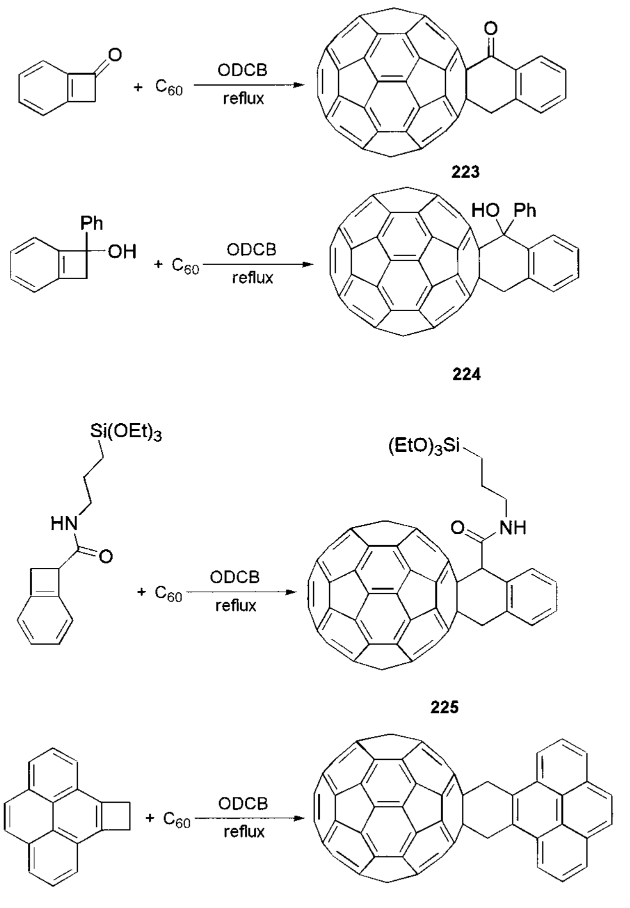
On the other hand, the thermal reaction of C_{60} with (η^5-bicyclo[3.2.0]hepta-1,3-dienyl)(η^4-tetraphenylcyclobutadiene)cobalt(I) (**240**) has been reported to yield cycloadduct **242**. The reaction is carried out in *o*-dichlorobenzene (ODCB) at 240 °C for 48 h in a sealed tube to give **242** in 28% yield as a stable crystalline solid.[213] It has been suggested that the [4 + 2] cycloaddition occurs by a "ring-slippage-reaction" involving a reversible change in hapticity from η^5 to η^3.

Interestingly, the ^{1}H NMR spectrum of cycloadduct **242** showed no ring inversion of the cyclohexene ring, in contrast to that observed for the *o*-xylene-bridged fullerenes.[214] The structure of **242** was determined unambiguously by X-ray analysis, which closely resembles those obtained from real oQDMs (Scheme 56).

2. *o-Quinodimethanes as Useful Tools in the Selective Functionalization of [60]Fullerene*

The selective synthesis of [60]fullerene bisadducts is currently a very important task for those chemists engaged in the chemistry of fullerenes since the first papers reported by Nishimura[215] and Diederich.[216] Thus, when an oQDM homologue was used for the modification of [60]fullerene, bisadducts turned out to be a complex mixture which could not be separated by a simple column chromatographic technique.

Scheme 53



223

224

225

226

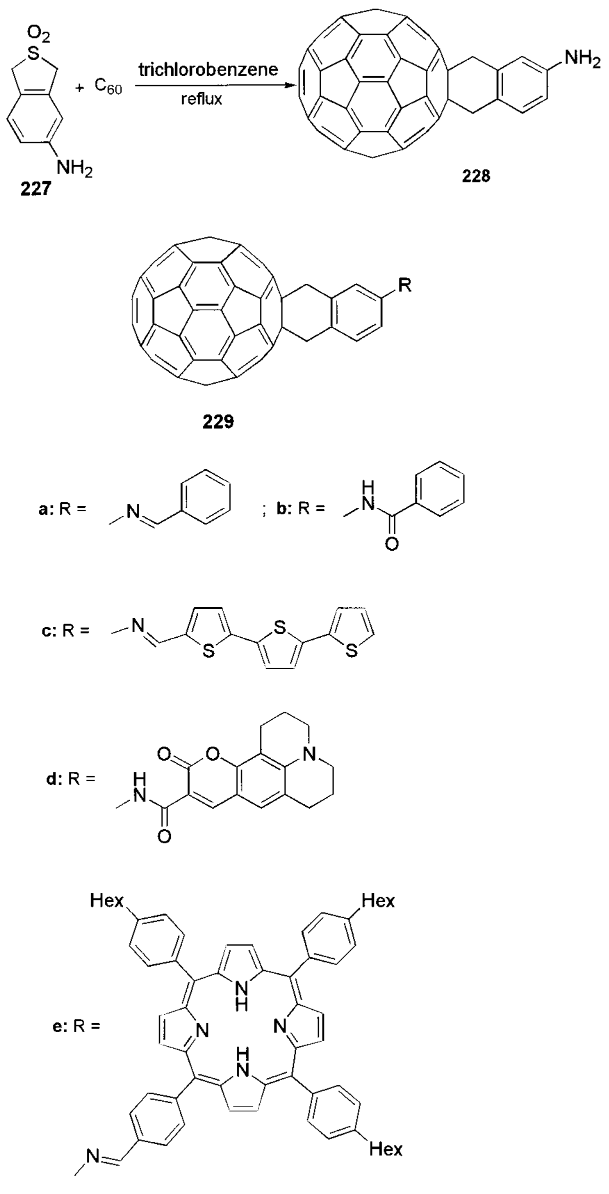
Diederich et al. first reported a sophisticated method based on the tether-directed remote functionalization of C_{60}.[216] The procedure is based in a first modification of a 6−6 junction of the fullerene by cyclopropanation reaction. Then, two sites around the equator of C_{60} were selectively modified by the Diels−Alder addition of the dienes attached at the end of the two tethers stretched from the cyclopropane ring to form a headphone-shaped trisadduct.

For the selective bisaddition of C_{60} using oQDM, α,ω-bis(3,4-bis(bromomethyl)phenoxy)alkanes (**243**), which in situ generates oQDMs at both ends by 1,4-elimination, was reacted with C_{60}. By changing the length of the tether connecting both oQDMs, it is possible to achieve a selective addition on the C_{60} core[217] (Scheme 57).

The linkage of all bisadducts could be cleaved quantitatively by treatment of excess boron tribromide in benzene at room temperature to give the corresponding bisphenols.

By using this methodology, the selective synthesis of C_{60} bisadducts was successfully carried out from two α,α'-dibromo-*o*-xylene moieties connected by an oligomethylene chain [$-(CH_2)_n-$, $n = 2-5$]. *cis*-2- and *cis*-3-bisadducts were selectively obtained when $n = 2$ and 3 but only one *e*-bisadduct with $n = 5$. A balance of stereochemical and electronic effects has been suggested as being responsible for the obtained selectivities, since these high selectivities are not accomplished in the absence of the chain.

Scheme 54

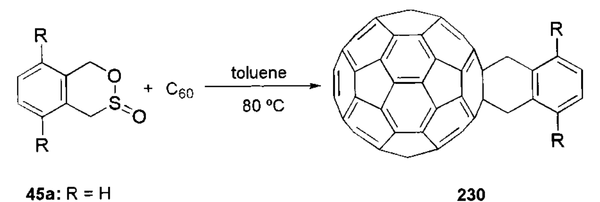


227

228

229

Scheme 55



45a: R = H
45c: R = OHex

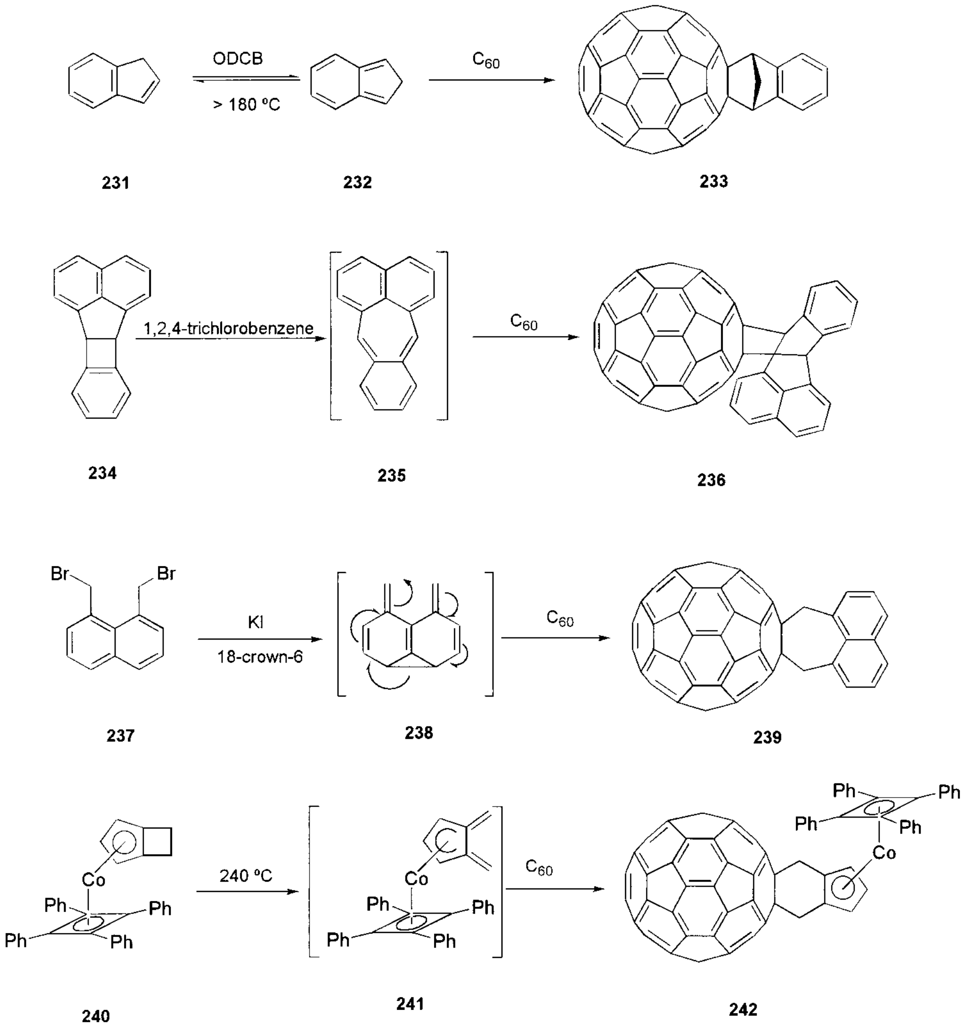
230

These [60]fullerene derivatives bearing two phenol moieties are of interest for further transformations in the search of bioactive compounds,[218] electrolytes or functional dyes,[219] and pearl-necklace-shaped [60]-fullerene polymers.[211]

A similar approach based on the regioselective introduction of two boronic acid groups into [60]-fullerene (**256**) using saccharides as imprinting templates has been reported very recently by Shinkai et al.[220] (Scheme 58).

It is interesting to remark that the regioselectivity obtained in the cycloadducts **257** is highly dependent

Scheme 56



on the saccharide structure (**252**–**255**) used as the template.

A topochemically controlled, regiospecific fullerene bisfunctionalization is an elegant approach reported by Kräutler et al.[221] In this case, the functionalization of C_{60} is based on a thermal, intermolecular anthracene transfer reaction in the solid state.

The crystalline 6,6-monoadduct (**258**) prepared from C_{60} and anthracene[222] undergoes a regiospecific thermal transformation into a solid 1:1 mixture of C_{60} and the antipodal bisanthracene adduct **259** as shown in Scheme 59.

The reaction is suggested to proceed by intermolecular anthracene transfer, in which a molecule of the starting compound acts as an intimate anthracene donor for the neighboring fullerene, which acts as an acceptor.[221] The occurrence of this reaction can be rationalized by the specific packing of molecules of **258** in the crystal, allowing a combination of a [4 + 2] cycloreversion and [4 + 2] cycloaddition steps. Although formally an oQDM is not involved in this process, the [4 + 2] cycloaddition reaction as well as the geometry of the resulting cycloadduct are close to the oQDM cycloadducts studied.

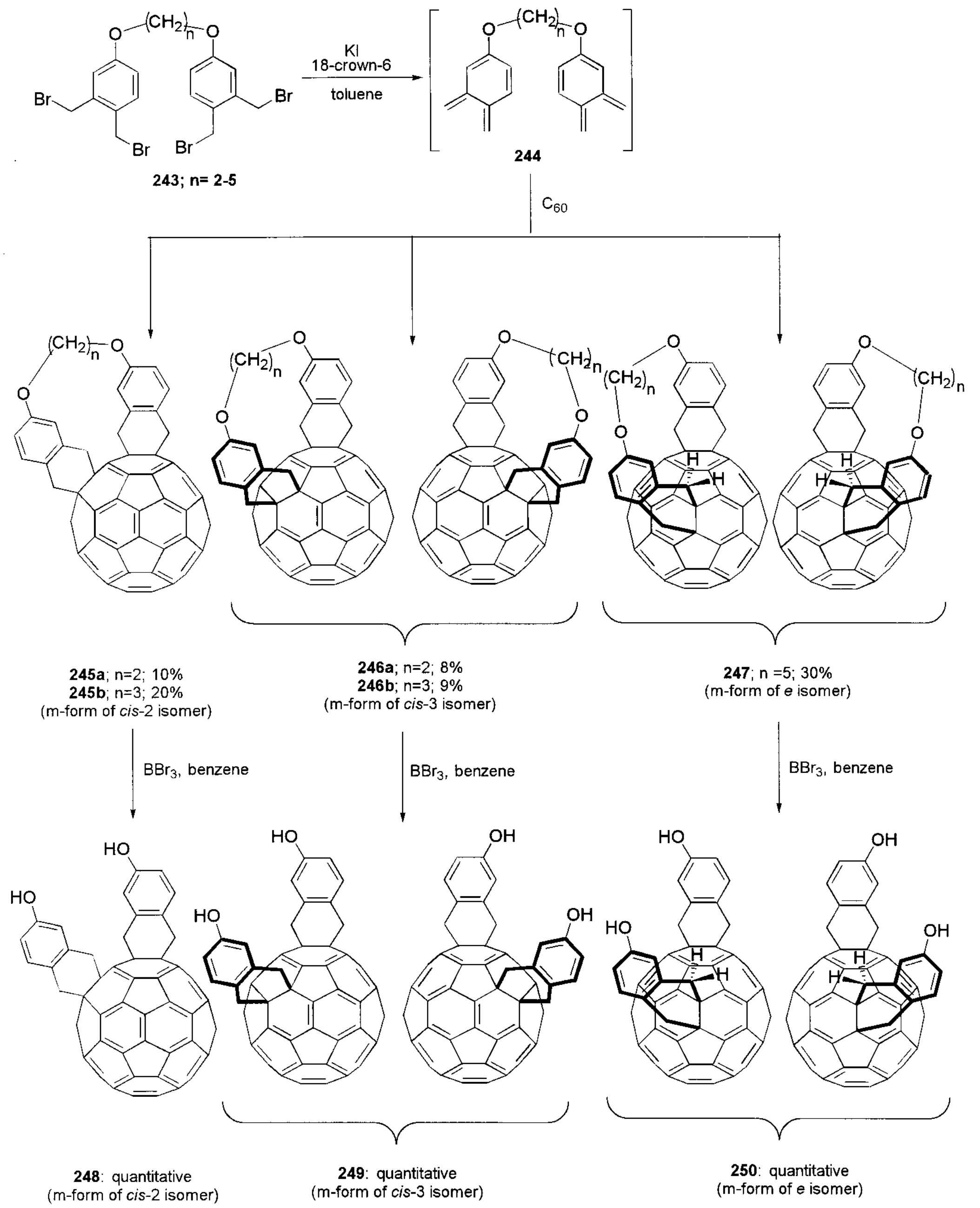
Compound **259** has also been used for the preparation of symmetric mixed hexaadducts (**260**) and equatorial D_{2h}-symmetric tetrakis adduct (**261**).[223] Now the two anthracene addends control the attachment of other addends toward the molecular equator, thus forming mixed symmetric hexaadducts. In a further step, the anthracene moieties are removed by heating the solid sample (195 °C, 5 min) to form symmetric tetrakis adduct. (Figure 9). This approach paves the way to the design and synthesis of novel three-dimensionally structured molecules.

3. Diels–Alder Adducts of [60]Fullerene and Heterocyclic o-Quinodimethanes

Heteroaromatic analogues of oQDMs as dienes have received much less attention, compared with the parent oQDM, despite their potential synthetic interest and, only recently, have been thoroughly reviewed.[3] Most studies involving heteroaromatic analogues of oQDM involve their generation, and only a few of them are related with their synthetic applications.

Heteroaromatic oQDMs are not easy to prepare, particularly those bearing functionalities that can be altered during the generation process of the reactive intermediate oQDM. Unlike the parent oQDM, a specific precursor is required for the preparation of each particular heteroaromatic oQDM and this is one of the reasons that many of these elusive intermediates are still unknown.

Scheme 57



The first reaction of heteroaromatic analogues of oQDM with C_{60} was reported by Eguchi *et al.*[224] and Martín et al.[225] involving the parent thieno-*o*-quinodimethane and substituted thieno-*o*-quinodimethanes, respectively.

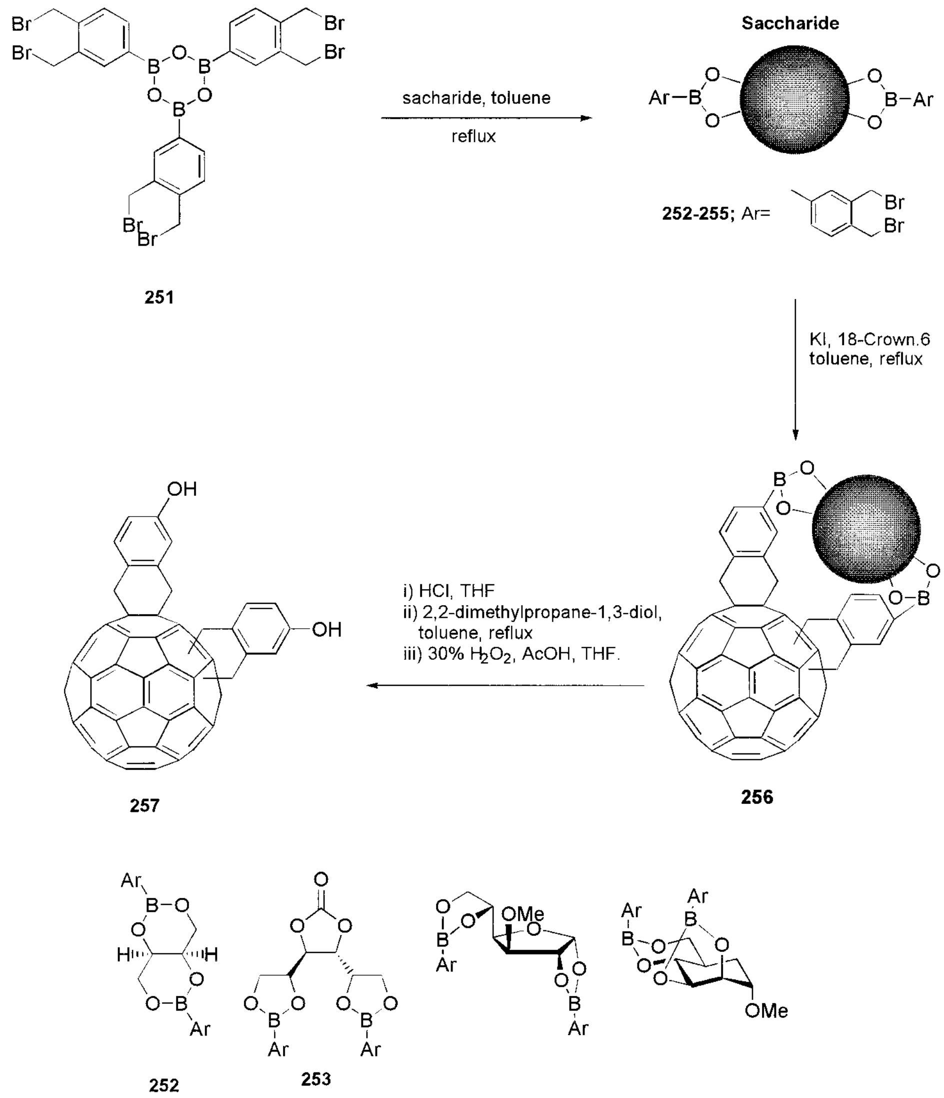
The intermediate thieno-oQDMs were generated in situ by iodide-induced 1,4-elimination from the respective 2,3-bis(halomethyl)thiophenes (**262a**−**c**, Scheme 60). The cycloaddition reaction is carried out in toluene to solubilize C_{60}, and consequently, 18-crown-6 ether is required as a phase-transfer catalyst.

Since these first reports and during more recent years, many other Diels−Alder reactions of heterocyclic analogues of oQDM to C_{60} have been reported.[226] Thus, heterocycles such as furan, oxazole, thiazole, indole, 1,4-diazine, and pyrimidine have been covalently attached to the C_{60} core. Although the first two pentagonal rings (furan and oxazole) were oxygen labile due, probably, to the ability of C_{60} to act as a good photosensitizer for producing singlet oxygen,[227] the remaining C_{60}-based heterocycles containing cycloadducts were obtained as stable solid compounds.

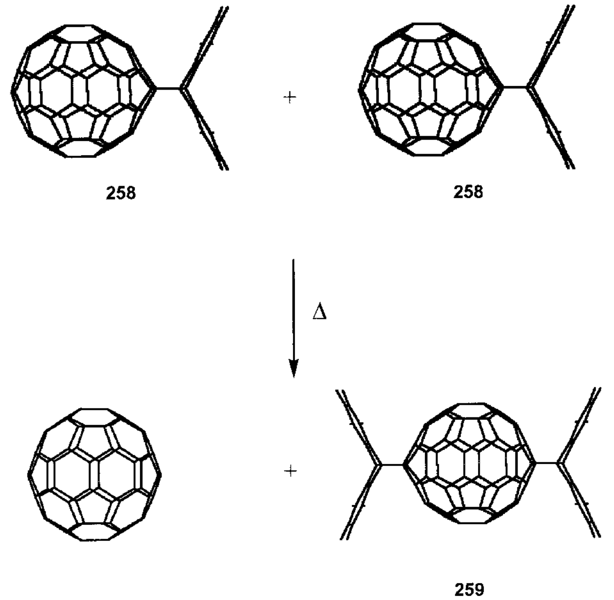
Thus, 2,3-dimethylene-2,3-dihydrofuran (**87**) was generated by 1,4-elimination of a benzoate derivative (**264**) through flash vacuum pyrolysis by following Trahanovsky's method.[228] Cycloadduct **265** (Scheme 61) was formed by trapping the diene intermediate with liquid nitrogen, to which a chlorobenzene solution of C_{60} was added and the mixture was allowed to stay at room temperature with protection from light to avoid photooxidation.[229]

The oxazole- and thiazole-linked C_{60} derivatives **268a,b** were obtained by cheletropic elimination from the respective starting materials **266a,b**, respec-

Scheme 58



Scheme 59



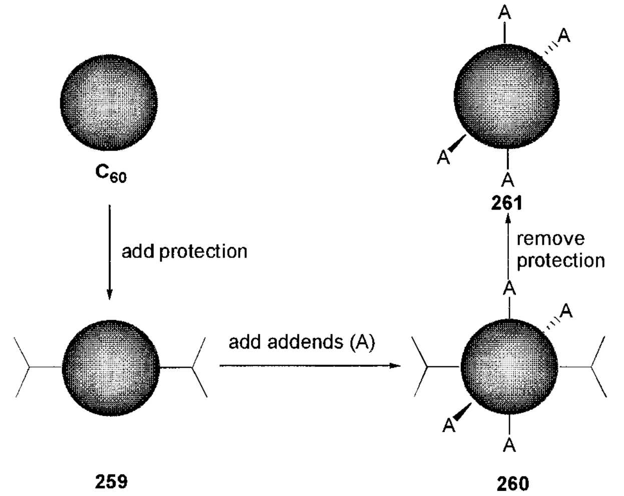
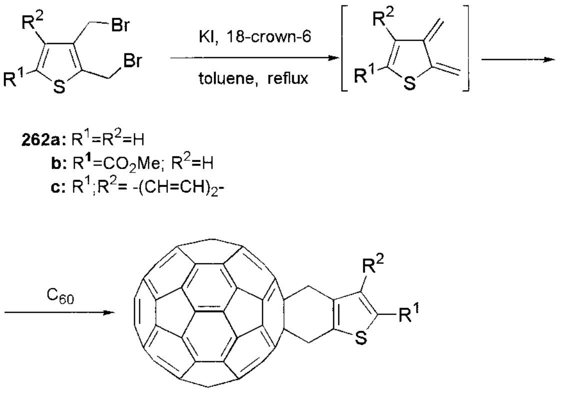


Figure 9. Basic scheme for the preparation of C_{60}-based symmetric tetrakis adducts.

tively. Thermolysis of the sulfolenes were carried out in refluxing chlorobenzene and dichlorobenzene to afford, respectively, diene intermediates **267** which react with C_{60} to yield cycloadducts **268a,b** in moderate yields.[229]

The indole-linked C_{60} cycloadduct **271** was obtained by generating the indole analogue of oQDM (**270**)

Scheme 60



262a: $R^1=R^2=H$
b: $R^1=CO_2Me$; $R^2=H$
c: R^1;R^2= -(CH=CH)$_2$-

263a-c

from the *N*-benzoyl-2,3-bis(bromomethyl)indole by following the standard procedure using KI/18-crown-6 conditions[229] (Scheme 61).

Diels–Alder adducts of C_{60} with six-membered 2,3-pyrazinoquinodimethanes have been recently reported by different research groups.[229–231] However, only in two cases[229–231] the heterocycle ring was connected to the C_{60} core from the substituted 2,3-pyrazinoquinodimethanes. [4 + 2] Cycloaddition of C_{60} with the corresponding 2,3-bis(bromomethyl)pyrazine derivatives (**274**), which can be easily prepared in a one-step procedure by condensation of 1,4-dibromo-2,3-butanedione (**273**) with 1,2-diphenylenediamine (**272a**), naphthalenediamine (**272b**), and 2,3-diaminobutenedinitrile (**272c**) (Scheme 62).

2,3-Pyrazinoquinodimethane derivatives (**275a**–**c**) were generated in situ by treatment of 2,3-bis(bromomethyl)pyrazine derivatives (**274a**–**c**) with sodium iodide in ODCB at 130 °C.

Variable-temperature NMR experiments reveal that these cycloadducts present a flipping cyclohexene ring with activation free energies depending upon the heterocyclic system covalently attached to the C_{60} cage. Interestingly, the activation energies found for the six-membered pyrazine adducts (**276**) were very close to that found for the carbocyclic compounds, and striking lower values were obtained for the five-membered thiophene adducts (**263**), which showed two different coalescence temperatures for the two different methylene units present in these compounds[231] (Table 2).

Table 2. Activation Free Energies Determined for C_{60}-Based Thiophene- and Pyrazine-Containing Cycloadducts

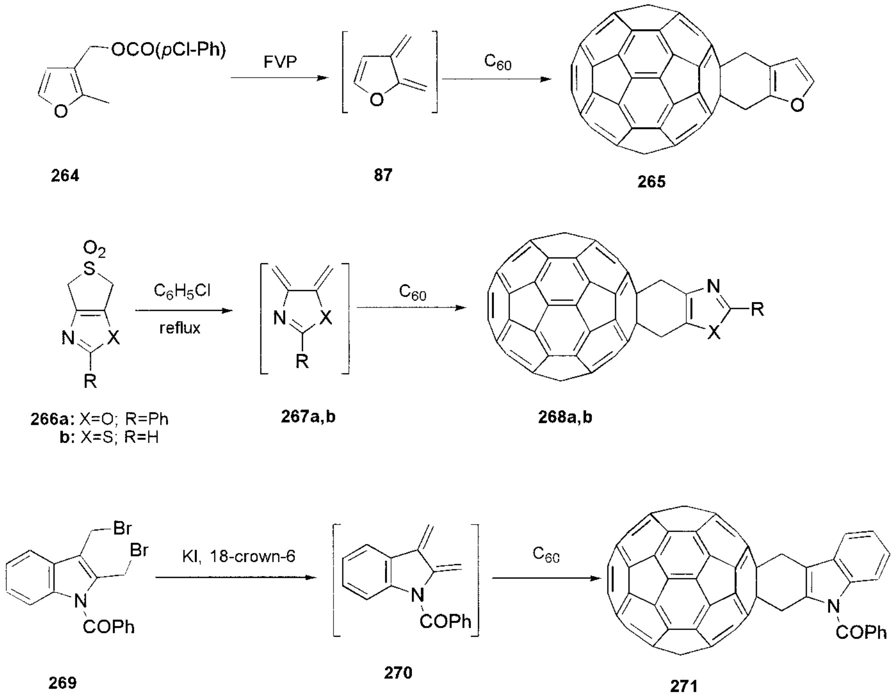
compd	T_c (K)	$\Delta\nu$ (Hz)	$\Delta G^\ddagger$ (kJ mol^{-1})[a]	$\Delta G^\ddagger$ (kJ mol^{-1})[b]
276a	323	104.4	64.7	64.5
276b	333	126.1	66.2	66.1
263b	245	26.2	51.3	50.2
263b	241	14.8	51.6	49.8
263c	223	51.0	45.3	44.9
263c	231	86.7	45.9	45.8

[a] Activation free energies at the coalescence temperatures according to $\Delta G^\ddagger = aT[9.972 + \log(T + \Delta\nu)]$. $a = 1.914 \times 10^{-2}$ kJ mol^{-1}. [b] Activation free energies at the coalescence temperatures according to $\Delta G^\ddagger = aT[9.972 + \log(T + (\delta\nu^2 + 6J^2_{AB})^{1/2})]$.

The electronic structure for the heterocyclic oQDMs indicate that these cycloadditions to C_{60} are controlled by the HOMO of the dienes, all the reactions being energetically favored.[231]

The photophysics of some pyrazine–fullerene dyads have been recently studied by Guldi[232] and represent a versatile approach to improve the light-harvesting efficiency of fullerenes. Photoexcitation of the pyrazine moieties in these dyads is followed by rapid intramolecular deactivation via energy transfer to the fullerene ground state with half-lives between 37 and 100 ps. In turn, energy transfer transforms the pyrazine singlet excited states into the highly

Scheme 61



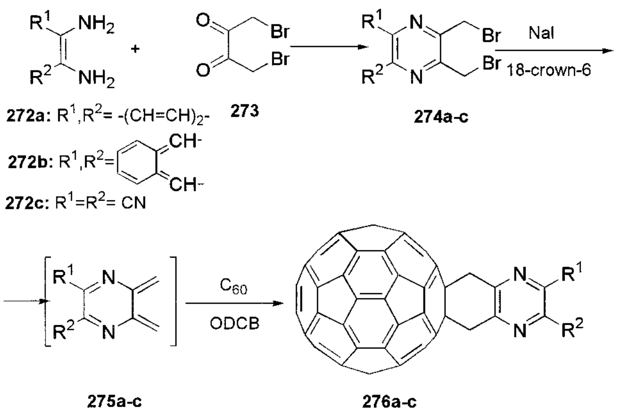
264 **87** **265**

266a: X=O; R=Ph
b: X=S; R=H

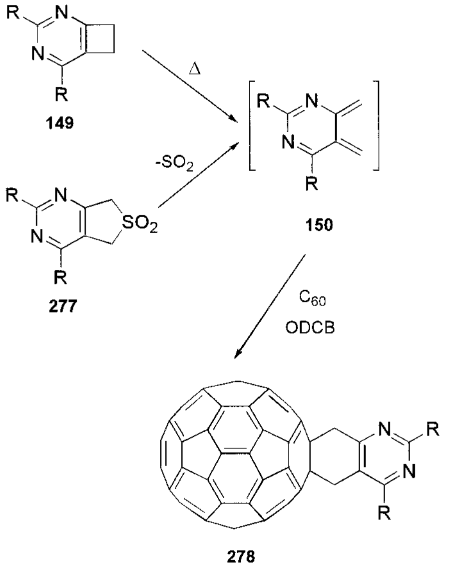
267a,b **268a,b**

269 **270** **271**

Scheme 62



Scheme 63



reactive fullerene triplet excited state. It is important to note that reports on intramolecular energy-transfer reactions to fullerenes are still relatively scarce.

Recently, the synthesis of novel pyrimidine-containing cycloadducts prepared by Diels–Alder reaction of C_{60} and pyrimidine oQDMs has been reported.[126,141,233] The pyrimidine ring occurs widely in compounds with biological and pharmacological activity, and therefore, pyrimidine-containing organofullerenes are of particular interest in the search for novel properties.[218]

Cyclobutapyrimidines (**149**) are easily prepared in a one-step synthesis from aliphatic or aromatic nitriles and aliphatic or alicyclic ketones (Scheme 39).[126a] Thermally allowed conrotatory [$\sigma^2 + \pi^2$] electrocyclic ring opening of cyclobutapyrimidines (**149**) in ODCB at 180 °C yields the reactive intermediate **150** which reacts with C_{60} to afford cycloadduct **278** as a stable solid (Scheme 63).[126b]

Pyrimidine oQDM (**150**) has also been generated very recently from pyrimidine-fused-3-sulfolenes (**277**) by thermal extrusion of sulfur dioxide.[125b,128b]

The dynamic behavior of the novel cycloadducts (**278**) has been investigated by using variable-temperature ^1H NMR measurements.[126b] The energy barriers for the boat-to-boat inversion of the cyclohexene ring show $\Delta G^{\ddagger}$ values (14.9–17.2 kcal/mol) with a significant dependence of the alkyl or aryl substitution on the pyrimidine ring. Interestingly, the redox properties of the novel organofullerenes, determined by cyclic voltammetry, indicate a certain interaction between the organic addend and the C_{60} moiety.[126b]

4. o-Quinodimethanes as Precursors for Electroactive C60-Based Dyads

[60]Fullerene is a redox-active chromophore which behaves like an electronegative molecule which can accept up to six electrons.[234] Moreover, the unique photophysical properties of fullerenes, and in particular the readily available C_{60}, attributed to a combination of the high symmetry of C_{60} and the pyramidal nature of their constituent carbon atoms,[235] are currently under investigation as artificial photosynthetic systems with efficient and long-lived charge separation. Thus, the design of organofullerenes endowed with electron-donor or electron-acceptor moieties represents a promising field as a consequence of the optical and electronic properties they can display.[6]

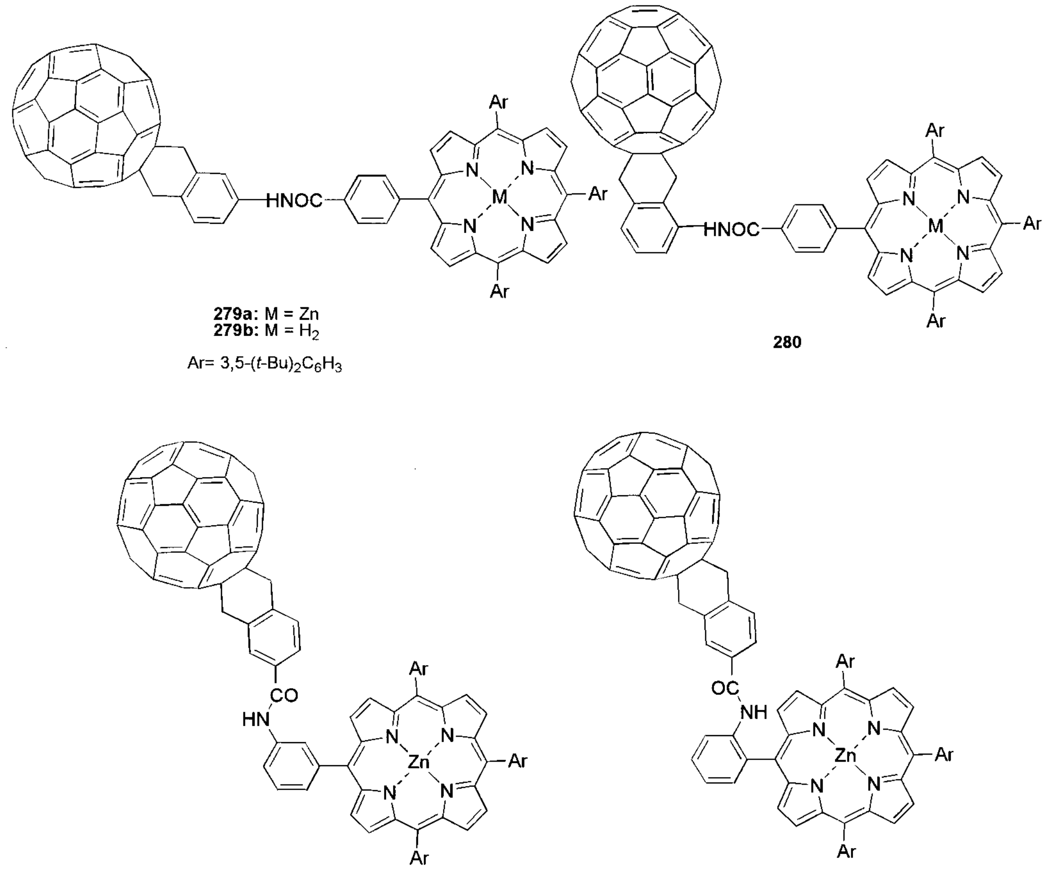
o-Quinodimethanes have also played an important role in the design of dyads as a versatile approach to stable cycloadducts bearing an electroactive moiety. Thus, different substituted porphyrins (**279**–**282**) have been connected to the C_{60} core through a substituted oQDM (Figure 10).[236]

Dyads **279a,b** bearing six *tert*-butyl groups on the aromatic rings of the porphyrin moiety to increase the solubility were prepared from the appropriately substituted oQDM forming the amido bond at the final stage of the synthesis.[237] A fluorescence quenching of both the singlet excited states of zinc and free-base porphyrins **279a,b** by the C_{60} moiety was observed in THF.

Other C_{60}-linked zinc porphyrins (**280**–**282**) were also synthesized by modifying the linking position at the *meso*-phenyl ring from *ortho* to *para*, and the linkage and solvent dependence of their photophysical properties were investigated.[238]

In our group we have reported the facile formation of [60]fullerene adducts from sultines via a Diels–Alder reaction as an alternative procedure for the functionalization of C_{60} under mild conditions.[78] We have used this approach for the preparation of novel organofullerenes in which the C_{60} core is linked to an electron-acceptor *p*-benzoquinone ring.[239] It is worth mentioning that in contrast to the wide variety of C_{60}-based donor–acceptor dyads reported, the number of organofullerenes in which an electron acceptor unit is covalently attached to the C_{60} cage is still very small.[6]

The synthesis of the C_{60}-based cycloadducts was carried out from the appropriately substituted sultines which react with C_{60} in refluxing toluene by extrusion of SO_2 to generate the substituted oQDM (**284**). This reactive diene is readily trapped by C_{60},



279a: M = Zn
279b: M = H_2
Ar= 3,5-(*t*-Bu)$_2C_6H_3$

280

281

282

Figure 10. Selected examples of C_{60}-based porphyrin-containing dyads.

acting as a good dienophile to afford the cycloadducts **285** in moderate yields (22−45%) [44−58% based on recovered C_{60}] (Scheme 64).

The experimental conditions used from sultines are milder than those recently reported to obtain cycloadduct **285b** from 3,6-dimethoxybenzocyclobutene, which requires heating in ODCB at 220 °C for 24 h, with similar yields.[240]

The prepared cycloadducts (**285**) were easily transformed into the corresponding *p*-benzoquinone derivatives (**287**) by removing the alkyl groups with boron tribromide and further oxidation with DDQ.[239]

The temperature-dependent ^{1}H NMR spectra of these cycloadducts show a dynamic process of the methylene protons. The activation free energy determined for the boat-to-boat inversion (11.3−11.6 kcal/mol) is remarkably lower than that determined for other related carbocyclic or heterocyclic analogues (see above). Geometrical features seem to be responsible for the low activation barriers. Interestingly, the attachment of the first electron in the reduction process takes place on either the C_{60} core or the *p*-benzoquinone ring depending upon the nature of the substituents on the quinone unit, which controls the relative energy of the LUMO.[239]

Although the strong electron-donor tetrathiafulvalene (TTF) had already been linked to the C_{60} core through a [3 + 2] dipolar cycloaddition,[241,242] more recently TTF and its derivatives have also been covalently attached to the C_{60} framework by using the oQDM analogue of TTF (2,3-dimethylene-TTF, **290**) (Scheme 65).[243,244]

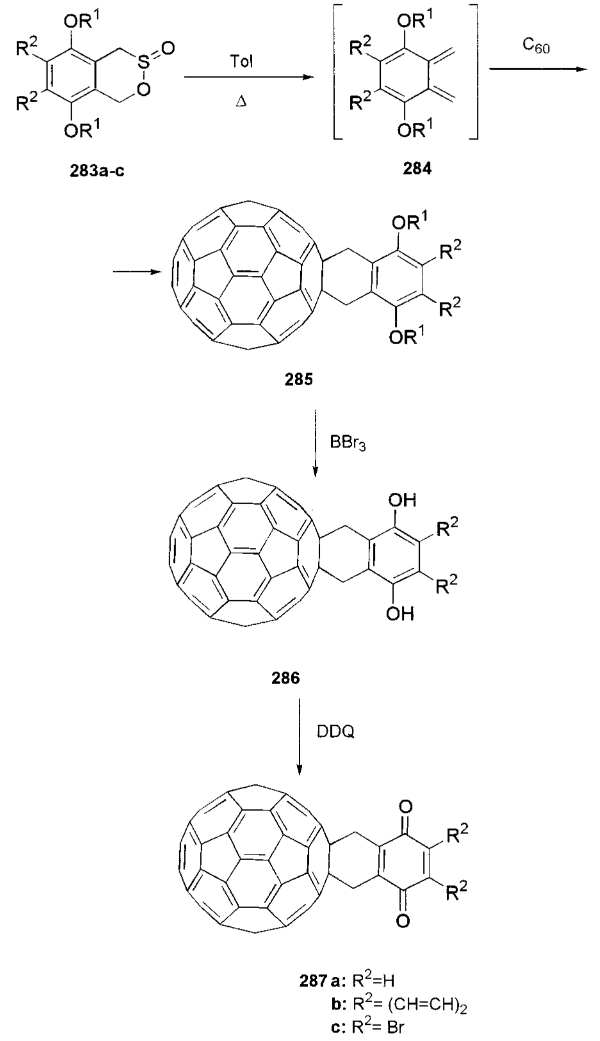
As already pointed out, tetrathiafulvalene (TTF)[245] is a strong electron-donor molecule which has been successfully used in the preparation of electrically conducting and superconducting organic materials.[246]

C_{60}−TTF dyads (**291**) were prepared from 2,3-bis(bromomethyl)-6,7-bis(methylsulfanyl)tetrathiafulvalene (**288**)[243] and the sulfone analogue (**289**)[244] as precursors of the transient-substituted 2,3-dimethylene−TTF (**290**) which was subsequently trapped by C_{60} (Scheme 65).

The spin density distributions of radical cations and radical anions derived from dyads **291** are mainly located on the TTF and fullerene moieties, respectively. The modification of the donor strength of the TTF unit enables the tuning of the HOMO−LUMO gap of these dyads, thus allowing one to study the interaction between the two electroactive fragments as a function of the donor strength. Nanosecond-resolved flash photolysis in the UV−vis region of some dyads (**291b**−**d**) in benzonitrile shows a rapid quenching of the excited triplet states.[244]

An alternative route for the preparation of dyads **291** had been previously attempted by Diels−Alder cycloaddition of 2-(thi)oxo-4,5-bis(methylene)-1,3-dithioles (**292**) to C_{60} as shown in Scheme 66. Three different routes were followed for the in situ genera-

Scheme 64



tion of the reactive diene (**292**).[247,248] However, further attempts for the construction of the TTF unit by coupling reactions from the obtained cycloadduct (**293**) were unsuccessful.

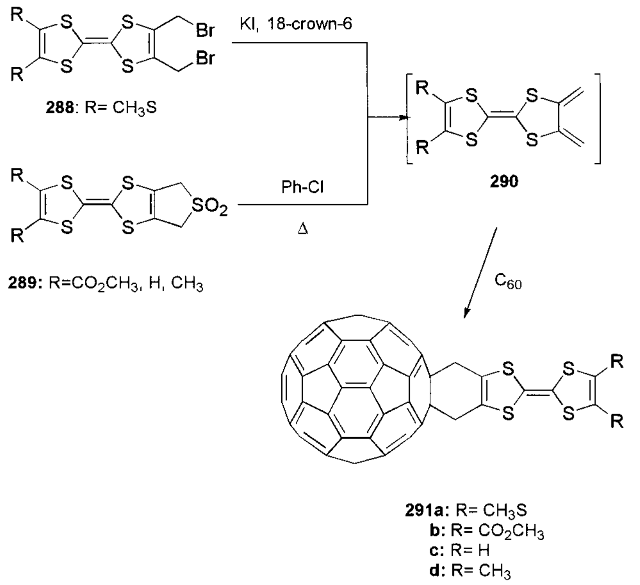
5. o-Quinodimethanes in the Chemistry of Higher Fullerenes

The development of the covalent chemistry of higher fullerenes, that is, homologues of C_{60} with 70 or more carbon atoms, has been mainly carried out on the C_{70} molecule due to its availability. More recently, pure derivatives of larger spheres such as C_{76}, C_{84}, as well as C_{78} have been isolated and characterized.[249]

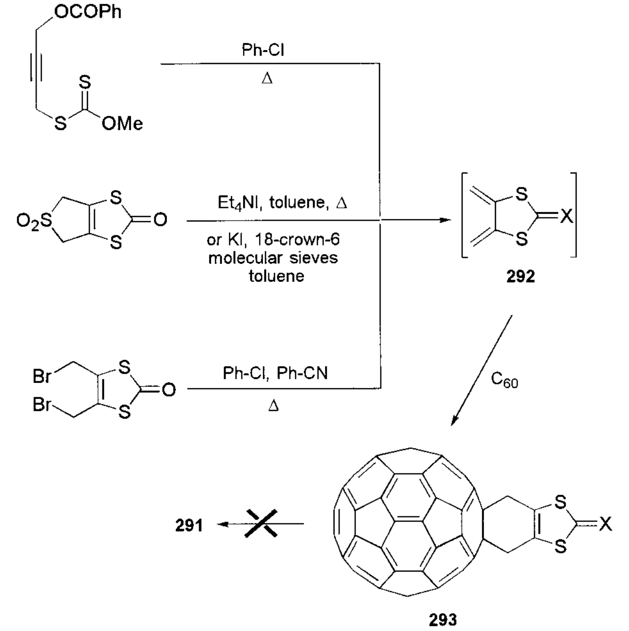
The Diels–Alder [4+2] cycloaddition of 4,5-dimethoxy-*o*-quinodimethane to C_{70} and C_{76} has been studied by Diederich et al.[250] Compared to C_{60}, the lower symmetry of the higher fullerenes leads to the formation of a large number of possible structural isomers which are usually difficult to separate.

In a similar way to that found for the parent C_{60}, Diels–Alder reaction on higher fullerenes occurs selectively at the junctions between two six-membered rings (6–6 bond). This fact, in addition to the formation of thermodynamically stable cycloadducts by aromatization, makes the reaction of higher fullerenes with oQDMs very attractive for regioselective studies.

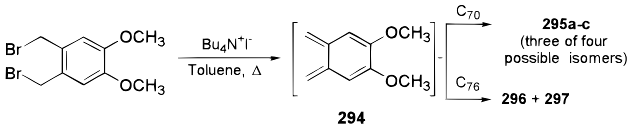
Scheme 65



Scheme 66

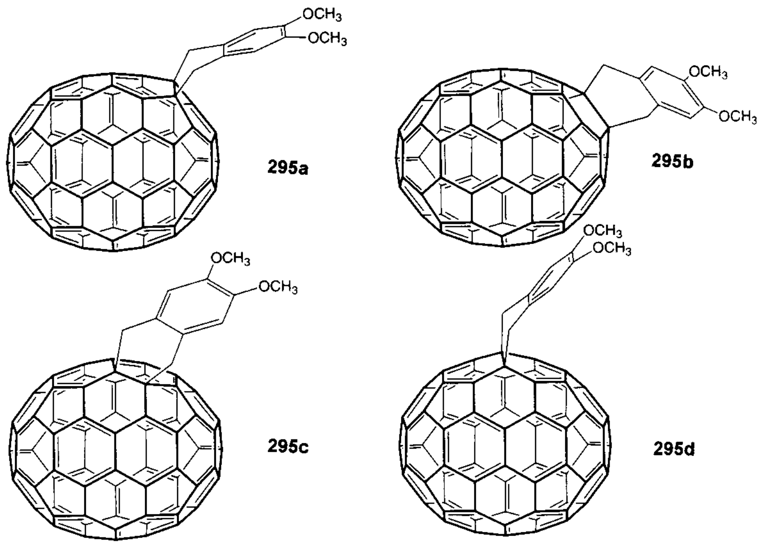


Scheme 67



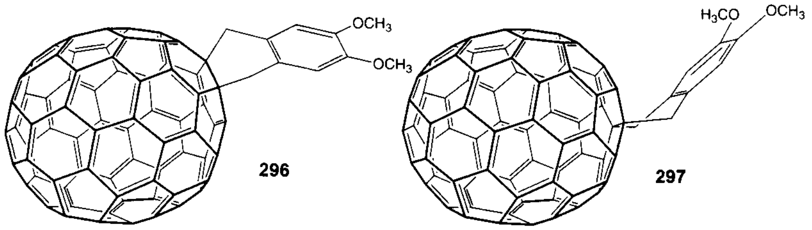
The 1,2-bis(bromomethyl)-4,5-dimethoxybenzene was refluxed in toluene in the presence of tetrabutylammonium iodide to generate the dimethoxy-substituted oQDM (**294**) which was trapped by C_{70} or C_{76} as shown in Scheme 67.

In the case of C_{70} (D_{5h} symmetry), three of the four possible isomers (**295a–d**) were isolated and characterized (**295a–c**) in 24%, 10%, and 1–2% yields, respectively. Formation of the equatorial adduct **295d** was not observed. The two most abundant products



295a **295b** **295c** **295d**

Figure 11. Four possible isomers resulting from cycloaddition of dimethoxy-oQDM to C_{70}. Only isomer **295d** was not observed. (Reprinted with permission from ref 250. Copyright 1994 Verlag Helvetica Chimica Acta.)



296 **297**

Figure 12. Isomers isolated from cycloaddition of dimethoxy-oQDM to C_{76}. (Reprinted with permission from ref 250. Copyright 1994 Verlag Helvetica Chimica Acta.)

were confirmed by X-ray crystallography.[251] The third minor constitutional isomer has an inherently chiral addition pattern (Figure 11).

On the other hand, the addition of 4,5-dimethoxy-*o*-quinodimethane (**294**) to C_{76} (D_2 symmetry) leads at least to six different isomers. On the basis of ^1H NMR spectroscopy and bond reactivities, a tentative assignment of the major product, which was isolated in pure form, as the C^1-symmetrical C(2)−C(3) adduct (±) **296** (Figure 12) was concluded, resulting from attack at the polar α-type bond.[250] Similarly, the structure of the C(1)−C(6) adduct (±)-**297** was assigned to a C_2-symmetrical monoadduct.

In this interesting study on the regioselectivity of higher fullerenes, a good correlation between the experimental results and the calculated pyramidalization angles[252] was found, thus rationalizing the formation of different isomers.

VII. *o*-Quinodimethanes in Polymer Chemistry

As we have seen in this manuscript, benzocyclobutenes are among the most suitable precursors of oQDM. Several reports on the polymer chemistry of benzocyclobutene have been published recently.[8,253] Polymeric materials prepared by thermally initiated polymerization of monomers based on benzocyclobutenes have attracted interest due to the unusual physical property profiles available from these materials.[254−259]

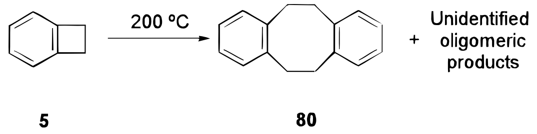
From a chemical point of view, the study of the polymerization of benzocyclobutenes can be divided into four main types depending on the nature of the basic benzocyclobutene monomers involved in the polymerization reaction: (i) monomers which contain only benzocyclobutene moieties as reactive groups; (ii) benzocyclobutene monomers that contain sites of unsaturation capable of reacting with an oQDM to give cycloaddition products; (iii) aryl-substituted vinylbenzocyclobutenes; and (iv) bisbenzocyclobutenes which readily react with molecules containing two sites of reactive unsaturation.

A. Polymerization of Benzocyclobutene Monomers Containing the Benzocyclobutene Functionality as the Only Reactive Species

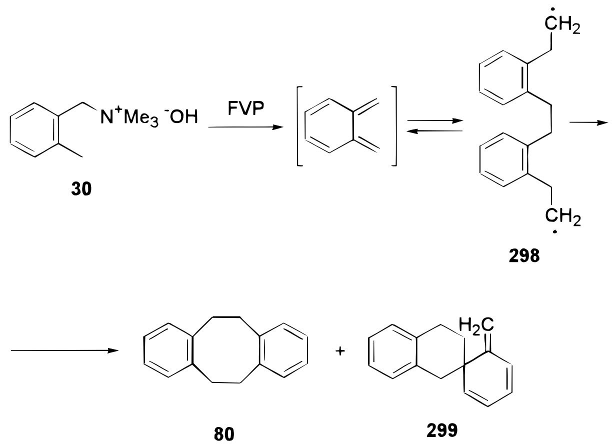
There seems to be a general agreement in the literature that the first step in the polymerization of a benzocyclobutene monomer is the thermally-induced ring-opening reaction to yield the corresponding oQDM intermediate.[260] When no other functionality is present in the benzocyclobutene monomer, the polymerization mechanism has largely been discussed in terms of the thermolysis reaction of the benzocyclobutene moiety and the self-addition products of the oQDM formed.

The fate of the oQDM formed appears to depend to a large extent upon the conditions under which it is generated. Thus, for example, the thermolysis of benzocyclobutene hydrocarbon in a sealed flask at 200 °C gave a 24% yield of 1,2,5,6-dibenzocyclooctadiene (**80**) along with a mixture of unidentified oligomeric materials[261] (Scheme 68). Formation of **80**

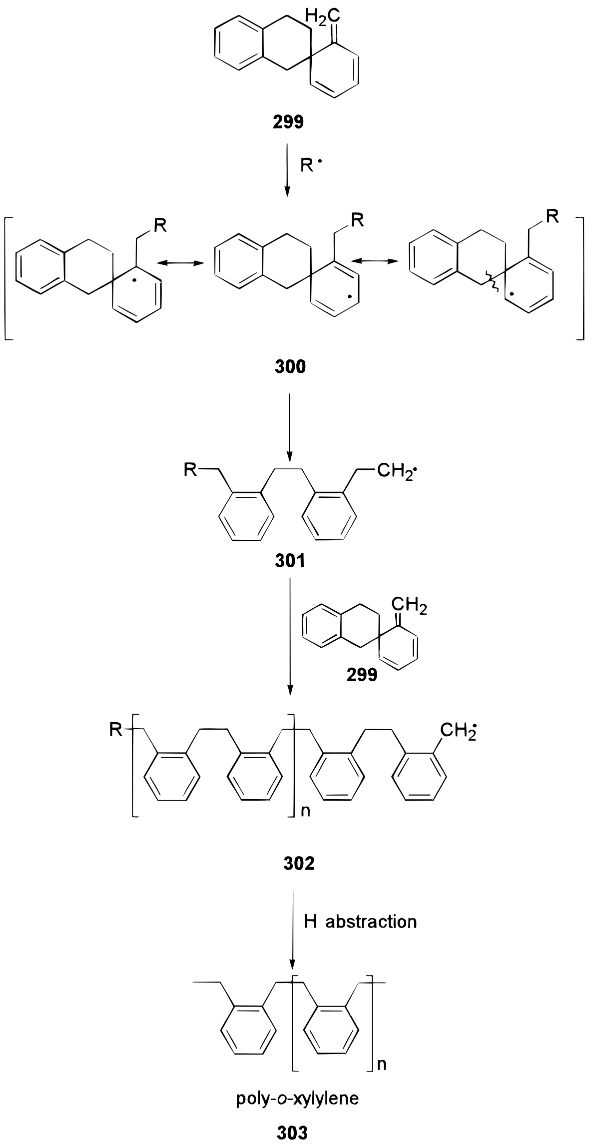
Scheme 68



Scheme 69



Scheme 70



may be explained as being the result of oQDM having considerable radical character.

In a series of experiments, Errede[262] prepared oQDM itself by the flash pyrolysis of *o*-methylbenzyltrimethylammonium hydroxide (**30**), the oQDM being quenched soon after it was formed by cooling to −78 °C. The product trapped out under these conditions was an approximately 25:75 mixture of a 1,2,5,6-dibenzocyclooctadiene **80** and the spiro *o*-quinodimethane dimer **299** (Scheme 69).

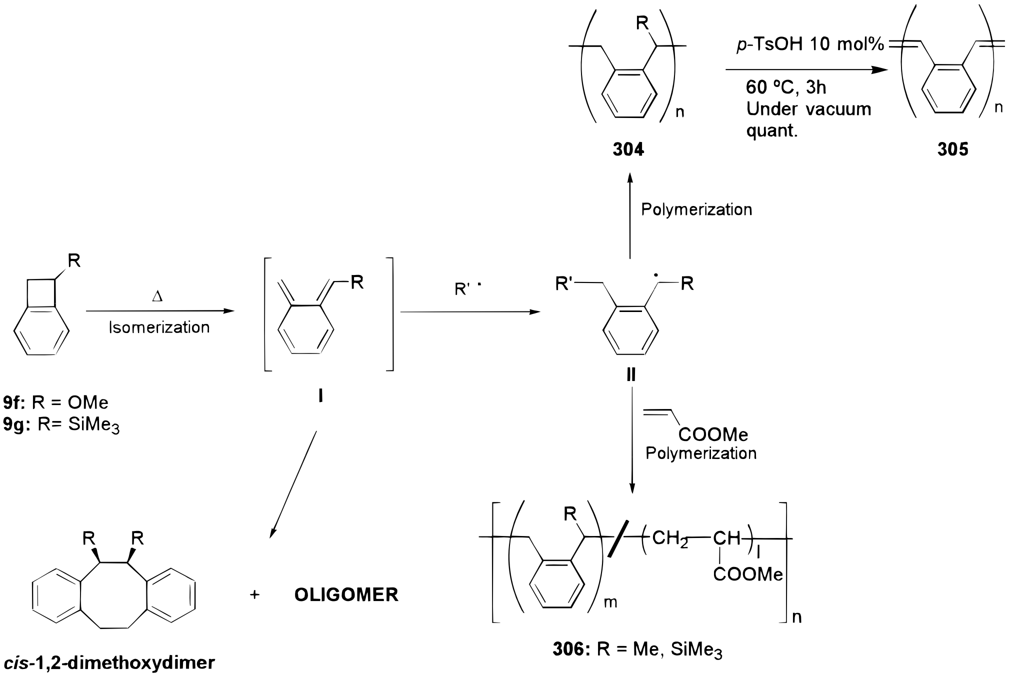
The spirodimer **299** is stable at low temperature, but upon warming, it polymerizes to poly-*o*-xylylene.

There is no experimental evidence of any 1,2,5,6-dibenzocyclooctadiene **80** being formed by heating the spirodimer **299**. Therefore, it appears that the polymerization of **299** and the formation of **80** occur through different intermediates. The mechanism proposed for this transformation involves the initial formation of an oQDM. When this is rapidly quenched, it can form a bibenzyl biradical **298** which can close to either the spirodimer **299** or 1,2,5,6-dibenzocyclooctadiene **80**. While the last one is thermally stable, the spirodimer **299** is not. Upon warming it can undergo some unspecified radical initiation to yield a monobibenzyl radical (**301**) which then attacks another molecule of spirodimer (**299**) to begin a chain-type polymerization being terminated by hydrogen-atom abstraction to yield poly-*o*-xylylene (**303**) (Scheme 70). However, the high isomerization temperature of unsubstituted benzocyclobutene (> 200 °C) renders the investigation of the polymerization of *o*-quinodimethanes difficult, and until recently, detailed studies of the polymerization of substituted oQDM have not been reported.[263−265]

As already mentioned, by introducing an electron-donating methoxy substituent into the cyclobutene ring, the isomerization temperature is effectively lowered, which allows one to study the radical polymerization of substituted oQDMs.

Methoxy-substituted benzocyclobutene is known to isomerize to oQDM at around 100 °C. When this benzocyclobutene derivative is heated at 120 °C in the absence of a radical initiator, no polymer is obtained but instead oligomeric products including dimers are found. At a temperature above 90 °C in the presence of a radical initiator, in the bulk, poly(1-methoxy-*o*-quinodimethane) (**304**) is obtained as a MeOH-insoluble polymer. Below 80 °C, no polymer is found.[263] The highest yield of polymer is observed at 110 °C in a range from 90 to 140 °C. Besides the necessity of a radical initiator, the temperature dependence of the polymerization suggests that the polymerization is a monomer isomerization polymerization. Thus, the mechanism proposed for the polymerization involves first isomerization of the benzocyclobutene derivative to the corresponding oQDM derivative (**I**) and second attack of the radical initiator to a methylene group of **I**. The formed radical species (**II**) will transfer to the benzyl position via aromatization, and the radical species successive attack to the next monomer afford the polymer (Scheme 71). Side reactions are thought to be the self-Diels−Alder reaction, which, together with oligomers, generated the *cis*-1,2-dimethoxy dimer, which could be isolated and characterized.

Scheme 71



Further studies have proved that this new type of radical polymerization can be applied successfully to the copolymerization with different vinyl monomers.[264] Thus, radical copolymerization of methoxy-substituted benzocyclobutene with different vinyl monomers at 120 °C by using di-*tert*-butyl peroxide (DTBP) as an initiator has been reported to yield the corresponding polymeric materials (**306**) (Scheme 71). On the other hand, treatment of poly(1-alkoxy-*o*-quinodimethane) (**304**) with *p*-toluenesulfonic acid monohydrate (10%) results in poly(*o*-phenylenevinylene) (**305**) quantitatively.[263,264] Therefore, benzocyclobutenes can be also used as building blocks for the preparation of conjugated polymers, these types of materials having gained extraordinary interest because of their electrooptic properties.[266,267]

B. Polymerization of Benzocyclobutene Monomers Containing Sites of Unsaturation

The propensity for the oQDM to function as a diene in the Diels–Alder reaction has led to a second type of polymerization of these compounds. Several monomers have been prepared in which α,*β*-disubstituted alkenes have been attached to the benzocyclobutene moiety and serve as dienophilic sites.[257,258] Monomers of this sort are often termed AB monomers to represent their dual and mutually interactive functional groups.

Although there are many examples of AB monomers in the polymer literature,[268] there are several practical problems associated with this type of synthesis, especially when the Diels–Alder reaction is involved in the polymer synthesis. In general, these reactive monomers containing a diene and a dienophile are difficult to store without some partial degree of oligomerization. On the other hand, if the diene or the dienophile is not very reactive under moderate conditions, then low molecular weight polymers are obtained while the use of more stringent conditions for the polymerization may lead to the retro-Diels–Alder reaction and side reactions can become more important.[253]

Thus, the use of benzocyclobutene as the source of the diene in a Diels–Alder polymerization offers a solution to the problems described above provided that benzocyclobutene-containing monomers can be stored indefinitely at room temperature, and it is only upon heating to temperatures close to 200 °C that the reactive diene, oQDM, is formed.

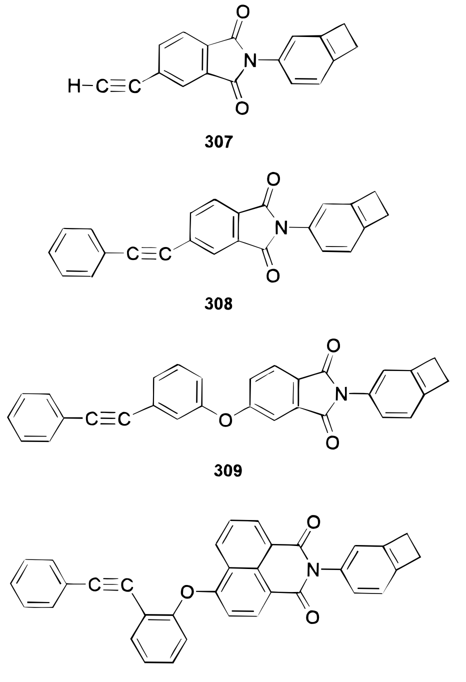
The most common dienophiles that have been successfully used in the formation of polymers from AB-type benzocyclobutene monomers have been acetylenes, olefins, and maleimides.[253]

In Figure 13 some representative examples of benzocyclobutene–acetylene-containing monomers (**307**–**310**) are shown.

Although there is a reasonable amount of data concerning the synthesis of these acetylenic benzocyclobutene imide monomers, little characterization has been performed on the resulting homopolymers.[269]

A second class of AB benzocyclobutene monomers and polymers are those derived from the reaction of benzocyclobutene with a double bond contained within the same molecule.[270,271] Some representative examples of these types of compounds (**311**–**312**) are depicted in Figure 14.

One recent example of polymerization of these types of compounds has been reported by Hahn and co-workers. They studied the polymerization chemistry of stilbene-containing benzocyclobutene monomers (**311a**) in order to obtain poly(tetrahydronaphthalene)s (**313**).[254] As expected, the dominant mode of polymerization is the Diels–Alder reaction of the *trans*-α,*β*-disubstituted olefin with the intermediate



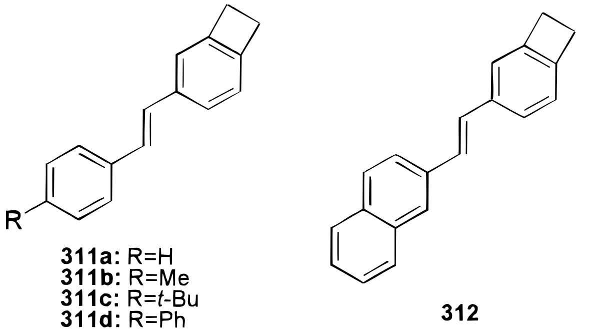
307

308

309

310

Figure 13. Selected examples of benzocyclobutene−acetylene-containing monomers used for the preparation of AB-type polymers.

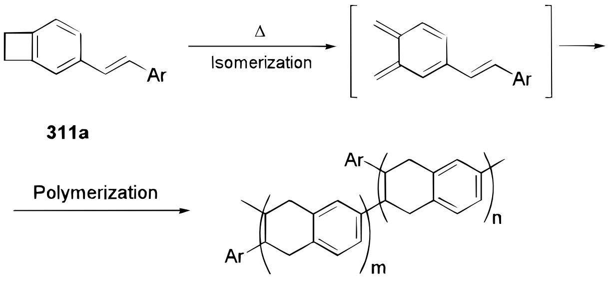


311a: R=H
311b: R=Me
311c: R=*t*-Bu
311d: R=Ph

312

Figure 14. Selected examples of vinyl-containing benzocyclobutene monomers used for the preparation of AB-type polymers.

Scheme 72



311a

313

oQDM which arises from the thermally-induced isomerization of the benzocyclobutene functionality (Scheme 72).

The rate-limiting step of the reaction is the ring-opening rearrangement of the benzocyclobutene ring which is followed by a relatively rapid Diels−Alder reaction.[254]

The third important type of AB monomers containing benzocyclobutene rings are those containing maleimide end groups which form substantially linear homopolymers.

Similar to the other AB monomers, the homopolymer-forming reaction involves the generation of an oQDM from the benzocyclobutene moiety followed by Diels−Alder reaction with the double bond of the maleimide moiety of a second monomer. These types of polymers have been extensively investigated by researchers at both the University of Dayton Research Institute and the Dow Chemical Co. Some representative examples of these cyclobutene AB monomers containing maleimide units (**314**−**321**) are shown in Figure 15.[272−274]

For a complete discussion on the synthesis, thermal stability, and reactivity of all these AB monomers in a Diels−Alder reaction as well as on the study of the solid-state properties of the polymers obtained, we refer the reader to the excellent comprehensive review article of Kirchhoff and Bruza.[253]

C. Polymeric Materials with Pendant Benzocyclobutene Groups

Generally, the most commonly reported alkenylbenzocyclobutene monomers are those represented in Figure 16 where the alkenyl moiety is a terminal vinyl group.

When $n = 0$ in **322**, the monomer in Figure 16 is the styrene analogue, 4-vinylcyclobutene, which is the only reported example of a benzocyclobutene with a vinyl group directly attached to the aromatic ring.[270,275] 4-Vinylbenzocyclobutene has been homo- and copolymerized by free radical and anionic methods and behaves very much like styrene.[253,276] Another alkenyl benzocyclobutene that has been extensively used in various polymer-forming applications is 4-(4-benzocyclobutenyl)-1-butene (**322**, $n = 2$).[277] It has been used in a variety of Ziegler−Natta-type polymerizations with simple α-monoolefins such as ethylene, propylene, or 4-methyl-1-pentene.[277]

In the most useful examples, these monomers possess a dual yet independent reactivity in that they can be polymerized through the alkene group in a way that leaves the benzocyclobutene ring intact.[253] These monomers are very interesting provided that they offer the possibility to synthesize polymers capable of undergoing Diels−Alder reactions.

Thus, Chino and co-workers recently reported on the synthesis of poly(4-vinylbenzocyclobutene) (**323**) which undergoes efficient Diels−Alder reaction with dienophiles to give quantitative conversion to the corresponding polymeric adducts (**325**)[278] (Scheme 73a). As the reaction conditions for the benzocyclobutene ring opening were somehow slightly severe (>200 °C), the same authors have reported in 1999 the synthesis of novel reacting polymers [poly(1-benzocyclobutenyl vinyl ether)] in which the presence of the electron-donating ether group linked to the benzocyclobutene moiety lowers the isomerization temperature to oQDM (Scheme 73b).[279]

Benzocyclobutene polymer **327** was obtained quantitatively by cationic polymerization in the presence of $BF_3 \cdot Et_2O$ as an initiator at −78 °C for 2 h in toluene. The spectral data indicate that the polymerization proceeds via a simple vinyl polymerization.

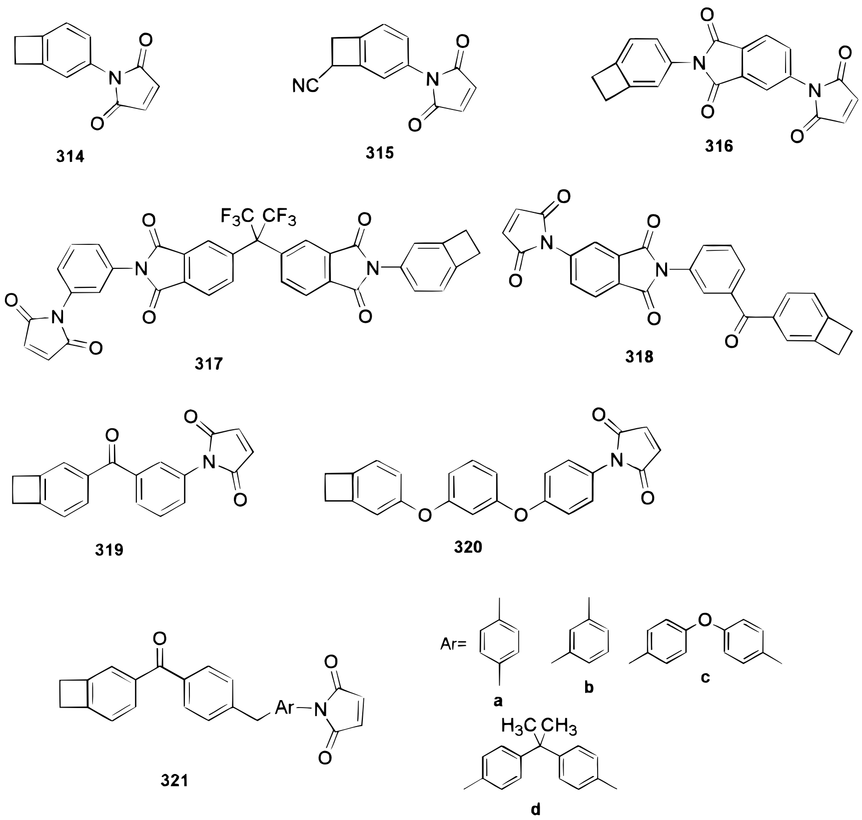


Figure 15. Selected examples of cyclobutene AB monomers endowed with maleimide units.

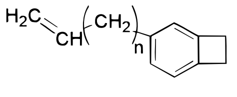


Figure 16. Alkenylbenzocyclobutene monomers are useful starting materials for the synthesis of polymers bearing pendant benzocyclobutene groups.

The isomerization temperature of **327** was found to be about 75 °C. When **327** was heated at 60 °C for 12 h in the absence of a dienophile, a cross-linking polymer was formed, probably by the intermolecular reaction of the benzocyclobutene moieties in the side chain. In the presence of maleic anhydride (**6**), the corresponding adduct polymer was obtained. The degree of incorporation of maleic anhydride and the yield of the adduct increased with the temperature. The reaction above 120 °C completely afforded the adduct polymer (**329**, $n = 0$). The reaction of **327** with *N*-phenylmaleimide (MI, **199**) at 120 °C could not afford a Diels−Alder adduct because MI predominantly undergo thermal polymerization.[280] To prevent the homopolymerization of MI, the Diels−Alder reaction of **327** with MI was performed in the presence of 4-*tert*-butylcathecol (1 mol %) as a radical inhibitor. Thus, the polymerization of MI could be inhibited to give the corresponding adduct polymer (**330**, $m = 0$).

On the other hand, by treatment of the adduct polymer having benzocyclobutene moieties (**329**, $n \neq 0$) with MI, adduct polymer **330** ($m,n \neq 0$) could be obtained.

While prepolymer **327** is soluble in most solvents such as benzene and THF, the Diels−Alder adduct polymers were highly insoluble.

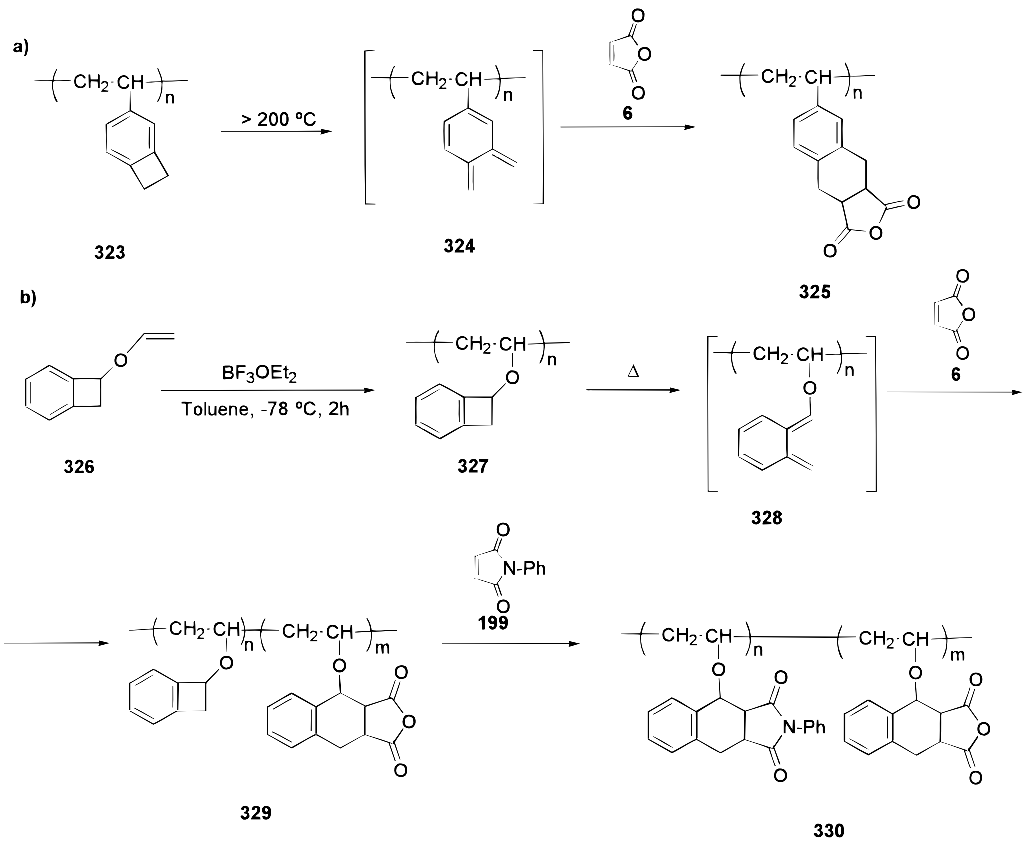
D. Polymerization of Bisbenzocyclobutenes with Molecules Containing Two Sites of Reactive Unsaturation

Bisbenzocyclobutenes (**331**) readily react with molecules which contain two sites of reactive unsaturation such as bismaleimides (**333**) to give the corresponding polymeric materials (**334**) (Scheme 74).[272a,281] This is, in essence, a type of Diels−Alder polymerization in which the bisdiene is latently embodied within two benzocyclobutene moieties. A great amount of work has been devoted to the study of this specific type of polymerization reaction. It is, however, out of the scope of the present review to give a comprehensive overview on the synthesis and applications of bisbenzocyclobutene provided that Kirchhoff and Bruza have summarized in a recent review article this type of polymerization reaction[253] and Farona has reviewed the preparation of monomeric units containing two benzocyclobutene groups.[8] Therefore, the reader is referred to these excellent review articles for a complete coverage of the field.

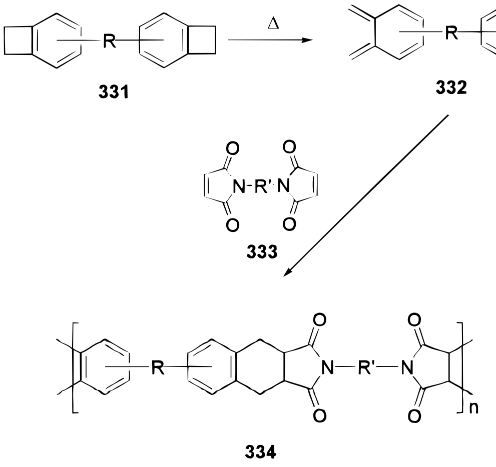
E. Polymerization of *o*-Quinodimethanes Generated from Precursors Different from Benzocyclobutene

The photochemical generation of oQDMs has also been used to synthesize polymeric materials. Meador and co-workers reported on the syntheses of polyimides by using oQDM generated photochemically from the corresponding *o*-methylphenyl ketone.[282] 2,5-Dibenzoyl-*p*-xylene (**335**) upon photolysis produces two photoenol moieties that can each undergo Diels−Alder cycloadditions.[283] Thus, photolysis of **336** in the

Scheme 73



Scheme 74



presence of bismaleimide (**337**) and *N*-phenylmaleimide (**199**) provide polyimides such as **338** (Scheme 75). By varying the stoichiometries of these reactants, polyimides with different *n* values may be obtained and in subsequent steps are converted into the corresponding anthryl systems **339**. This route offers a photochemical alternative to traditional thermal cures used in the preparation of polyimide thin films for electronics packaging and optical applications.

The photochemical generation of oQDMs has been recently used for the syntheses of random copolymers through Diels–Alder reaction of oQDM with unsaturated polymers. Thus, *o*-tolualdehyde (**61a**) reacts with the double bonds of polybutadiene (**340**) under photolytic conditions, changing the homopolymer into a random copolymer (**341**) (Scheme 76). By using molecules containing two *o*-tolualdehyde functionalities (**342**), the corresponding cross-linked products (**343**) are obtained.[284]

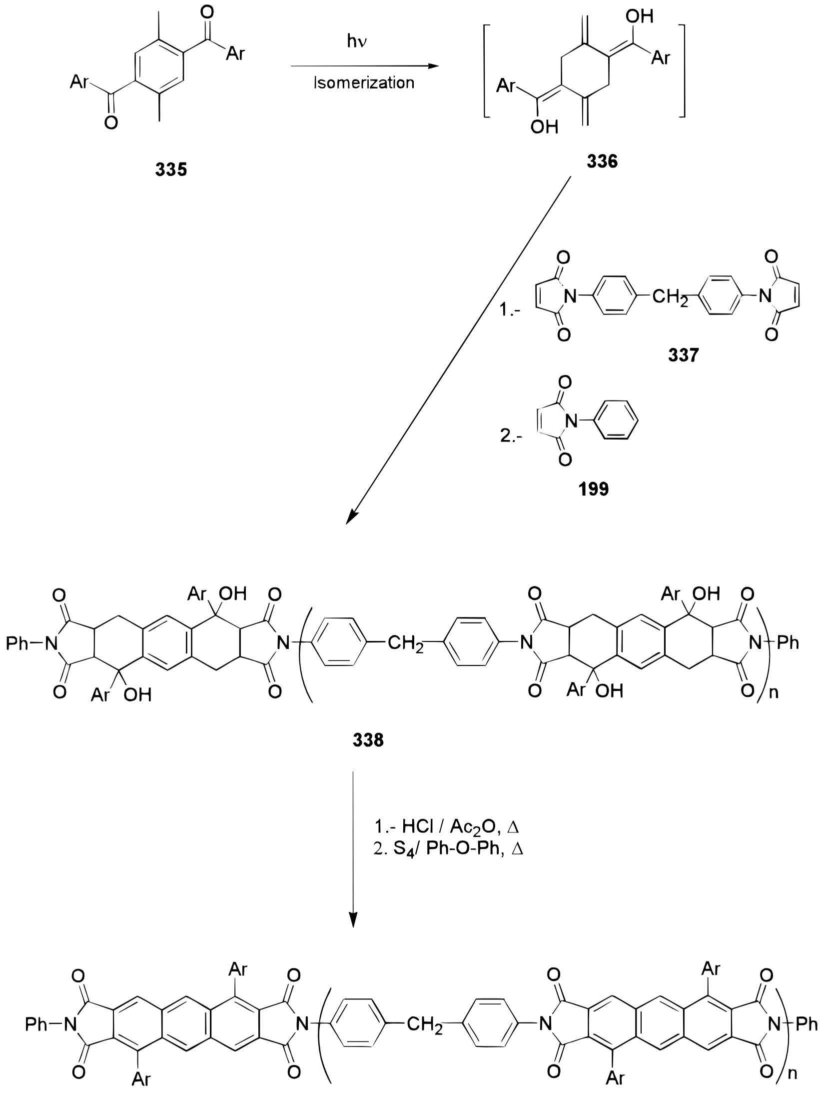
F. Fullerenes and Polymer Chemistry

Incorporation of C_{60} into a polymer has been recognized as a simple means of combining the unique properties of C_{60} with macromolecular characteristics such as mechanical strength and good processability.[285,286] Furthermore, the application of fullerenes (e.g., as catalyst or stationary phase) often requires their immobilization, and this can be attained, in principle, in two ways: either by admixing of [60]fullerene to a polymer (noncovalent immobilization) or by linking either C_{60} or C_{60} derivatives covalently to a carrier polymeric material. The latter may be advantageous in cases where (i) the fullerene unit should be more strongly bound, (ii) heterogeneous mixtures of [60]fullerene and the polymer tend to undergo phase separation, or (iii) a precise tuning of the material properties is desirable.[287] According to the type of covalent connection of the fullerene units in the polymer, a distinction can be made between main-chain polymers (in chain, "polyfullerene"),[288] side-chain polymers (on-chain, "polymer bound"),[289] and dendrimers[290] (Figure 17).

o-Quinodimethanes have also played a role in the development of new C_{60}-containing polymeric materials both as pendant groups and as a part of the main chain.

In principle, the construction of main-chain polymers is possible by repetitive cycloaddition of [60]-

Scheme 75



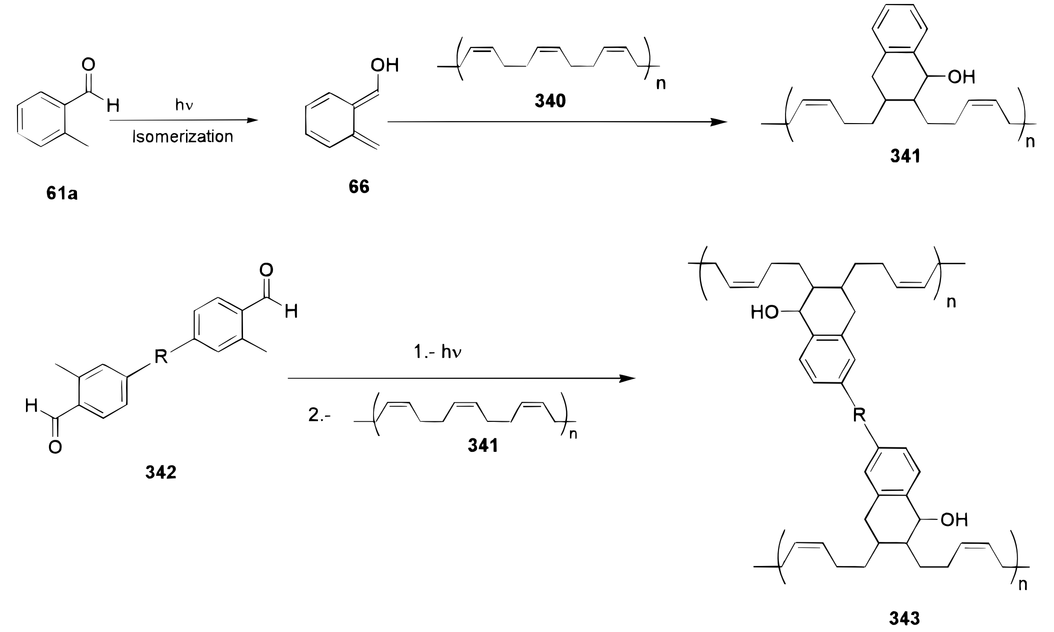
fullerene, which acts as a multifunctional dienophile, with a bis-*o*-quinodimethane (**345**) (Scheme 77).[287] Flexible, solubilizing hexyloxy chains are introduced on the bis-*o*-quinodimethane precursor (**344**) in order to increase the solubility of the polymer after cycloaddition. Thus, when the bis-*o*-quinodimethane precursor (**344**) was treated with an equimolecular amount of C_{60} in refluxing 1,2,4-trichlorobenzene, after 20 h reaction, a soluble mixture of the oligomer **346** ($n = 0-5$) was formed. Comparison of the solubility of the various oligomers reveals noteworthy differences. While the "higher" oligomers remain dissolved for an unlimited period in chloroform, the "dumbbell compound" (**346**, $n = 0$) precipitates and it could be only redissolved in halogenated aromatic solvents.

When the oligomeric mixture obtained from the above reaction was further treated with an additional equivalent of bis-sulfone (**344**), an insoluble product was obtained. This result was due to multiple additions to the fullerene core which lead to cross linking.

In additions of oQDMs to [60]fullerene, the tris-adducts are easily formed whereas the tetrakis adducts are not. Therefore, when the polymerization reaction is carried out with a mixture of the monosulfone (**347**) and the bisdiene precursor (**344**), the cross linking is effectively suppressed, thus allowing preparation of soluble polymers (**348**)[287] (Scheme 78). Thus, the molecular weight was increased by using a **347**/**344** mixture (7:3) and soluble polymers with molecular weights on the order of 34 000 (M_w) and 7200 (M_n) are obtained. As a consequence of the high solubility of this polymer, it is possible to prepare thin amorphous films by spin coating which are of great importance in order to study the solid-state properties of these materials.

There are also examples of polymeric materials containing fullerene units as pendant groups. As we have seen previously, a common strategy to introduce the oQDM functionality as a pendant group in polymeric materials involves the introduction of benzocyclobutene-containing monomers through copolymerization with vinyl monomers. Thus, free radical polymerization of the benzocyclobutenone-containing monomer (**349**) and styrene in different feed ratios afforded the copolymers **350** (Figure 18).

Scheme 76



The C_{60}-containing polymers **351** may be readily obtained from the reaction of C_{60} and **350** in refluxing 1,2-dichlorobenzene.[291] GPC analysis indicates that the weight-average molecular weight of the C_{60}-containing polymer **351** is slightly higher than those of the polymeric precursor (**350**) and both polymers are monomodal with nearly equal polydispersity indexes. Therefore, a specific 1:1 addition occurred for the precursor polymers. Polymers **351** are readily dissolved at room temperature in many common organic solvents. This solubility behavior is similar to polystyrene but unlike C_{60} itself, demonstrating the advantage of having a polymer-bonded fullerene for improved processability.

[60]Fullerene can also be incorporated into certain polymers by using the benzocyclobutenone group by postpolymerization. Thus, polyethylene-*graft*-maleic anhydride is readily converted to benzocyclobutenone-containing polymer **352** upon imidization with 5-aminobenzocyclobutenone in melt at about 150 °C. Grafting of **352** with an excess of C_{60} may be carried out in refluxing 1,2-dichlorobenzene yielding light brown **353** quantitatively.

This so-called "benzocyclobutenone route" is useful to prepare a variety of benzocyclobutenone-containing polymers by copolymerization with a wide range of vinyl monomers. Furthermore, the amount of C_{60} present in a polymer is dictated by the benzocyclobutenone content in the same polymer, and the latter can be easily controlled through copolymerization or grafting.[291]

VIII. *o*-Quinodimethanes as Nitric Oxide Cheletropic Traps (NOCT)

One of the most interesting and recent applications of *o*-quinodimethanes is their role as a trapping agent for nitric oxide (nitric oxide cheletropic traps, NOCTs).[7]

NO has been identified to be an important cellular messenger molecule in the mammalian body,[292,293] is involved in the regulation of blood pressure, participates in the inhibition of the aggregation of platelets, and plays an active role in the regulation functions of the heart, the muscles, the lung, and the kidney.[7]

For the monitoring and quantitation of $^{\bullet}NO$ formation in biological systems, a number of physicochemical and biochemical analytical methods have been developed.[294] Unfortunately, none of these methods fulfills the desirable requirements for general use with the variety of biological specimens, viz. specific-

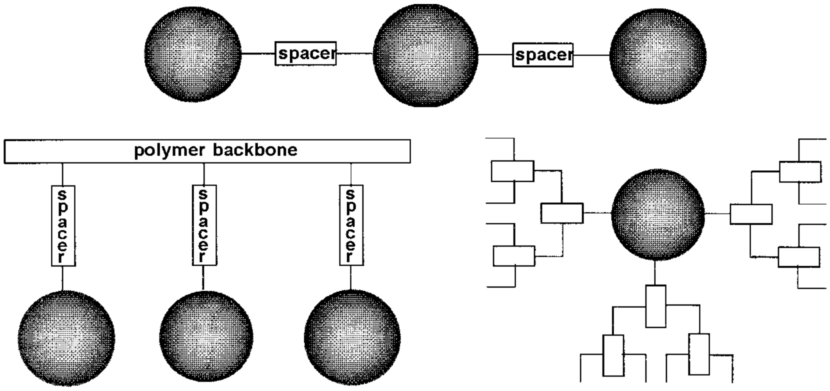
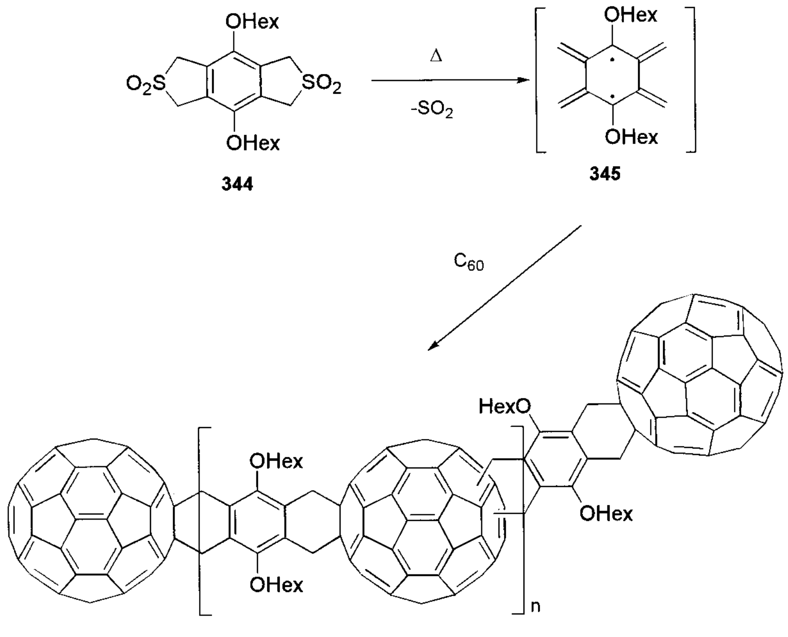


Figure 17. C_{60}-based polymers and dendrimers according to the type of covalent linkage of the fullerene units in the polymer.

Scheme 77

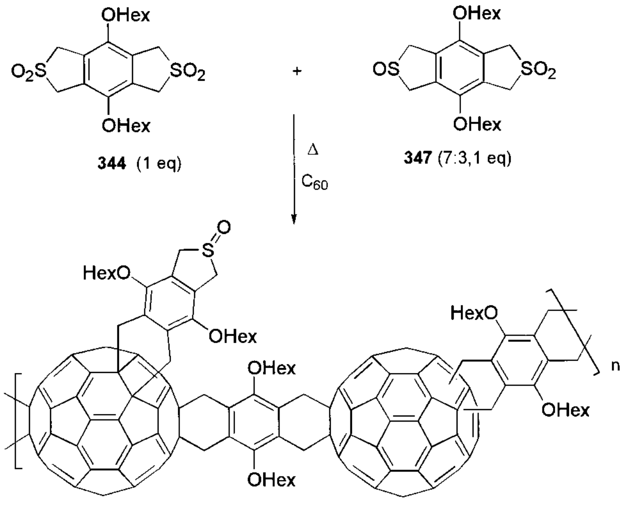


344

345

346

Scheme 78

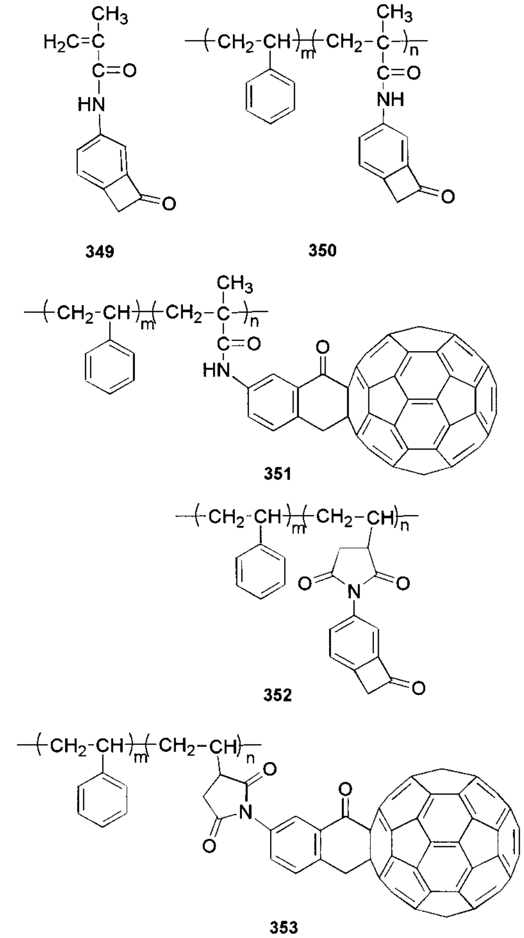


348

ity for $^{\bullet}$NO, high sensitivity, tolerance for the various physiological conditions, easy structural modifications, and the potential to monitor $^{\bullet}$NO formation with temporal and spacial resolution.[295] To overcome some of these difficulties, the most attractive route appeared to be a chemical reaction by which $^{\bullet}$NO could be converted into a persistent nitroxide radical. The latter could be monitored, quantitated, and imaged by electron spin resonance (ESR) spectroscopy, and with this aim, Korth and Sustmann recently developed an alternative method, based on the reaction of NO with oQDM derivatives.[7,295−299]

7,7,8,8-Tetramethyl-*o*-quinodimethane (**355**) seemed likely to meet the foregoing criteria. It reacts efficiently with $^{\bullet}$NO to produce the corresponding 1,1,3,3-tetramethylisoindolin-2-oxyl radical (**356**) (Scheme 79), which is a radical eminently suitable for quantitative ESR measurements since it is completely stable at ambient temperature and can be synthesized as a pure compound.[300]

The scope of the NOCT methodology has been explored by modifying the basic oQDM structure in



349

350

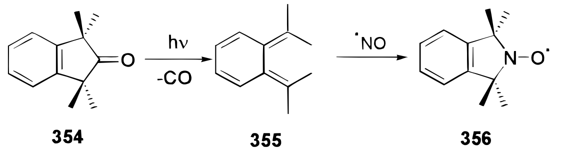
351

352

353

Figure 18. Examples of benzocyclobutenone-containing polymers obtained by "the benzocyclobutenone route".

Scheme 79



order to (i) increase their lifetime by stabilizing the system thermodynamically and/or kinetically by suppression of possible decay reactions, (ii) confer special properties to the NOCTs, such as water-, lipid-solubility or amphilicity, (iii) increase the preparative yield, and (iv) increase the rate of reaction with •NO. In Figure 19 are depicted some prototypical structures of NOCTs that form persistent nitroxide radical on reaction with NO.[7]

An extension of the π-conjugated system produces an increased thermodynamic stabilization of the oQDM structure (**359**) and therefore a higher lifetime of phenyl- (**357**) and indenyl-substituted derivatives (Scheme 80). Additional incorporation of alkoxy substituents particularly increases the lifetime of the NOCTs because no 1,5-H shift process can occur. However, photolysis of the parent ketones (**357**) produced only a low concentration of the NOCTs because the benzocyclobutenes (**358**) were formed as the major products[7] (Scheme 80).

To avoid the different types of thermal decay of oQDMs, derivatives **361** in which the exocyclic double bonds are fixed have been prepared (Scheme 81). These oQDM derivatives exhibit a high thermal stability and produce very intense ESR spectra of nitroxides when reacting with NO.

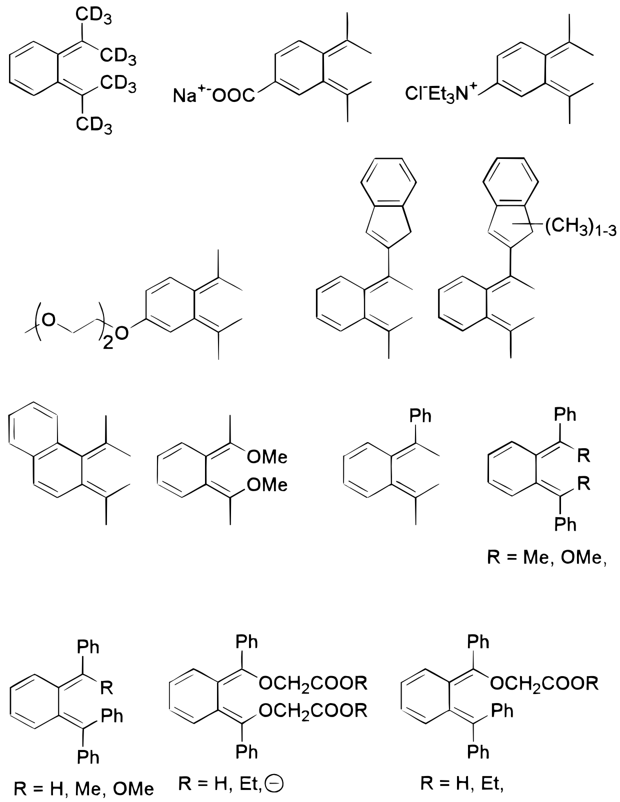
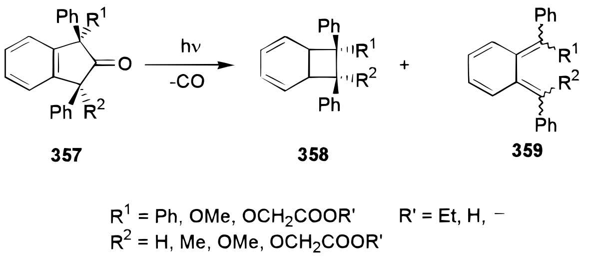
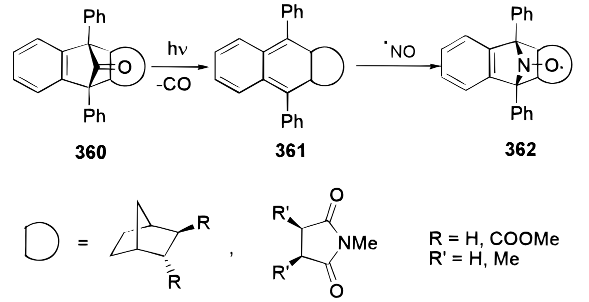


Figure 19. Selected oQDM derivatives used as NOCTs which form persistent nitroxide radicals.

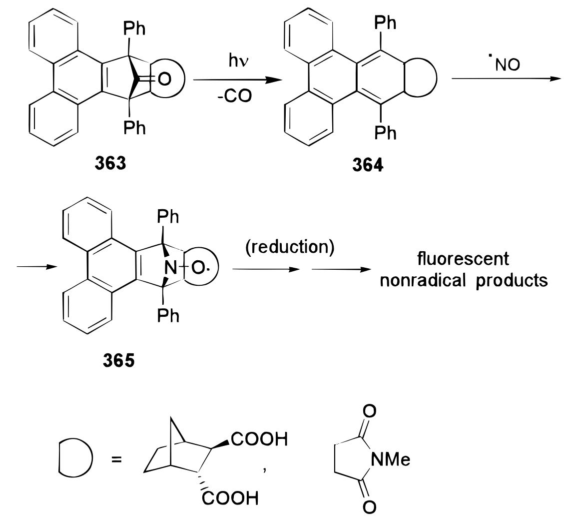
Scheme 80



Scheme 81



Scheme 82



However, the general disadvantage of applying nitroxide radicals in biological environments still lies in their reduced lifetime. Therefore, a new method based on the NOCT concept that uses fluorescence spectroscopy as a sensitive probe for detecting trapped nitric oxide has been developed.[299] The so-called *fluorescent nitric oxide cheletropic traps* (FNOCTs) take advantage of the fact that aromatic π systems (**365**) that are formed by reaction of •NO with suitable selected NOCTs (**364**) exhibit fluorescence properties (Scheme 82). Therefore, the sensitivity is significantly increased over the ESR spectroscopy, and the limited lifetime of the initially formed nitroxide radical is beneficially used.

With the FNOCTs, the trapping of •NO can be monitored independently by three sensitive spectroscopic methods: the formation of the radicals can be observed by ESR spectroscopy, the decay of oQDM can be followed by UV−Vis spectroscopy, and fluorescence spectroscopy monitors the formation of the nitroxides as well as their degradation products.[297]

Although oQDMs have played an important role in this field, for a more exhaustive and general study on this specific topic, the reader is referred to a recent review article on this field by Korth and Sustmann.[7]

IX. Summary and Perspectives

Since the last review article devoted to oQDMs almost a decade ago,[2] the interest of these reactive intermediates and the prospects for useful applications in organic synthesis has increased drastically. The aim of the present review has been to illustrate the fact that oQDMs offer a wide scope as an efficient intermediate in a variety of different fields running from the theoretical interest to practical applications within, for example, the chemistry of polymers or as nitric oxide cheletropic traps.

Although great effort has been dedicated to the thermal generation of oQDMs in the past years, recent major advances have been concerned with the photochemical as well as the electrochemical generation procedures. Both procedures exhibit some interesting advantages over the thermal method, leading to the oQDMs under milder experimental conditions, thus opening up their applications in organic synthesis. In this regard, electrogenerated oQDMs have a radical-like reactivity which can be efficiently used as a powerful tool in electropolymerization processes for the preparation of useful electroactive polymers such as poly(*o*-phenylenevinylene) or poly-*o*-xylylene. Microwave irradiation has also been successfully used in the generation of oQDMs from sultines. An interesting accelerating microwave effect leading to oQDMs in higher yields in shorter times has been observed. These findings are of particular interest for the generation of oQDMs in the presence of molecules which can decompose under long heating periods of time, and therefore, this approach deserves to be studied in depth on other precursors of oQDMs.

Heterocyclic oQDMs are currently being intensively studied and are of interest in the preparation of biologically active compounds. Although a wide variety of heterocyclic oQDMs have already been synthesized, more work is needed for the development of more general synthetic strategies for the generation of these intermediates which are usually prepared by following particular synthetic procedures.

The versatility of oQDMs as synthetic intermediates has been classified according to their applicability in different fields. oQDMs have been used from the very beginning in the chemistry of natural products, and some recent examples presented in this article indicate the vitality of these intermediates in the inter- and intramolecular asymmetric synthesis of biologically active compounds. Due to the extensive literature on this topic, it is out of the scope of this review and the reader has been referred to other excellent specialized works.

One of the most recent and appealing applications of oQDMs has been in the emerging chemistry of fullerenes. oQDMs have proved to be efficient intermediates for the functionalization of fullerenes, forming thermally stable cycloadducts which are able to undergo further chemical transformations in the search of optical, electric, or magnetic properties. Interestingly, modified fullerenes derived from heterocyclic oQDMs have also been prepared in the quest for biological and pharmacological properties. oQDMs have been successfully used as useful synthetic tools in the design of different C_{60}-based electroactive dyads which mimic the photosynthetic process. This is an outstanding and realistic application of organic materials for the preparation of plastic solar cells constituted by polymers and modified fullerenes in the search for alternative energy resources.

Another recent and promising utility of oQDMs is the selective functionalization of fullerenes. Selective bis-addition of oQDM to C_{60} has been accomplished by using the tether-directed remote functionalization which represents one of the most capable approaches for the bis-functionalization of fullerenes.

oQDMs have thus played a very important role in the functionalization of C_{60}, and this trend will be followed in the future for the modification of higher fullerenes. The stability of the formed cycloadducts from oQDMs and C_{60} is of great interest in the preparation of optoelectronic devices with practical applications.

Although oQDMs have also found application for the synthesis of electron-donor and -acceptor species, their applicability in this field has been sporadic and seems to be restricted to a few relevant cases.

oQDMs have a striking usefulness in the chemistry of polymers, and a large number of recent papers have dealt with this matter. Different polymeric materials have been easily prepared by thermally initiated polymerization of monomers based on benzocyclobutenes. We have classified the different polymers synthesized depending upon the nature of the substitution pattern of the benzocyclobutene monomers involved in the polymerization process. Although oQDMs have also been photochemically generated by precursors other than benzocyclobutene, for the synthesis of polymers, most of the reported polymerization processes based on oQDMs have been carried out from substituted benzocyclobutenes.

A very promising field of applicability of oQDMs has been found in the combination of C_{60} with the polymer chemistry, and relevant examples in which C_{60} is placed as a pendant group or as a part of the main polymeric chain have been presented. Although these systems have not yet found a practical application, the development of known efficient methodologies for the chemical modification of fullerenes has opened up new perspectives in this field.

Nitric oxide cheletropic traps (NOCT) represent an outstanding and practical application of oQDMs which efficiently react with nitric oxide to produce a persistent radical that can be monitored by spectroscopic methods. The monitoring and quantitation of nitric oxide formation in biological systems is of great interest due to the role that $^{\bullet}$NO plays as an important cellular messenger, and oQDMs have proved to be useful intermediates for the trapping of this molecule.

In summary, oQDMs maintain a strong presence in organic synthesis, both from generation and application points of view. Theoretical aspects as well as practical purposes of oQDMs will be thus an issue for discussion in the coming years.

X. Acknowledgments

We thank all the people of our research group who have enthusiastically collaborated in the search of these fascinating intermediates and whose names are cited in the references. We also thank the DGICYT of Spain (Project PB95-0428-CO2) for financial support. This work is dedicated to Professor José L. Soto on the occassion of this 70th anniversary.

XI. References and Notes

(1) Cava, M. P.; Napier, D. R. *J. Am. Chem. Soc.* **1957**, *79*, 1701.
(2) For the last general review on oQDMs, see: Martín, N.; Seoane, C.; Hanack, M. *Org. Prep. Proc. Int.* **1991**, *23*, 237.
(3) (a) Chou, T. S. *Rev. Heteroatom. Chem.* **1993**, *8*, 65. (b) Collier, S. J.; Storr, R. C. In *Progress in Heterocyclic Chemistry*; Gribble, G. W., Gilchrist, T. L., Eds.; Pergamon: New York, 1998; Vol. 10, pp 25–48.
(4) Nemoto, H.; Fukumoto, K. *Tetrahedron* **1998**, *54*, 5425 and references therein.
(5) Eguchi, S.; Ohno, M.; Kojima, S.; Koide, N.; Yashiro, A.; Shirakawa, Y.; Ishida, H. In *Recent Advances in the Chemistry of Fullerenes and Related Materials*, *Proceedings of the Electrochemical Society;* 1996, Vol. 3, p 1233.
(6) Martín, N.; Sánchez, L.; Illescas, B.; Pérez, I. *Chem. Rev.* **1998**, *98*, 2527.
(7) Korth, H. G.; Sustmann, R. In *Free Radicals in Biology and Environment*; NATO ASI Series 3, 1997; Vol. 27, pp 331–349.
(8) Farona, M. F. *Prog. Polym. Sci.* **1996**, *21*, 505.
(9) Martín, N.; Hanack, M. *J. Chem. Soc., Chem. Commun.* **1988**, 1522.
(10) Utley, J. H. P. *Acta Chem. Scand.* **1998**, *52*, 237.
(11) Fujiwara, M.; Mishima, K.; Tamai, K.; Tanimoto, Y.; Mizuno, K.; Ishii, Y. *J. Phys. Chem. A* **1997**, *101*, 4912.
(12) Fishwick, C. W. G.; Jones, D. W. In *The Chemistry of Quinonoid Compounds*; Patai, S., Rappoport, Z., Eds; John Wiley & Sons Ltd.; New York, 1988, Vol. 2, pp 403–453.
(13) (a) Roth, W. R.; Biermann, M.; Dekker, H.; Jochems, R.; Mosselman, C.; Hermann, H. *Chem. Ber.* **1978**, *111*, 3892. (b) Roth, W. R.; Scholz, B. P. *Chem. Ber.* **1981**, *114*, 3741.
(14) (a)Münzel, N.; Schweig, A. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 471. (b) Houk, K. N.; Li, Y.; Evanseck, J. D. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 682.
(15) Roth, W. R.; Ebbrecht, T.; Beitat, A. *Chem. Ber.* **1988**, *121*, 1357.
(16) (a) Flynn, C. R.; Michl, J. *J. Am. Chem. Soc.* **1974**, *96*, 3280. (b) Baird, N. C. *J. Am. Chem. Soc.* **1972**, *94*, 4941. (c) Roth, W. R.; Biermann, M.; Erker, G.; Jelich, K.; Gerhartz, W.; Górner, H. *Chem. Ber.* **1980**, *113*, 586. (d) Roth, W. R.; Scholz, B. P. *Chem. Ber.* **1982**, *115*, 1197. (e) Lahti, P. M.; Rossi, A. R.; Berson, J. A. *J. Am. Chem. Soc.* **1985**, *107*, 2273**.** (f) Roth, W. R.; Adamczak, O.; Breuckmann, R.; Lennartz, H.-W.; Boese, R. *Chem. Ber.* **1991**, *124*, 2499.
(17) Flynn, C. R.; Michl, J. *J. Am. Chem. Soc.* **1973**, *95*, 5802.
(18) Migirdicyan, E.; Baudet, J. *J. Am. Chem. Soc.* **1975**, *97*, 7400.
(19) Tseng, K. L.; Michl, J. *J. Am. Chem. Soc.* **1977**, *99*, 4840.
(20) McCullough, J. J. *Acc. Chem. Res.* **1980**, *13*, 270.
(21) Kametani, T.; Honda, T.; Ebisawa, Y.; Ichikawa, H. *Tetrahedron* **1985**, *41*, 3643.
(22) (a) Chou, C. H.; Trahanovsky, W. S. *J. Am. Chem. Soc.* **1986**, *108*, 4138. (b) Trahanovsky, W. S.; Macias, J. R. *J. Am. Chem. Soc.* **1986**, *108*, 6820.
(23) Doering, W. V. E.; Roth, W. R.; Breuckmann, R.; Figge, L.; Lennartz, H.-W.; Fessner, W.-D.; Prinzbach, H. *Chem. Ber.* **1988**, *121*, 1.
(24) Roth, W. R.; Rekowski, V.; Börner, S.; Quast, M. *Liebigs Ann.* **1996**, 409.
(25) Paul, T.; Boese, R.; Steller, I.; Bandmann, H.; Gescheidt, G.; Korth, H.-G.; Sustmann, R. *Eur. J. Org. Chem.* **1999**, *551*, 1.
(26) Miranda, M. A.; Pérez-Prieto, J.; Font-Sanchis, E.; Scaiano, J. C. *Chem. Commun.* **1998**, 1541.
(27) Miller, R. D.; Kolc, J.; Michl, J. *J. Am. Chem. Soc.* **1976**, *98*, 8510.
(28) McMahon, R. J.; Chapman, O. L. *J. Am. Chem. Soc.* **1987**, *109*, 683.
(29) Scaiano, J. C.; Wintgens, V.; Netto-Ferreira, J. C. *Pure Appl. Chem.* **1990**, *62*, 1557.
(30) Ilic, P.; Trinajstic, N. *J. Org. Chem.* **1980**, *45*, 1738.
(31) Bauld, N. L.; Cessac, J.; Chang, C.-S.; Farr, F. R.; Holloway, R. *J. Am. Chem. Soc.* **1976**, *98*, 4561.
(32) Lorenz, M.; Clark, T.; von Ragué Schleyer, P.; Neubauer, K.; Grampp, G. *J. Chem. Soc., Chem. Commun.* **1992**, 719.
(33) Grützmacher, H.-F.; Barkow, A. *Acta Chem. Scand.* **1997**, *51*, 619.
(34) Kreile, J.; Münzel, N.; Schulz, R.; Schweig, A. *Chem. Phys. Lett.* **1984**, *108*, 609.
(35) Bouchoux, G.; Salpin, J.-Y. *Rapid Commun. Mass Spectrom.* **1994**, *8*, 325.
(36) Oppolzer, W. *Synthesis* **1978**, 793.
(37) Charlton, J. L.; Alauddin, M. M. *Tetrahedron* **1987**, *43*, 2873.
(38) Klundt, I. L. *Chem. Rev.* **1970**, *70*, 471.
(39) Wong, H. N. C.; Lau, K. L.; Tam, K. F. *Topics in Current Chemistry*; Meijere, A., Ed.; Springer: Berlin, 1986; Vol. 133, pp 124–130.
(40) Kametani, T.; Tsukubi, M.; Shiratori, Y.; Kato, Y.; Nemoto, H.; Ihara, M.; Fukumoto, K.; Satoh, F.; Inoue, H. *J. Org. Chem.* **1977**, *42*, 2672.
(41) Arnold, B. J.; Sammes, P. G.; Wallace, T. W. *J. Chem. Soc., Perkin Trans 1* **1974**, 409.
(42) Choy, W.; Yang, H. *J. Org. Chem.* **1988**, *53*, 5796.
(43) Kametani, T.; Tsubuki, M.; Nemoto, H.; Suzuki, K. *J. Am. Chem. Soc.* **1981**, *103*, 1256.
(44) (a) Niwayama, S.; Kallel, E. A.; Spellmeyer, D. C.; Sheu, C.; Houk, K. N. *J. Org. Chem.* **1996**, *61*, 2813. (b) Jefford, C. W.; Bernardinelly, G.; Wang, Y.; Spellmeyer, D. C.; Buda, A.; Houk, K. N. *J. Am. Chem. Soc.* **1992**, *114*, 1157. (c) Kshirsagar, T. A.; Portoghese, P. S. *J. Org. Chem.* **1998**, *63*, 1706.
(45) (a) Huisgen, R.; Seidl, H. *Tetrahedron. Lett.* **1964**, 3381. (b) Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 2099.
(46) Shimada, S.; Osoda, K.; Narasaka, K. *Bull. Chem. Soc. Jpn.* **1993**, *66*, 1254.
(47) (a) Schiess, P.; Heitzmann, M. *Tetrahedron Lett.* **1978**, 4569. (b) Trahanovsky, W. S.; Turner, B. W. *J. Am. Chem. Soc.* **1985**, *107*, 4995.
(48) (a) Moss, R. J.; Rickborn, B. *J. Org. Chem.* **1984**, *49*, 3694. (b) Naito, K.; Rickborn, B. *J. Org. Chem.* **1980**, *45*, 4061. (c) Smith, J. G.; Dibble, P. W. *J. Org. Chem.* **1983**, *48*, 5361. (d) Moss, R. J.; Rickborn, B. *J. Org. Chem.* **1986**, *51*, 1992.
(49) Tuschka, T.; Naito, K.; Rickborn, B. *J. Org. Chem.* **1983**, *48*, 70
(50) (a) Alder, K.; Fremery, M. *Tetrahedron* **1961**, *14*, 190. (b) Moss, R. J.; Rickborn, B. *J. Org. Chem.* **1986**, *51*, 1992. (c) Ito, Y.; Nakatsuka, M.; Saegusa, T. *J. Am. Chem. Soc.* **1980**, *102*, 863. (d) Han, B. H.; Boudjouk, P. *J. Org. Chem.* **1982**, *47*, 751. (e) McOmie, J. F. W.; Parry, D. H. *Synthesis* **1973**, 416. (f) Stephan, D.; Gorgues, A.; Le Coq, A. *Tetrahedron Lett.* **1984**, *25*, 5649. (g) Rubottom, G. M.; Wey, J. E. *Synth. Commun.* **1984**, *14*, 507. (h) Ito, Y.; Yonezawa, K.; Saegusa, T. *J. Am. Chem. Soc.* **1974**, *39*, 2769.
(51) Chew, S.; Ferrier, R. J. *J. Chem. Soc., Chem. Commun.* **1984**, 911.
(52) (a) Jensen, F. R.; Coleman, W. E. *J. Am. Chem. Soc.* **1958**, *80*, 6149. (b) Wiseman, J. R.; Pendery, J. J.; Otto, C. A.; Chiong, K. G. *J. Org. Chem.* **1980**, *45*, 516.
(53) (a) Ito, Y.; Amino, Y.; Nakatsuka, M.; Saegusa, T. *J. Am. Chem. Soc.* **1983**, *105*, 1586. (b) Ito, Y. *Current Trends in Organic Synthesis*; Nozaki, N., Ed.; Pergamon Press: New York, 1982; pp 169–175.
(54) Ohtsuka, H.; Migita, T. *J. Am. Chem. Soc.* **1988**, *110*, 2014.
(55) (a) Maeda, Y.; Sato, Y. *J. Org. Chem.* **1996**, *61*, 5188. (b) Maeda, Y.; Sato, Y. *Chem. Pharm. Bull.* **1998**, *46*, 508.
(56) (a) Woo, S. H. *Tetrahedron Lett.* **1993**, *34*, 7587. (b) Sano, H.; Kawata, K.; Kosugi, M. *Synlett.* **1993**, 831. (c) Sano, H.; Mashio, H.; Nakayama, T.; Kosugi, M. *Tetrahedron Lett.* **1996**, *49*, 8891.
(57) (a) Lenihan, B. D.; Shechter, H. *Tetrahedron Lett.* **1994**, *35*, 7505. (b) Lenihan, B. D.; Shechter, H. *J. Org. Chem.* **1998**, *63*, 2072. (c) Lenihan, B. D.; Shechter, H. *J. Org. Chem.* **1998**, *63*, 2086.
(58) Hartke, K.; Bien, N.; Massa, W.; Wocadlo, S. *Liebigs Ann.* **1996**, 1159.
(59) Carpino, L. A. *J. Org. Chem.* **1969**, *34*, 461 and references therein.
(60) Oppolzer, W. *Heterocycles* **1980**, *14*, 1615.
(61) (a) Spangler, R. J.; Beckman, B. G. *Tetrahedron Lett.* **1976**, 2517. (b) Spangler, R. J.; Beckmann, B. J.; Kim, J. H. *J. Org. Chem.* **1977**, *42*, 2989.
(62) Das, K. G.; Afzal, J.; Hazra, B. G.; Bhawal, B. M. *Synth. Commun.* **1983**, *13*, 787.
(63) Carpino, L. A. *J. Chem. Soc., Chem. Commun.* **1966**, 494.
(64) (a) Spangler, R. J.; Kim, H. J. *Synthesis* **1973**, 107. (b) Shebarov, Y. S.; Vasilev, N. I.; Levina, R. Y. *Obshch Khim.* **1961**, *31*, 2478; *Chem. Abstr.* **1962,** *56*, 7312.
(65) (a) Wiersum, U. E.; Mijs, W. J. *J. Chem. Soc., Chem. Commun.* **1972**, 347. (b) Bornstein, J.; Remy, D. E.; Shields, J. E. *J. Chem. Soc., Chem. Commun.* **1972**, 1149. (c) Fieser, L. F.; Haddadin, M. J. *Can. J. Chem.* **1965**, *43*, 1599. (d) Wege, D. *Tetrahedron Lett.* **1971**, 2337. (e) Warrener, R. N. *J. Am. Chem. Soc.* **1971**, *93*, 2346.
(66) (a) Cava, M. P.; Deana, A. A. *J. Am. Chem. Soc.* **1959**, *81*, 4266. (b) Cava, M. P.; Deana, A. A.; Muth, K. *J. Am. Chem. Soc.* **1959**,

81, 6458. (c) Cava, M. P.; Mitchell, M. J.; Deana, A. A. *J. Org. Chem.* **1960**, *25*, 1481.

(67) Jung, F.; Molin, M.; Van den Elzen, R.; Durst, T. *J. Am. Chem. Soc.* **1974**, *96*, 935.

(68) Askari, S.; Lee, S.; Perkins, R. P.; Scheffer, J. R. *Can. J. Chem.* **1985**, *63*, 3526.

(69) Jarvis, W. F.; Hoey, M. D.; Finocchio, A. L.; Dittmer, D. C. *J. Org. Chem.* **1988**, *53*, 5750.

(70) (a) Durst, T.; Tetreault-Ryan, L. *Tetrahedron Lett.* **1978**, *19*, 2353. (b) Charlton, J. L.; Durst, T. *Tetrahedron Lett.* **1984**, *25*, 5287. (c) Durst, T.; Charlton, J. L.; Mount, D. B. *Can. J. Chem.* **1986**, *64*, 246.

(71) Connolly, T. J.; Durst, T. *Tetrahedron Lett.* **1997**, *38*, 1337.

(72) Connolly, T. J.; Durst, T. *Tetrahedron* **1997**, *53*, 15957.

(73) Marson, C. M.; Giles, P. R. *J. Org. Chem.* **1995**, *60*, 8067.

(74) Dittmer, D. C.; Hoey, M. D. In *The Chemistry of Sulfinic acids, Esters and Their Derivatives* ; Patai, S., Ed.; Wiley: Chichester, 1990; p 240.

(75) Roberts, D. W.; Williams, D. L. *Tetrahedron* **1987**, *43*, 1027.

(76) Hoey, M. D.; Dittmer, D. C. *J. Org. Chem.* **1991**, *56*, 1947.

(77) For reviews on recent advances on organic synthesis using microwaves, see: (a) Loupy, A.; Petit, A.; Hamelin, J.; Texier-Boullet, F.; Jacquault, P.; Mathé, D. *Synthesis* **1998**, 1213. (b) Mingos, D. M. P.; Baghurst, D. R. *Chem. Soc. Rev.* **1991**, *20*, 1. (c) Langa, F.; de la Cruz, P.; de la Hoz, A.; Díaz-Ortiz, A.; Díez-Barra, E. *Contemp. Org. Synth.* **1997**, 337.

(78) Illescas, B.; Martín, N.; Seoane, C.; de la Cruz, P.; Langa, F.; Wudl, F. *Tetrahedron Lett.* **1995**, *36*, 8307.

(79) De la Cruz, P.; de la Hoz, A.; Langa, F.; Illescas, B.; Martín, N. *Tetrahedron* **1997**, *53*, 2599.

(80) Chung, W. S.; Lin, W. J.; Liu, W. J.; Chen, L. G. *Chem. Commun.* **1995**, 2537.

(81) Quinkert, G.; Stark, H. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 637.

(82) (a) Quinkert, G. *Pure Appl. Chem.* **1964**, *9*, 607. (b) Quinkert, G.; Wiersdorff, W.-W.; Finke, M.; Opitz, K.; von der Haar, F.-G. *Chem. Ber.* **1968**, *101*, 2302. (c) Grellmann, K.-H.; Palmowski, J.; Quinkert, G. *Angew. Chem. Int. Ed. Engl.* **1971**, *10*, 196. (d) Quinkert, G.; Palmowski, J.; Lorenz, H.-P.; Wiersdorff, W.-W. Finke, M. *Angew. Chem., Int. Ed. Engl.* **1971**, *10*, 198. (e) Quinkert, G.; Tabata, T.; Hickmann, E. A. J.; Dobrat, W. *Angew. Chem., Int. Ed. Engl.* **1971**, *10*, 199.

(83) Starr, C. R.; Eastman, R. H. *J. Org. Chem.* **1966**, *31*, 1393.

(84) Jones, D. W.; Pomfret, A. *J. Chem. Soc., Perkin Trans 1* **1991**, 263.

(85) Sammes, P. G. *Tetrahedron* **1976**, *32*, 405.

(86) Connors, R.; Durst, T. *Tetrahedron Lett.* **1992**, *33*, 7277.

(87) Haag, R.; Wirz, J.; Wagner, P. J. *Helv. Chim. Acta* **1977**, *60*, 2595.

(88) In water/acetonitrile (1:4): Das, P. K.; Encinas, M. V.; Small, R. D.; Scaiano, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 6965.

(89) In toluene: Kumar, C. V.; Chattopadhyay, S. K.; Das, P. D. *J. Am. Chem. Soc.* **1983**, *105*, 5143.

(90) Griesbeck, A. G.; Stadtmüller, S. *Chem. Ber.* **1993**, *126*, 2149.

(91) (a)Arnold, B. J.; Mellows, S. M.; Sammes, P. G.; Wallace, T. W. *J. Chem. Soc., Perkin Trans. 1* **1974**, 401. (b) Arnold, B. J.; Sammes, P. G.; Wallace, T. W. *J. Chem. Soc., Perkin Trans. 1* **1974**, 415.

(92) Durst, T.; Kozma, E. Z.; Charlton, J. L. *J. Org. Chem.* **1985**, *50*, 4829.

(93) Connolly, T. J.; Durst, T. *Tetrahedron* **1997**, *53*, 15969.

(94) Hornback, J. M.; Barrows, R. D. *J. Org. Chem.* **1982**, *47*, 4285.

(95) McCullough, J. J. *Can. J. Chem.* **1968**, *46*, 43.

(96) Fujihara, H.; Yabe, M.; Furukawa, N. *J. Org. Chem.* **1993**, *58*, 5291.

(97) Furukawa, N. *Bull. Chem. Soc. Jpn.* **1997**, *70*, 2581.

(98) Reviews: (a) Kleinermanns, K.; Wolfrum, J. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 38. (b) Wilson, R. M.; Schnapp, K. A.; Hannemann, K.; Ho, D. M.; Memarian, H. R.; Azadnia, A.; Pinhas, A. R.; Figley, T. M. *Spectrochim. Acta, Part A* **1990**, *46*, 551. (c) Wilson, R. M.; Adam, W.; Schulte Oestrich, R. *Spectrum* **1991**, *4*, 8. (d) Wilson, R. M.; Schnapp, K. A. *Chem. Rev.* **1993**, *93*, 223. (e) Johnston, L. J. *Chem. Rev.* **1993**, *93*, 251.

(99) (a)Ouchi, A.; Koga, Y. *J. Org. Chem.* **1997**, *62*, 7376. (b) Tomioka, H. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 1501.

(100) (a) Ouchi, A.; Adam, W. *J. Chem. Soc., Chem. Commun.* **1993**, 628. (b) Ouchi, A.; Yabe, A.; Adam, W. *Tetrahedron Lett.* **1994**, *35*, 6309. (c) Ouchi, A.; Koga, Y. *Tetrahedron Lett.* **1995**, *36*, 8999. (d) Ouchi, A.; Koga, Y. *J. Org. Chem.* **1998**, *63*, 6780.

(101) For a review, see: Platz, M. S.; Maloney, V. M. In *Kinetics and Spectroscopy of Carbenes and Biradicals;* Platz, M. S., Ed.; Plenum Press: New York, 1990; p 239.

(102) Admasu, A.; Platz, M. S.; Marcinek, A.; Michalak, J.; Gudmundsdóttir, A. D.; Gebicki, J. *J. Phys. Org. Chem.* **1997**, *10*, 207.

(103) Covitz, J. H. *J. Am. Chem. Soc.* **1967**, *89*, 5403.

(104) Hussain, A.; Motevalli, M.; Utley, J. H. P.; Wyatt, P. B.; Gao, Y. *J. Org. Chem.* **1993**, *58*, 3578.

(105) (a) Eru, E.; Hawkes, E.; Utley, J. H. P.; Wyatt, P. B. *Tetrahedron* **1995**, *51*, 3033. (b) Oguntoye, E.; Szunerits, S.; Utley, J. H. P.; Wyatt, P. B. *Tetrahedron* **1996**, *52*, 7771.

(106) (a) Chou, T. S.; Tsai, C. Y. *Heterocycles* **1992**, *34*, 663. (b) Chou, T. S.; Tsai, C. Y.; Lee, S. J. *J. Chin. Chem. Soc.* **1997**, *44*, 299.

(107) (a) Trahanovsky, W. S.; Chou, C. S.; Cassady, T. *J. Org. Chem.* **1994**, *59*, 2613. (b) Chou, C. H.; Trahanovsky, W. S. *J. Org. Chem.* **1995**, *60*, 5449. (c) Leung, M. K.; Trahanovsky, W. S. *J. Am. Chem. Soc.* **1995**, *117*, 841.

(108) Chung, W. S.; Lin, W. J.; Liu, W. D.; Chen, L. G. *J. Chem. Soc., Chem. Commun.* **1995**, 2537.

(109) (a) Liu, G. B.; Mori, H.; Katsumura, S. *Chem. Commun.* **1996,** 2251. (b) Hariri, M. A.; Pautet, F.; Fillion, H. *Synlett* **1994**, 459.

(110) (a) Chou, T. S.; Chang, R. C. *J. Chem. Soc., Chem. Commun.* **1992**, 549. (b) Chou, T. S.; Tsai, C. Y. *J. Chin. Chem. Soc.* **1993**, *40*, 581. (c) Vicente, M. G. H.; Tomé, A. C.; Walter, A.; Cavaleiro, J. A. S. *Tetrahedron Lett.* **1997,** *38*, 3639.

(111) (a) Chou, T. S.; Tsai, C. Y. *J. Chem. Soc., Chem. Commun.* **1991**, 1287. (b) Tso, H. H.; Tsay, H.; Li, J. H. *Synth. Commun.* **1995**, *25*, 3435. (c) Crew, A. P.; Jenkins, G.; Storr, R. C.; Yelland, M. *Tetrahedron Lett.* **1990,** *31*, 1149. (d) Chaloner, L. M.; Crew, A. P. A.; O'Neill, P. M.; Storr, R. C.; Yelland, M. *Tetrahedron* **1992**, *48*, 8101. (e) Zwanenburg, D. J.; de Haan, H.; Wynberg, H. *J. Org. Chem.* **1966**, *31*, 3363. (f) Chou, T. S.; Wang, C. T. *Tetrahedron* **1996**, *38*, 12459.

(112) Van den Berg, K. J.; Leusen, A. M. *Rec. Trav. Chim. Pays-Bas* **1993**, *112*, 7.

(113) Chou, T. S.; Chen, H. C.; Tsai, C. Y. *J. Org. Chem.* **1994**, *59*, 2241. Chao, I.; Lu, H. F.; Chou, T. S. *J. Org. Chem.* **1997**, *62*, 7882.

(114) (a) Chou, T. S.; Chang, R. C. *Tetrahedron Lett.* **1992**, *33*, 8121. (b) Tso, H. H.; Yang, N. Y.; Chang, Y. M. *J. Chem. Soc., Chem. Commun.* **1995**, 1349.

(115) Mitkidou, S.; Stephanidou-Stephanitou, J. *Tetrahedron Lett.* **1991**, *32*, 4603.

(116) (a) Chou, T. S.; Chang, R. C. *Heterocycles* **1993**, *36*, 2839. (b) Tso, H. H.; Chang, Y. M.; Tsay, H. *Synth. Commun.* **1996**, *26*, 569. (c) Chauhan, P. M. S.; Crew, A. P. A.; Jenkins, G.; Storr, R. C.; Walker, S. M.; Yelland, M. *Tetrahedron Lett.* **1990**, *31*, 1487. (d) Chaloner, L. M.; Crew, A. P. A.; Storr, R. C. *Tetrahedron Lett.* **1991**, *32*, 7609. (e) Tomé, A. C.; Cavaleiro, J. A. S.; Storr, R. C. *Synlett* **1996**, 531.

(117) (a) Mertzanos, G. E.; Alexandrou, N. E.; Tsoleridis, C. A.; Mitkidou, S.; Stephanidou-Stephanitou, J. *Heterocycles* **1994**, *37*, 967. (b) Mitkidou, S.; Stephanidou-Stephanitou, J. *Tetrahedron Lett.* **1990**, *31*, 5197.

(118) Potter, A. J.; Storr, R. C. *Tetrahedron Lett.* **1994**, *35*, 5293.

(119) (a)Hariri, M. A.; Jouve, K.; Pautet, F.; Domard, M.; Fenet, B.; Fillion, H. *J. Org. Chem.* **1997**, *62*, 405. (b) Jouve, K.; Pautet, F.; Domard, M.; Fillion, H. *Eur. J. Org. Chem.* **1998**, *2047*, 7.

(120) Tso, H. H.; Candraseharam, M. *Tetrahedron Lett.* **1996**, *37*, 4189.

(121) Mertzanos, G. E.; Stephanidou-Stephanitou, J.; Tsoleridis, C. A.; Alexandrou, N. E. *Tetrahedron Lett.* **1992**, *33*, 4499.

(122) (a) Klemm, L. H.; Johnson, W. O.; White, D. V. J. *Heterocycl. Chem.* **1972**, *9*, 843. (b) Spinner, E.; Yeoh, G. B. *J. Chem. Soc. B* **1971**, 289.

(123) Carly, P. R.; Compernolle, Hoornaert, G. *Tetrahedron Lett.* **1995**, *36*, 2113.

(124) Carly, P. R.; Capelle, S. L.; Compernolle, F.; Hoornaert, G. J. *Tetrahedron* **1996**, *52*, 11889

(125) (a) Tomé, A. C.; Cavaleiro, J. A. S.; Storr, R. C. *Tetrahedron Lett.* **1993**, *34*, 6639. (b)Tomé, A. C.; Cavaleiro, J. A. S.; Storr, R. C. *Tetrahedron* **1996**, *52*, 1735.

(126) (a) Herrera, A.; Martínez, R.; González, B.; Illescas, B.; Martín, N.; Seoane, C. *Tetrahedron Lett.* **1997**, *38*, 4873. (b) González, B.; Herrera, A.; Illescas, B.; Martín, N.; Martínez, R.; Moreno, F.; Sánchez, L.; Sánchez, A. *J. Org. Chem.* **1998**, *63*, 6807. (c) García Martínez, A.; Herrera Fernández, A.; Moreno Jiménez, F.; García Fraile, A.; Subramanian, L. R.; Hanack, M. *J. Org. Chem.* **1992**, *57*, 1627.

(127) Chou, T. S.; Ko, C. W. *Molecules* **1996**, *1*, 93.

(128) (a) Tomé, A. C.; O'Neill, P. M.; Storr, R. C.; Cavaleiro, J. A. S. *Synlett* **1993**, 347. (b) Tomé, A. C.; Cavaleiro, J. A. S.; Storr, R. C. *Tetrahedron* **1996**, *52*, 1723.

(129) (a) Ko, C. W.; Chou, T. S. *J. Org. Chem.* **1998**, *63*, 4645. (b) Chou, C. H.; Trahanovsky, W. S. *J. Org. Chem.* **1986**, *51*, 4208.

(130) (a) Bedford, S. B.; Begley, M. J.; Cornwall, P.; Knight, D. W. *Synlett* **1991**, 627. (b) Bedford, S. B.; Begley, M. J.; Cornwall, P.; Foreman, J. P.; Knight, D. W. *J. Chem. Soc., Perkin Trans. 1* **1996**, 2827.

(131) (a) Vice, S. F.; de Carvalho, H. N.; Taylor, N. G.; Dimitrenko, G. I. *Tetrahedron Lett.* **1989**, *30*, 7289. (b) Pindur, U.; Erfanian-Abdoust, *Chem. Rev.* **1989**, *89*, 1681.

(132) (a) Dyker, G.; Kreher, R. P. *Chem. Ber.* **1988**, *121*, 1203. (b) Ko, C. W.; Chou, T. S. *Tetrahedron Lett.* **1997**, *38*, 5315.

(133) White, L. A.; O'Neill, P. M.; Park, B. K.; Storr, R. C. *Tetrahedron Lett.* **1995**, *33*, 5983.

(134) Chung, W. S.; Liu, J. H. *Chem. Commun.* **1997**, 205.

(135) Alexandrou, N. E.; Mertzanos, G. E.; Stephanidou-Stephanitou, J.; Tsoleridis, C. A.; Zachariou, P. *Tetrahedron Lett.* **1995**, *37*, 6777.
(136) Chou, T. S.; Chen, H. C. *Tetrahedron Lett.* **1996**, *37*, 7823.
(137) White, L. A.; Storr, R. C. *Tetrahedron* **1996**, *52*, 3117.
(138) (a) Arias, F.; Boulas, P.; Zuo, Y.; Diomínguez, O.; Gómez-Kaifer, M.; Echegoyen, L. In *Fullerenes: Recent Advances in the Chemistry and Physics of Fullerenes and Related Materials;* Kadish, K. M., Ruoff, R. S., Eds.; The Electrochemical Society, Inc.: Pennington, NJ, 1996; Vol. 3, pp 165−176. (b) Domínguez, O.; Echegoyen, L.; Cunha, F.; Tao, N. *Langmuir* **1998**, *14*, 821.
(139) Tomé, A. C.; Enes, R. F.; Cavaleiro, J. A. S.; Martarello, L; Kirsch, G. *Synlett* **1997**, 1444.
(140) Reck, S.; Näther, C.; Friedrichsen, W. *Heterocycles* **1998**, *48*, 853 and references therein.
(141) Tomé, A. C.; Enes, R. F.; Tomé, J. P. C.; Rocha, J.; Neves, M. G. P. M. S.; Cavaleiro, J. A. S.; Elguero, J. *Tetrahedron* **1998**, *54* 11141.
(142) (a) Jullien, J.; Pechine, J. M.; Pérez, F.; Piade, J. J. *Tetrahedron Lett.* **1979**, *20*, 3079. (b) Jullien, J.; Pechine, J. M.; Pérez, F.; Piade, J. J. *Tetrahedron Lett.* **1980**, *21*, 611.
(143) (a) Gallagher, T.; Magnus, P. *J. Am. Chem. Soc.* **1982**, *104*, 1140. (b) Gallagher, T.; Magnus, P.; Huffman, J. C. *J. Am. Chem. Soc.* **1983**, *105*, 4750. (c) Gallagher, T.; Magnus, P. *J. Am. Chem. Soc.* **1983**, *105*, 2086. (d) Magnus, P.; Gallagher, T.; Brown, P.; Pappalardo, P. *Acc. Chem. Res.* **1984**, *17*, 35. (e) Magnus, P.; Cairns, P. M.; Kim, C. S. *Tetrahedron Lett.* **1985**, 26, 1963. (f) Wiseman, J. R.; Chen, C. H. *Shangai Keji Daxue Xuebao* **1990**, *13*, 1; *Chem. Abstr.* **1991**, *114*, 142999d. (g) Leusink, F. R.; Have, R. T.; van den Berg, K. J.; van Leusen, A. M. *J. Chem. Soc., Chem. Commun.* **1992**, 1401.
(144) (a) Jackson, P. M.; Moody, C. J. *Tetrahedron Lett.* **1988**, *29*, 5817. (b) Jackson, P. M.; Moody, C. J.; Shah, P. *J. Chem. Soc., Perkin Trans. 1* **1990**, 2909. (c) Jackson, P. M.; Moody, C. J. *J. Chem. Soc., Perkin Trans. 1* **1990**, 681. (d) Jackson, P. M.; Moody, C. J.; Mortimer, R. J. *J. Chem. Soc., Perkin Trans 1* **1991**, 2941. (e) Jackson, P. M.; Moody, C. J. *Tetrahedron* **1992**, *48*, 447. (f) Fray, E. B.; Moody, C. J.; Shah, P *Tetrahedron* **1993**, *49*, 7353. (g) For a review, see: Afarinkia, K.; Vinader, V.; Nelson, T. D.; Posner, G. H. *Tetrahedron* **1992**, *48*, 9111.
(145) (a) van Leusen, A. M.; van den Berg, K. J. *Tetrahedron Lett.* **1988**, *29*, 2689. (b) van den Berg, K. J.; van Leusen, A. M. *Rec. Trav. Chim. Pays-Bas* **1993**, *112*, 7.
(146) (a) Saroja, B.; Srinivasan, P. C. *Tetrahedron Lett.* **1984**, *25*, 5429. (b) Chadwick, D. J.; Plant, A. *Tetrahedron Lett.* **1987**, *28*, 6085. (c) Haber, M.; Pindur, U. *Tetrahedron* **1991**, *32*, 1463. (d) Pindur, U.; Haber, M. *Heterocycles* **1991**, *32*, 1463. (e) Heffner, R. J.; Joullié, M. M. *Synth. Commun.* **1991**, *21*, 1055. (f) Al Hariri, M.; Pautet, F.; Fillion, H.; Domard, M.; Fenet, B. *Tetrahedron* **1995**, *51*, 9595.
(147) For reviews on the chemistry of 3-sulfolenes as precursors for conjugated dienes, see: (a) Chou, T. S.; Tso, H. H. *Org. Prep. Proc. Int.* **1989**, *21*, 257. (b) Chou, T. S.; Chou, S. S. P. *J. Chin. Chem. Soc.* **1992**, *39*, 625. (c) Ando, K.; Takayama, H. *Heterocycles* **1994**, *37*, 1417.
(148) Chou, T. S.; Tsai, C. Y. *Tetrahedron Lett.* **1992**, *33*, 4201.
(149) (a) Stone, K. J.; Greenberg, M. M.; Blackstock, S. C.; Berson, J. A. *J. Am. Chem. Soc.* **1989**, *111*, 3659. (b) Bush, L. C.; Heath, R. B.; Berson, J. A. *J. Am. Chem. Soc.* **1993**, *115*, 9830.
(150) (a) Braverman, S.; Duar, Y.; Segev, D. *Tetrahedron Lett.* **1976**, 3181. (b) Garratt, P. J.; Neoh, S. B. *J. Org. Chem.* **1979**, *44*, 2667
(151) Ando, K.; Kankake, M.; Suzuki, T.; Takayama, H. *Tetrahedron* **1995**, *51*, 129.
(152) Nemoto, H.; Satoh, A.; Fukumoto, K. *Tetrahedron* **1995**, *51*, 10159 and references therein.
(153) Sauer, J.; Sustman, R. *Angew. Chem., Int. Ed. Engl.* **1980**, *18*, 779.
(154) (a) Winkler, J. D. *Chem. Rev.* **1996**, *96*, 167. (b) Sustmann, R.; Korth, H. G.; Nüchter, U.; Siangouri-Feulner, I.; Sicking, W. *Chem. Ber.* **1991**, *124*, 2811. (c) Manoharan, M.; Venuvanalingam, P. *J. Phys. Org. Chem.* **1998**, *11*, 133. (d) Kahn, S. D.; Pau, C. F.; Overman, L. E.; Hehre, W. J. *J. Am. Chem. Soc.* **1986**, *108*, 7381. (e) Sustmann, R.; Tappanchai, S.; Bandmann, H. *J. Am. Chem. Soc.* **1996**, *118*, 12555 and references therein.
(155) (a) Charlton, J. L.; Plourde, G. L.; Koh, K.; Secco, A. S. *Can. J. Chem.* **1989**, *67*, 574. (b) Charlton, J. L.; Koh, K.; Plourde, G. L. *Tetrahedron Lett.* **1989**, *30*, 3279. (c) Charlton, J. L.; Plourde, G. L.; Koh, K.; Secco, A. S. *Can. J. Chem.* **1990**, *68*, 2022. (d) Charlton, J. L.; Koh, K. *Synlett* **1990**, 333. (e) Charlton, J. L.; Koh, K. *J. Org. Chem.* **1992**, *57*, 1514.
(156) Frigelli,, F.; Taticchi, A. *Dienes in Diels−Alder Reaction*; John Wiley & Sons: New York, 1990; pp 39−41 and 56−60.
(157) Helmchen, G.; Karge, R.; Weetman, J. In *Modern Synthetic Methods*; Sheffold, R., Ed.; Springer-Verlag: New York, 1986; Vol. 4, pp 262−306.
(158) Kagan, H. B.; Riant, O. *Chem. Rev.* **1992**, *92*, 1007.
(159) (a) Ito, Y.; Amino, Y.; Nakatsuka, M.; Saegusa, T. *J. Am. Chem. Soc.* **1983**, *105*, 1586. (b) Charlton, J. L. *Tetrahedron Lett.* **1985**, *26*, 3413. (c) Charlton, J. L. *Can. J. Chem.* **1986**, *64*, 720. (d) Charlton, J. L.; Plourde, G. L.; Penner, G. H. *Can. J. Chem.* **1989**, *67*, 1010. (e) Charlton, J. L.; Alauddin, M. M. *J. Org. Chem.* **1986**, *51*, 3490.
(160) Kündig, E. P.; Leresche, J. *Tetrahedron* **1993**, *49*, 5599.
(161) Brieger, G.; Bennett, J. N. *Chem. Rev.* **1980**, *80*, 63.
(162) (a) Carlson, R. G. *Ann. Rep. Med. Chem.* **1974**, *9*, 270. (b) Mehta, G. *J. Chem. Educ.* **1976**, *53*, 551. (c) Oppolzer, W. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 10. (d) Fallis, A. G. *Can. J. Chem.* **1984**, *62*, 183. (e) Ciganek, E. *Org. React.* **1984**, *32*, 1. (f) Taber, D. F. Intramolecular Diels−Alder and Alder Ene Reactions; In *Reactivity and Structure Concepts in Organic Chemistry*, Springer-Verlag: Berlin, 1984; Vol. 18. (g) Desimoni, G.; Tacconi, G.; Barco, A. Pollini, G. P. *ACS Monograph 180*, American Chemical Society: Washington, DC, 1980.
(163) Funk, R. L.; Vollhardt, K. P. C. *Chem. Soc. Rev.* **1980**, *9*, 41.
(164) (a) Kametani, T. *Pure Appl. Chem.* **1979**, *51*, 747. (b) Kametani, T.; Nemoto, H. *Tetrahedron* **1981**, *37*, 3. (c) Quinkert, G.; Stark, H. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 637.
(165) For some recent works, see: (a) Trehan, I. R.; Singh, N. P.; Jain, V. K. *Indian J. Chem. Sect. B.: Org. Chem. Incl. Med. Chem.* **1995**, *34B*, 484. (b) Pellisier, H.; Santelli, M. *Tetrahedron* **1996**, *52*, 9093. (c) Wilmouth, S.; Pellisier, H.; Santelli, M. *Tetrahedron* **1998**, *54*, 10079. (d) Nemoto, H.; Miyata, J.; Yoshida, M.; Raku, N.; Fukumoto, K. *J. Org. Chem.* **1997**, *62*, 7850.
(166) Kametani, T.; Nemoto, H.; Ishikawa, H.; Shirogama, K.; Matsumoto, H.; Fukumoto, K. *J. Am. Chem. Soc.* **1977**, *99*, 3461.
(167) Oppolzer, W.; Roberts, D. A. *Helv. Chim. Acta* **1980**, *63*, 1703.
(168) Quinkert, G. *Chimia* **1977**, *31*, 225.
(169) Funk, R. L.; Vollhardt, K. P. C. *J. Am. Chem. Soc.* **1979**, *101*, 215.
(170) Kametani, T.; Nemoto, H.; Tsubuki, M.; Purvaneckas, B.-E; Aizawa, M.; Nishiuchi, M. *J. Chem. Soc., Perkin Trans 1* **1979**, 2803.
(171) Blazejewski, J. C.; Haddad, M.; Wakselman, C. *Tetrahedron Lett.* **1994**, *35*, 2021.
(172) Oppolzer, W.; Keller, K. *J. Am. Chem. Soc.* **1971**, *93*, 3836.
(173) (a) Ward, R. S. *Chem. Soc. Rev.* **1982**, *11*, 75. (b) Ward, R. S. *Synthesis* **1992**, 719.
(174) Mann, J.; Piper, S. E. *J. Chem. Soc., Chem. Commun.* **1982**, 430.
(175) Coll, G.; Costa, A.; Deyá, P. M.; Flexas, F.; Rotger, C.; Saá, J. M. *J. Org. Chem.* **1992**, *57*, 6222.
(176) (a) Jones, D. W.; Thompson, A. M. *J. Chem. Soc., Perkin Trans 1* **1993**, 2533. (b) Jones, D. W. *J. Chem. Soc., Perkin Trans 1* **1994**, 399.
(177) Meier, H. *Organic Semiconductors*; Verlag Chemie: Weinheim, 1974.
(178) André, J. M.; Gouverneur, L.; Leroy, G. *Bull. Chem. Soc. Belg.* **1967**, *76*, 661.
(179) Roncali, J. *Chem. Rev.* **1997**, *97*, 173.
(180) Jozefiak, T. H.; Miller, L. L. *J. Am. Chem. Soc.* **1987**, *109*, 6560.
(181) Thomas, A. D.; Miller, L. L. *J. Org. Chem.* **1986**, *51*, 4160.
(182) Rak, S. F.; Miller, L. L. *J. Am. Chem. Soc.* **1992**, *114*, 1388.
(183) Wartini, A. R.; Valenzuela, J.; Staab, H. A.; Neugebauer, F. A. *Eur. J. Org. Chem.* **1998**, *221*, 1.
(184) Morris, J.; Becker, C.; Fronczek, F.; Daly, W.; McLaughlin, M. *J. Org. Chem.* **1994**, *59*, 6484.
(185) (a) Ferraris, J.; Cowan, D. O.; Walatka, V. V.; Perlstein, J. H. *J. Am. Chem. Soc.* **1973**, *95*, 948. (b) Coleman, L. B.; Cohen, M. J.; Sandman, A. J.; Yamagishi, F. G.; Garito, A. F.; Heeger, A. J. *Solid State Commun.* **1973**, *12*, 1125.
(186) (a) Bryce, M. R.; Murphy, L. C. *Nature* **1984**, *309*, 119. (b) Bryce, M. R. *Chem. Soc. Rev.* **1991**, *20*, 355. (c) Shukat, G.; Fanghänel, E. *Sulfur Rep.* **1993**, *14*, 155. (d) Adam. M.; Müllen, K. *Adv. Mater.* **1994**, *6*, 439. (e) Garín, J. *Adv. Heterocycl. Chem* **1995**, *62*, 249. (f) Bryce, M. R. *J. Mater. Chem.* **1995**, *5*, 1481. Otsubo, T.; Aso, Y.; Takimiya, K. *Adv. Mater.* **1996**, *8*, 203. (g) Day, P.; Kurmoo, M. *J. Mater. Chem.* **1997**, *8*, 1291. (h) Coronado, E.; Gómez-García, C. J. *Chem. Rev.* **1998**, *98*, 273. (i) Bryce, M. R. *Adv. Mater.* **1999**, *11*, 11.
(187) (a) Martín, N.; Segura, J. L.; Seoane, C. *J. Mater. Chem.* **1997**, *7*, 1661. (b) Hünig, S. *J. Mater. Chem.* **1995**, *5*, 1469.
(188) Martín, N.; Seoane, C. In *Handbook of Conductive Molecules and Polymers*; Nalwa, H. S., Ed.; John Wiley & Sons Ltd.: New York, 1997.
(189) Martín, N.; Behnisch, R.; Hanack, M. *J. Org. Chem.* **1989**, *54*, 2563.
(190) Martín, N.; Segura, J. L.; Seoane, C.; de la Cruz, P.; Langa, F.; Ortí, E.; Viruela, P. M.; Viruela, R. *J. Org. Chem.* **1995**, *60*, 4077.
(191) Barranco, E.; González, A.; Martín, N.; Pingarrón, J. M.; Segura, J. L.; Seoane, C. *Synth. Met.* **1993**, *56*, 1717.
(192) Martín, N.; Navarro, J. A.; Seoane, C.; Albert, A.; Cano, F. H.; Becker, J. Y.; Khodorkovsky, V.; Harlev, E.; Hanack, M. *J. Org. Chem.* **1992**, *57*, 5726.
(193) Barranco, E.; Martín, N.; Segura, J. L.; Seoane, C.; de la Cruz, P.; Langa, F.; González, A.; Pingarrón, J. M. *Tetrahedron* **1993**, *49*, 4881.
(194) Jannsen, R. A. J.; Christiaans, M. P. T.; Hare, C.; Martín, N.; Sariciftci, N. S.; Heeger, A. J.; Wudl, F. *J. Chem. Phys.* **1995**, *103*, 8840.

(195) (a) Martín, N.; Sánchez, L.; Seoane, C.; Fernández, C. *Synth. Met.* **1996**, *78*, 137. (b) Martín, N.; Sánchez, L.; Seoane, C.; Ortí, E.; Viruela, P. M.; Viruela, R. *J. Org. Chem.* **1998**, *63*, 1268. (c) Martín, N.; Ortí, E.; Sánchez, L.; Viruela, P.; Viruela, R. *Eur. J. Org. Chem.* **1999**, *1239*, 9.

(196) Krätschmer, W.; Lamb, L. D.; Fostiropoulos, K.; Huffman, D. R. *Nature* **1990**, *347*, 354.

(197) (a) Hirsch, A. In *The Chemistry of the Fullerenes*; Georg Thieme Verlag: Stuttgart, 1994. (b) Taylor, R.; Walton, D. R. M. *Nature* **1993**, *363*, 685. (c) Diederich, F.; Thilgen, C. *Science* **1996**, *271*, 317. (d) Fullerenes and Related Structures, Hirsch, A., Ed.; *Top. Curr. Chem.* **1999**, *199*, 1−235.

(198) As a review, see: Thilgen, C.; Herrmann, A.; Diederich, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2268.

(199) For a review on addition reactions of C_{60}, see: Hirsch, A. *Synthesis* **1995**, 895.

(200) Meidine, M. F.; Roers, R.; Langley, G. J.; Avent, A. G.; Darwish, A. D.; Firth, S.; Kroto, H. W.; Taylor, R.; Walton, D. R. M. *J. Chem. Soc., Chem. Commun.* **1993**, 1342.

(201) Belik, P.; Gügel, A.; Spikermann, J.; Müllen, K. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 78.

(202) (a) Diederich, F.; Jonas, U.; Gramlich, V.; Herrmann, A.; Ringsdorf, H.; Thilgen, C. *Helv. Chim. Acta* **1993**, *76*, 2445. (b) Belik, P.; Gügel, A.; Kraus, A.; Walter, M.; Müllen, K. *J. Org. Chem.* **1995**, *60*, 3307.

(203) Tago, T.; Minowa, T.; Okada, Y.; Nishimura, J. *Tetrahedron Lett.* **1993**, *34*, 8461.

(204) Gügel, A.; Kraus, A.; Spickermann, J.; Belik, P.; Müllen, K. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 559.

(205) Belik, P.; Gügel, A.; Kraus, A.; Spickermann, J.; Enkelmann, V.; Frank, G.; Müllen, K. *Adv. Mater.* **1993**, *5*, 854.

(206) Zhang, X.; Foote, Ch. S. *J. Org. Chem.* **1994**, *59*, 5235.

(207) (a) Tomioka, H.; Yamamoto, K. *J. Chem. Soc., Chem. Commun.* **1995**, 1961. (b) Tomioka, H.; Ichihashi, M.; Yamamoto, K. *Tetrahedron Lett.* **1995**, *36*, 5371.

(208) Kraus, A.; Schenider, M.; Gügel, A. Müllen, K. *J. Mater. Chem.* **1997**, *7*, 763.

(209) (a) Walter, M.; Gügel, A.; Spickermann, J.; Belik, P.; Kraus, A.; Müllen, K. *Fullerenes Sci. Technol.* **1996**, 101.

(210) Puplovskis, A.; Kacens, J.; Neilands, O. *Tetrahedron Lett.* **1997**, *38*, 285.

(211) Taki, M.; Takigami, S.; Watanabe, Y.; Nakamura, Y. Nishimura, J. *Polym. J.* **1997**, *29*, 1020.

(212) Pyo, S.; Shu, L.; Echegoyen, L. *Tetrahedron Lett.* **1998**, *39*, 7653.

(213) Iyoda, M.; Sultana, F.; Sasaki, S.; Butenschön, H. *Tetrahedron Lett.* **1995**, *36*, 579.

(214) Rubin, Y.; Khan, S.; Freedberg, D. I.; Yeretzian, C. *J. Am. Chem. Soc.* **1993**, *115*, 344.

(215) (a) Nakamura, Y.; Minowa, T.; Tobita, S.; Shizuka, H.; Nishimura, J. *J. Chem. Soc., Perkin Trans. 2* **1995**, 2351. (b) Nakamura, Y.; Minowa, T.; Hayashida, Y.; Tobita, S.; Shizuka, H.; Nishimura, J. *J. Chem. Soc., Faraday Trans.* **1996**, *92*, 377. (c) Nakamura, Y.; Taki, M.; Tobita, S.; Shizuka, H.; Yokoi, H.; Ishiguro, K.; Sawaki, Y.; Nishimura, J. *J. Chem. Soc., Perkin Trans. 2* **1999**, 127.

(216) Isaacs, L.; Haldimann, R. F.; Diederich, F. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2339.

(217) Taki, M.; Sugita, S.; Nakamura, Y.; Kasashima, E.; Yashima, E.; Okamoto, Y.; Nishimura, J. *J. Am. Chem. Soc.* **1997**, *119*, 926.

(218) For recent reviews, see: (a) Jensen, A. W.; Wilson, S. R.; Schuster, D. I. *Bioorg. Med. Chem.* **1996**, *4*, 767. (b) Da Ros, T.; Prato, M. *Chem. Commun.* **1999**, 663.

(219) Linsen, T. G.; Dürr, K.; Hanack, M.; Hirsch, A. *J. Chem. Soc., Chem. Commun.* **1995**, 103.

(220) Ishi-I, T.; Nakashima, K.; Shinkai, S. *Chem. Commun.* **1998**, 1407.

(221) Kräutler, B.; Müller, T.; Maynoll, J.; Gruber, K.; Kratky, C.; Ochsenbein, P.; Schwarzenback, D.; Bürgi, H.-B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1204.

(222) (a) Schlueter, J. A.; Seaman, J. M.; Taha, S.; Cohen, H.; Lykke, K. R.; Wang, H. H.; Williams, J. M. *J. Chem. Soc., Chem. Commun.* **1993**, 972. (b) Tsuda, M.; Ishida, T.; Nogami, T.; Kurono, S.; Ohashi, M. *J. Chem. Soc., Chem. Commun.* **1993**, 1296. (c) Komatsu, K.; Murata, Y.; Sugita, N.; Takeuchi, K.; Wan, T. S. M. *Tetrahedron Lett.* **1993**, *34*, 8473.

(223) Schwenninger, R.; Müller, T.; Kräutler, B. *J. Am. Chem. Soc.* **1997**, *119*, 9317.

(224) Ohno, M.; Koide, N.; Eguchi, S. *Heterocycl. Commun.* **1995**, *1*, 125.

(225) Fernández-Paniagua, U. M.; Illescas, B. M.; Martín, N.; Seoane, C. *J. Chem. Soc., Perkin Trans 1* **1996**, 1077.

(226) For a more general review of heterocyclic-containing [60]-fullerene derivatives, see: Eguchi, S.; Ohno, M.; Kojima, S.; Koide, N.; Yashiro, A.; Shirakawa, Y.; Ishida, H. *Fullerene Sci. Technol.* **1996**, *4*, 303.

(227) (a) Arbogast, J. W.; Darmanyan, A. P.; Foote, C. S.; Rubin, Y.; Diederich, F.; Alvarez, M. M.; Anz, S. J.; Whetten, R. J. *J. Phys. Chem.* **1991**, *95*, 11. (b) Wasiliewsky, M. R.; O′Neil, M. P.; Lykke, K. R.; Pellin, M. J.; Gruen, D. M. *J. Am. Chem. Soc.* **1991**, *113*, 2774. (c) For a recent review on the photophysics and photochemistry of fullerene materials, see; Sun, Y.-P. Marcel Dekker: New York, 1997; Vol. 1.

(228) Trahanovsky, W. S.; Cassady, T. J.; Woods, T. L. *J. Am. Chem. Soc.* **1981**, *103*, 6691.

(229) Ohno, M.; Koide, N.; Sato, H.; Eguchi, S. *Tetrahedron* **1997**, *53*, 9075.

(230) Torres-García, G.; Luftmann, H.; Wolff, C.; Mattay, J. *J. Org. Chem.* **1997**, *62*, 2752.

(231) Fernández-Paniagua, U. M.; Illescas, B.; Martín, N.; Seoane, C.; de la Cruz, P.; de la Hoz, A.; Langa, F. *J. Org. Chem.* **1997**, *62*, 3705.

(232) Guldi, D. M.; Torres-García, G.; Mattay, J. *J. Phys. Chem.* **1998**, *102*, 9679.

(233) Tomé, A. C.; Enes, R.; Cavaleiro, J.; Elguero, J. *Tetrahedron Lett.* **1997**, *38*, 2557.

(234) (a) Arias, F.; Xie, Q.; Wu, Y.; Lu, Q.; Wilson, S. R.; Echegoyen, L. *J. Am. Chem. Soc.* **1994**, *116*, 6388. (b) Allemand, P.-M.; Koch, A.; Wudl, F.; Rubin, Y.; Diederich, F.; Alvarez, M. M.; Anz, S. J.; Whetten, R. L. *J. Am. Chem. Soc.* **1991**, *113*, 1050. (c) Haufler, R. E.; Conceiçao, J.; Chibante, L. F. P.; Chai, Y.; Byrne, N. E.; Flanagan, S.; Haley, M. M.; O′Brien, S.; Pan, C.; Xiao, Z.; Billups, W. E.; Ciufolini, M. A.; Hauge, R. H.; Margrave, J. L.; Wilson, L. J.; Curl, R. F.; Smalley, R. E. *J. Phys. Chem.* **1990**, *94*, 1050.

(235) Williams, R. M.; Koeberg, M.; Lawson, J. M.; An, Y.-Z.; Rubin, Y.; Paddon-Row, M. N.; Verhoeven, J. W. *J. Org. Chem.* **1996**, *61*, 5055.

(236) For a review, see: Imahori, H.; Sakata, Y. *Adv. Mater.* **1997**, *9*, 537.

(237) Imahori, H.; Hagiwara, K.; Akiyama, T.; Taniguchi, S.; Okada, T.; Sakata, Y. *Chem. Lett.* **1995**, 265.

(238) Imahori, H.; Hagiwara, K.; Aoki, M.; Akiyama, T.; Taniguchi, S.; Okada, T.; Shirakawa, M.; Sakata, Y. *J. Am. Chem. Soc.* **1996**, *118*, 11771.

(239) Illescas, B. M.; Martín, N.; Seoane, C.; Ortí, E.; Viruela, P. M.; Viruela, R.; de la Hoz, A. *J. Org. Chem.* **1997**, *62*, 7585.

(240) (a) Iyoda, M.; Sultana, F.; Sasaki, S.; Yoshida, M. *J. Chem. Soc., Chem. Commun.* **1994**, 1929. (b) Iyoda, M.; Sasaki, S.; Sultana, F.; Yoshida, M.; Kuwatani, Y.; Nagase, S. *Tetrahedron Lett.* **1996**, *37*, 7987.

(241) Martín, N.; Sánchez, L.; Seoane, C.; Andreu, R.; Garín, J.; Orduna, J. *Tetrahedron Lett.* **1996**, *37*, 5979.

(242) Prato, M.; Maggini, M.; Giacometti, C.; Scorrano, G.; Sandonà, G.; Farnia, G. *Tetrahedron* **1996**, *52*, 5221.

(243) Boulle, C.; Rabreau, J. M.; Hudhomme, P.; Cariou, M.; Jubault, M.; Gorgues, A.; Orduna, J.; Garín, J. *Tetrahderon Lett.* **1997**, *38*, 3909.

(244) Llacay, J.; Veciana, J.; Vidal-Gancedo, J.; Bourdelande, J. L.; González-Moreno, R.; Rovira, C. *J. Org. Chem.* **1998**, *63*, 5201.

(245) Wudl, F.; Wobschall, D.; Hufnagel, E. J. *J. Am. Chem. Soc.* **1972**, *94*, 3372.

(246) Williams, J. M.; Ferraro, J. R.; Thorn, R. J.; Carlson, K. D.; Geiser, U.; Wang, H. H.; Kini, A. M.; Whangbo, M.-H. In *Organic Superconductors (Including Fullerenes)*; Prentice Hall: Englewood Cliffs, NJ, 1992.

(247) Boulle, C.; Cariou, M.; Bainville, M.; Gorgues, A.; Hudhomme, P.; Orduna, J.; Garín, J. *Tetrahedron Lett.* **1997**, *38*, 81.

(248) Llacay, J.; Mas, M.; Molins, E.; Veciana, J.; Rovira, C. *Chem. Commun.* **1997**, 659.

(249) For a recent review, see: Thilgen C.; Herrmann, A.; Diederich, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2268.

(250) Herrmann, A.; Diederich, F.; Thilgen C.; ter Meer, H.-U.; Müller, W. H. *Helv. Chim. Acta* **1994**, *77*, 1689.

(251) Seiler, P.; Herrmann, A.; Diederich, F. *Helv. Chim. Acta* **1995**, *78*, 344.

(252) (a) Hawkins, J. M.; Meyer, A. *Science* **1993**, *260*, 1918. (b) Haddon, R. C.; Scott, L. T. *Pure Appl. Chem.* **1986**, *58*, 137. (c) Haddon, R. C. *Science* **1993**, *261*, 1545.

(253) Kirchhoff, R. A.; Bruza, K. J. *Prog. Polym. Sci.* **1993**, *18*, 85.

(254) Hahn, S. F.; Martin, S. J.; McKelvy, M. L. *Macromolecules* **1992**, *25*, 1539.

(255) Iwatsuki, S. *Advances in Polymer Science*; Springer-Verlag: Berlin, Heidelberg, 1984.

(256) Tan, T. S.; Arnold, F. E. *J. Polym. Sci., Polym. Chem. Ed* **1988**, *26*, 1819.

(257) Tan, T. S.; Arnold, F. E. *J. Polym. Sci., Polym. Chem. Ed.* **1987**, *25*, 3159.

(258) Tan, T. S.; Arnold, F. E. *J. Polym. Sci., Polym. Chem. Ed* **1988**, *26*, 3103.

(259) Hahn, S. F.; Townsend, P. H.; Burdeaux, D. C.; Gilpin, J. A. *Polymeric Materials for Electronics and Interconnection*; Lupinski, J. H., Moore, R. S., Eds.; ACS Symposium Series 407; American Chemical Society: Washington, DC, 1989.

(260) Kirchhoff, R. A.; Bruza, K. J.; Carriere, C. J.; Rondan, N. G.; Sammler, R. L. *J. Macromol. Sci. Chem.* **1991**, *A28(11, 12)*, 1079.

(261) Jensen, F. R.; Coleman, W. E.; Berlin, A. J. *Tetrahedron Lett.* **1962**, 15.

(262) (a) Errede, L. A. *J. Am. Chem. Soc.* **1961**, *83*, 949. (b) Errede, L. A. *J. Polym. Sci.* **1961**, *XLIX*, 253.

(263) Chino, K.; Takata, T.; Endo, T. *Macromol. Rapid Commun.* **1996**, *17*, 339.

(264) Chino, K; Takata, T.; Endo, T. *Macromolecules* **1997**, *30*, 6715.

(265) Chino, K.; Takata, T.; Endo, T. *Macromol. Rapid Commun.* **1996**, *17*, 163.

(266) Hide, F.; Díaz-García, M. A.; Schwartz, B. J.; Heeger, A. J. *Acc. Chem. Res.* **1997**, *30*, 430.

(267) (a) Segura, J. L. *Acta Polym.* **1997**, *49*, 319. (b) Kraft, A.; Grimsdale, A. C.; Holmes, A. B. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 402.

(268) Williams, F. J.; Relles, H. M.; Manello, J. S.; Donahue, P. E. *J. Org. Chem.* **1977**, *42*, 3419.

(269) (a) Tan, L. S.; Arnold, F. E. *J. Polym. Sci. Polym. Chem.* **1987,** *25*, 3159. (b) Tan, L. S.; Arnold, F. E. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1985**, *26*, 178.

(270) Kirchhoff, R. A.; Schrock, A. K.; Hahn, S. F. U.S. Patent 4,724,-260, 1988.

(271) Kirchhoff, R. A.; Schrock, A. K.; Hahn, S. F. U.S. Patent 4, 783, 514, 1988.

(272) (a) Tan, L. S.; Arnold, F. E. *Polym. Prepr. (Am. Chem. Soc. Div. Polym. Chem.)* **1986**, *27*, 453. (b) Tan, L. S.; Arnold, F. E. U.S. Patent 4,916,235, 1990.

(273) Bishop, M. T.; Bruza, K. J.; Laman, S. A.; Lee, W. M.; Woo, E. P. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1992**, *33*, 362.

(274) (a) Bacon, R. G. R.; Steward, O. J. *J. Chem. Soc.* **1965**, 4953. (b) Williams, A. L.; Kinney, R. E.; Bridger, R. F. *J. Org. Chem.* **1967**, *30*, 2501. (c) Lindley, J. *Tetrahedron* **1984**, *40*, 1433.

(275) Wong, P. K. U.S. Patent 4,687,815, 1987.

(276) (a) Wong, P. K. U.S. Patent 4,698,394, 1987. (b) Wong, P. K. U.S. Patent 4,968,754, 1990.

(277) (a) Wong, P. K. U.S. Patent 4,622,375, 1986. (b) Wong, P. K. U.S. Patent 4, 667,004, 1987. (c) Wong, P. K. U.S. Patent 4,-667,005, 1987.

(278) Endo, T.; Koizumi, T.; Takata, T.; Chino, K. *J. Polym. Sci., Part A: Polym. Chem.* **1995**, *33*, 707.

(279) Chino, K.; Takata, T.; Endo, T. *J. Polym. Sci., Part A: Polym. Chem.* **1999**, *37*, 59.

(280) Montheard, J.-P.; Camps, M.; Chatzopouls, M. *Makromol. Chem.* **1985**, *186*, 2513.

(281) (a) Hahn, S. F.; Kirchhoff, R. A. U.S. Patent 4,739,030, 1988. (b) Tan, L.-S.; Arnold, F. E.; Soloski, E. J. *J. Polym. Sci., Polym. Chem.* **1988**, *26*, 3103. (c) Tan, L.-S.; Soloski, E. J.; Arnold, F. E. *Polym. Mater. Sci. Eng.* **1987**, *56*, 650.

(282) Meador, M. A. B.; Meador, M. A.; Williams, L. L.; Scheiman, D. A. *Macromolecules* **1996**, *29*, 8983.

(283) Meador, M. A. *NASA TM 89386*, 1987.

(284) Jordan, G. K.; Farona, M. F. *Polym. Bull.* **1998**, *40*, 9.

(285) (a) Prato, M. *J. Mater. Chem.* **1997**, *7*, 1097. (b) Geckeler, K. E. *Trends Polym. Sci.* **1994**, *2*, 355.

(286) Hirsch, A. *Adv. Mater.* **1993**, *5*, 859 and references therein.

(287) Gügel, A.; Belik, P.; Walter, M.; Kraus, A.; Harth, E.; Wagner, M.; Spickerman, J.; Müllen, K. *Tetrahedron* **1996**, *52*, 1996.

(288) (a) Loy, D. A.; Assink, R. A. *J. Am. Chem. Soc.* **1992**, *4*, 1153. (b) Li, J.; Yoshizawa, T.; Ikuta, M.; Ozawa, M.; Nakahara, K.; Hasegawa, T.; Kitazawa, K.; Hayashi, M.; Kinbara, K.; Nohara, M.; Saigo, K. *Chem. Lett.* **1997**, 1037. (c) Kuzmany, H.; Winter, J.; Burger, B. *Synth. Met.* **1997**, *85*, 1173.

(289) (a) Shi, S.; Khemani, K. C.; Li, Q.; Wudl, F. *J. Am. Chem. Soc.* **1992**, *114*, 10656. (b) Geckeler, K. E.; Hirsch, A. *J. Am. Chem. Soc.* **1993**, *32*, 78. (c) Patil, A. O.; Schriver, G. W.; Carstensen, B.; Lundberg, R. D. *Polym. Bull.* **1993**, *30*, 187. (d) Zhang, N.; Schricker, S. R.; Wudl, F.; Prato, M. Maggini, M.; Scorrano, G. *Chem. Mater.* **1995**, *7*, 441. (e) Dai, L.; Mau, W. H. *Synth. Met.* **1997**, *86*, 2277. (f) Benincori, Brenna, E.; Sannicolò, F.; Trimarco, L.; Zotti, G.; Sozzani, P. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 648. (g) Dai, L.; Mau, A. W. H.; Zhang, X. *J. Mater. Chem.* **1998**, *8*, 325.

(290) (a) Samulski, E. T.; DeSimone, J. M.; Hunt, M. O.; Menceloglu, Y. Z.; Jarnagin, R. C.; York, G. A.; Labat, K. B.; Wang, H. *Chem. Mater.* **1992**, *4*, 1153. (b) Camps, X.; Schönberger, H.; Hirsch, A. *Chem. Eur. J.* **1997**, *3*, 561. (c) Brettreich, M.; Hirsch, A. *Tetrahedron Lett.* **1998**, *39*, 2731. (d) Chiang, L. Y.; Wang, L. Y.; Kuo, C.-S. *Macromolecules* **1995**, *28*, 7574.

(291) Wang, Z. Y.; Kuang, L.; Meng, X. S.; Gao, J. P. *Macromolecules* **1998**, *31*, 5556.

(292) (a) *The Biology of Nitric Oxide;* Marletta, M. A., Ed.; Portland Press: London, 1992; Parts 1 and 2. (b) *The Biology of Nitric Oxide;* Moncada, S., Feelisch, M., Busse, R., Higgs, E. A., Eds.; Portland Press: London, 1995; Parts 3 and 4. (c) *The Biology of Nitric Oxide;* Moncada, S., Stamler, J., Gross, S., Higgs, E. A., Eds.; Portland Press: London, 1996; Part 5. (d) Moncada, S.; Nisticò, G.; Higgs, E. A. *Nitric Oxide: Brain and Immune System*; Portland Press: London, 1994. (e) Butler, A. R.; Williams, D. L. H. *Chem. Soc. Rev.* **1993**, *22*, 233.

(293) *Methods in Nitric Oxide Research*; Feelisch, M., Stamler, J. S., Eds.; Wiley: Chichester, 1996.

(294) (a) Archer, S. *FASEB J.* **1993**, *7*, 349. (b) Cristol, J. P.; Guérin, M. C.; Torreilles, J. *C. R. Acad. Sci. Paris, Life Sci.* **1994**, *317*, 549.

(295) Paul, T.; Hassan, M. A.; Korth, H.-G.; Sustmann, R.; Avila, D. V. *J. Org. Chem.* **1996**, *61*, 6835.

(296) Korth, H. G.; Ingold, K. U.; Sustmann, R.; de Groot, H.; Sies, H. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 891.

(297) Korth, H. G.; Sustmann, R.; Lommes, P.; Paul, T.; Ernst, A.; de Groot, H.; Hughes, L.; Ingold, K. U. *J. Am. Chem. Soc.* **1994**, *116*, 2767.

(298) Korth, H. G.; Sustmann, R.; Lommes, P.; Paul, T.; Ernst, A.; Ingold, K. U.; Hughes, L.; de Groot, H.; Sies, H. Cheletropic Spin Traps for Nitric Oxide (NOCTs) in Biological Systems; In *The Biology of Nitric Oxide*; Moncada, S., Feelisch, M., Busse, R., Higgs, E. A., Eds.; Portland Press: London, 1994; Vol. 4, pp 220−224.

(299) (a) Bätz, M.; Korth, H.-G.; Sustmann, R. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1501. (b) Bätz, M.; Korth, H. G.; Meineke, P.; Sustmann, R. *Methods Enzymol.* **1999**, *301*, 532.

(300) Griffiths, P. G.; Moad, G.; Rizzardo, E.; Solomon, D. H. *Aust. J. Chem.* **1983**, *36*, 397.

CR990011E