The synthesis and reactions of novel butadiyne derivatives

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The Synthesis and Reactions of Novel Butadiyne Derivatives

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DECLARATION

The work described in this thesis was carried out in the Department of Chemistry at the University of Durham between October 2004 and November 2007. All the work was carried out by the author unless otherwise stated and has not been previously submitted for a degree at this or any other university.

"Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning."

Albert Einstein

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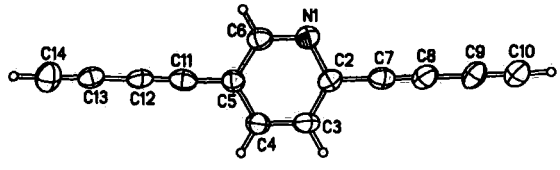
Abstract

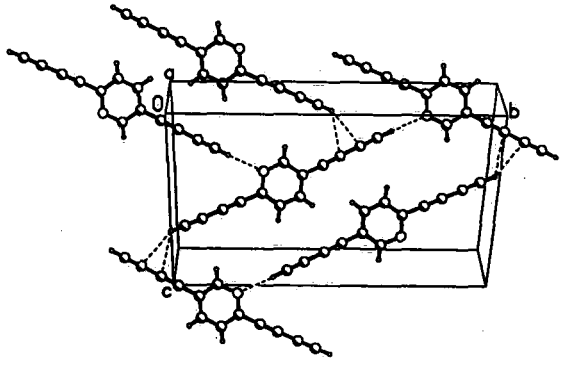
The Synthesis and Reactions of Novel Butadiyne Derivatives.

Kara West, University of Durham, November 2007

The synthesis, isolation and characterisation of aryl and heteroarylbutadiynes is herein reported. X-ray structural analysis for terminal butadiynes **72**, **118**, **143**, **157**, **162** and **172** has been obtained. The packing diagrams indicate, in most cases, a hydrogen bonding interaction between the terminal acetylenic proton and the appropriate atom in the ring. An important feature of our synthetic methodology is the use of the 2-hydroxy-2-propyl protecting group, which facilitates purification from protected species, due to a large difference in polarity.

The synthesis of mono- and di-deprotected bis-butadiynes is also reported; indeed X-ray structural analysis of di-deprotected pyridyl bis-butadiyne **234** has been obtained, as shown in the figure below.





The reactions of aryl and heteorarylbutadiynes and bis-butadiynes have also been investigated, leading to the synthesis of molecular-wire precursors **262** and **264.**

Dedication

This work is dedicated to my beloved grandparents, Louis and Marie, whose love, support and sacrifices paved the way for me to achieve all that I have, and all that I still have to do.

To my loving parents, thank you. Your continuous love and support built the foundations for this work. I am truly blessed to have such parents. I hope you are proud of me.

And finally, to my husband..... ta!

Acknowledgements

I would firstly like to thank my supervisor, Prof. Martin R. Bryce for his continual guidance and advice. I am especially grateful for the opportunity to work within the MRB research group for the past three years and on such an interesting subject. Thanks also for allowing me to attend the conferences I have.

Special thanks to Dr Andrei Batsanov for all X-ray structural analysis. His skills have formed a huge part of this work and have greatly improved the quality of results reported herein.

Special thanks also to Dr Changsheng Wang for his constant help, advice and supply of various starting materials. His encouragement to "just give it a go" motivated me to attempt reactions I might have otherwise overlooked.

To all members, both past and present, of Lab 104 (the place where magic happens); thank you! The past three years have been extremely enjoyable and I have learnt so much from you all (I hope I've managed to impart some wisdom along the way). A special mention to Laura Hayward, who worked with me as part of her MChem studies, and whose work is represented in this thesis. I hope working with me on arylbutadiynes didn't put you off chemistry for life.

Thanks to the analytical services at Durham, whose continual help and advice aided the results reported herein.

.Finally, I would like to thank EPSRC for funding.

Abbreviations

AcOH	Acetic acid
$Cu(OAc)_2$	Copper acetate
C_6D_6	Deuterated benzene
$CDCl_3$	Deuterated chloroform
DCM	Dichloromethane
$Pd(PPh_3)_2Cl_2$	Dichlorobis(triphenylphosphine)palladium (II)
Et_2O	Diethyl ether
DMF	Dimethylformamide
DMSO	Dimethylsulphoxide
EtOH	Ethanol
GC-MS	Gas Chromatography and Mass Spectrometry
HOMO	Highest Occupied Molecular Orbital
HI	Hydroiodic acid
LUMO	Lowest Unoccupied Molecular Orbital
Lithium di-*iso*popylamine	LDA
MeOH	Methanol
NMR	Nuclear Magnetic Resonance
$PhB(OH)_2$	Phenylboronic acid
KOH	Potassium hydroxide
t-BuOK	Potassium *tert*-butoxide
t-BuOH	*tert*-Butanol
TBAF	TetraButylammonium fluoride
t-BuLi	*tert*-butyllithium
THF	Tetrahydrofuran
$Pd(PPh_3)_4$	Tetrakistriphenylphoshine palladium
TLC	Thin Layer Chromatography
Et_3N	Triethylamine
TIPS	Tri*iso*propylsilane

TMSA	Trimethylsilylacetylene
$(CH_3)_3SiCl$	Trimethylsilyl chloride

Chapter I. Introduction

I.1 An overview

The need for increasingly small computational and electronic devices has resulted in a great deal of research in the past 20 years. At present, requirements are being met by the miniaturization of silicon based chips, the "top down" or lithographic approach. In 1975, Intel co-founder Gordon Moore predicted there could be a doubling of silicon densities every 2 years, *i.e.* a doubling of devices per silicon chip. This statement, or "Moore's Law" has held true for 30 years; however, it has been predicted that Moore's Law will be accurate for 20 more years at most, given the current rate of technological advances.[1] Quantum tunnelling and excessive power consumption are just two examples of the difficulties encountered if miniaturisation continues on such a scale.[2] A possible alternative is the "bottom up" approach, wherein specific molecules are synthesised with inherent properties, which can form the junctions in nanodevices. It was Richard Feynman, the eminent physicist who, in 1959 said

> "*I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements - and by little I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms...there is plenty of room to make them smaller. There is nothing I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now. In fact, there may be certain advantages.*" [3]

Aviram and Ratner, in 1974, first proposed using the inherent properties of a molecule, to be assembled with other components to make an electrical device.[4] This theory built on earlier work by Kuhn *et al*, who had reported reproducible electrical transport measurements through organic molecules.[5] Significant progress could only be realised, however, with the advent of many technological advances, such as scanning tunnelling microscopy, used to characterise and measure the junctions. The assembly of functioning devices is only possible with the fabrication of the many other electrical components such as switches, diodes, logic gates *etc.*

The history of this field is relatively brief, with some of the earliest work by Kuhn *et al* in the 1970's, wherein the group reported some of the first effective self-assembly

techniques comprising molecular bond formation between molecules and the desired surface. The mid-1980's witnessed the introduction of Scanning Probe Microscopy (SPM), enabling the measurement and manipulation of molecular structures and hence brought about a renewed impetus in the synthesis of organic molecules for use in electronic devices, including the fullerene C_{60} as an electromechanical gate[6] and transport measurements on thiol-terminated organic molecules sandwiched between a gold surface and a gold nanocrystal.[7] Currently, there is much research in the field of "molecular electronics", which is defined as "*electronics whose behaviour is dictated by the chemical, physical and electronic structures of molecules*".[8] Currently the wire part of the device is attracting considerable interest, with the ability to tune the intrinsic properties of a relatively long molecular system being extremely desirable.

Several different types of wires have been proposed, all of which must be able to conduct either electrons or holes to ensure electrical conductivity through the circuit. Another requirement of the wire is that it has to be of a bespoke length to bridge the gap between the two components within the circuit. Currently gaps of *ca.* 10 nm can be engineered using lithography techniques, and hence the synthetic chemists are faced with a challenge of synthesising a wire that is 10 nm in length, which can be extremely difficult if polymerisation is to be avoided.

The most common types of wires reported are conjugated molecules, which can conduct electrons through their electron rich π-systems. Usually such conjugated molecules comprise alternating single and double/triple bonds and often include π-electron rich systems such as aromatic moieties. The desire for a linear conjugated wire has driven much research in the direction of utilising the *sp* carbons in triple bonds rather than the sp^2 carbons in double bonds, thus eliminating possible isomerisation which can occur if double bonds are utilised.

Having synthesised the molecular wire junction, the next task is the attachment of the organic molecule to the metal electrode (simulating the integration of the junction into the circuit). There have been several reported approaches to this problem.

One approach is the donor-bridge-acceptor system wherein the addition of a redox active metal centre at the termini of the wires, will act as either donor or acceptor for the electrons being transferred across the bridge or wire of the system (**Fig I.1**).

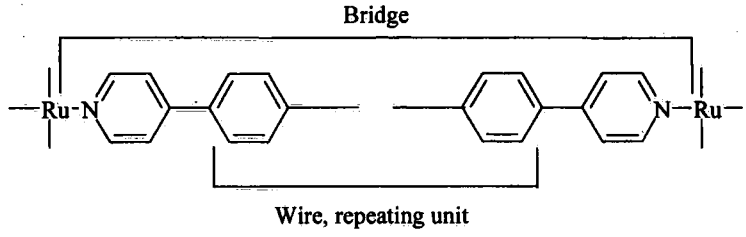
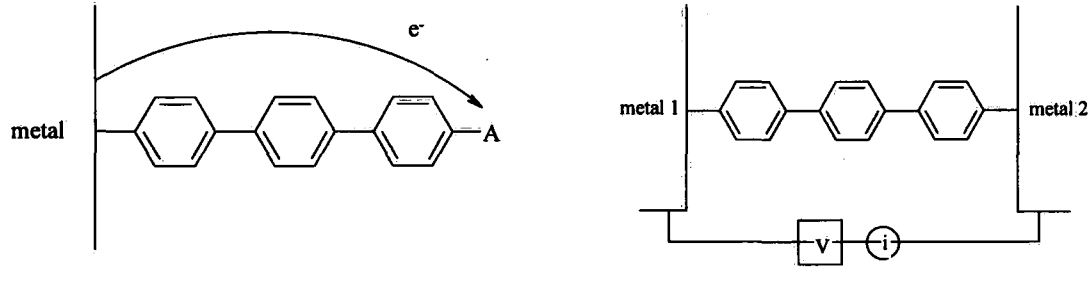


Figure I.1 Illustration of a molecular wire in a mixed valence system.[9]

The main advantage of this system is that the electron transferred is generated *in situ*, hence avoiding the need to connect the molecule to an external system. For this system to function efficiently, and hence allow conduction of electrons, there must be sufficient overlap between the *d*-orbitals of the metal centre and the π-orbitals of the bridging fragment. The overlapping of these orbitals, however, results in there being a significant contribution from the active metal centre, thus it is extremely difficult to determine which properties have arisen from the bridging wire, or from the metal centres. Another important factor is the definition of where the actual "wire" starts. As illustrated in **Fig I.1**, there is a clear difference between the "wire", which is the repeating unit, and the "bridge" which is the distance between the two metal centres, and which must include coordination to the metal centre.

To fully determine how the structure of the bridge affects the electron transfer rate, the donor or acceptor, or both, can be replaced by a conducting surface, **Fig I.2**. The problem of how to attach an organic molecule to a solid conducting surface thus arises. The most common approach involves the incorporation of thioacetate end groups into the wire, which will hydrolyse once in solution to form a thiol.[10] When exposed to a gold surface, a gold-thiolate bond will form (**Fig I.3**).



Modified electrode in solution Molecular junction between two electrodes

Figure I.2 Substitution of donor, acceptor groups, or both, by a gold electrode.[11]

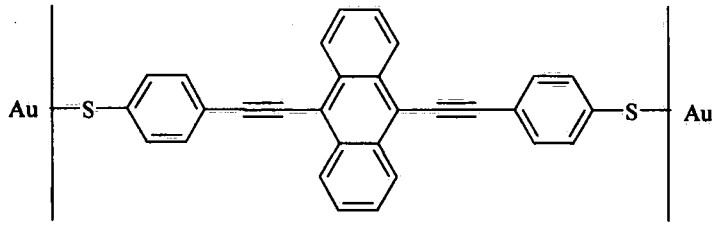


Figure I.3 Example of gold-thiolate bond formation. [12]

More recently the use of a thiocyanate end group has been reported which is air, moisture and light stable and does not require *in situ* deprotection.[13] The use of dithiocarbamates has also been explored, which can form on a gold surface when a 1:1 molar mixture of carbon disulphide and secondary amines are exposed to a gold surface, **Fig I.4**.[14] The use of the nitrogen-gold affinity has also been shown to be a successful route, by way of pyridyl moieties being used as end-capping groups.[15]

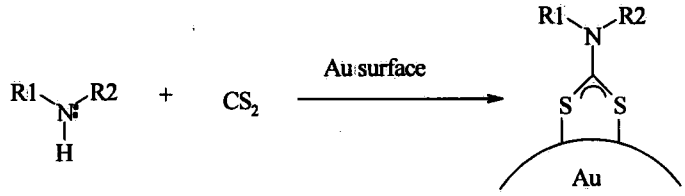


Figure I.4 Dithiocarbamate ligands forming on a gold surface, taken from[14]

Another alternative to the gold-thiolate linkage is the alkyne electrografting technique used to graft alkynes onto a silicon surface,[16] or the photochemical linkage of alkenes onto proton-terminated silicon surfaces.[17]

The position of the anchor group on the organic wire can also have a profound effect. In a recent study *meta* phenylthiolate versus *para* phenylthiolate was investigated (**Fig I.5**). The authors concluded that in the *meta* position conjugation is reduced and, hence by comparison with the *para* isomer, it is favourable to have the anchoring group in the *para* position.

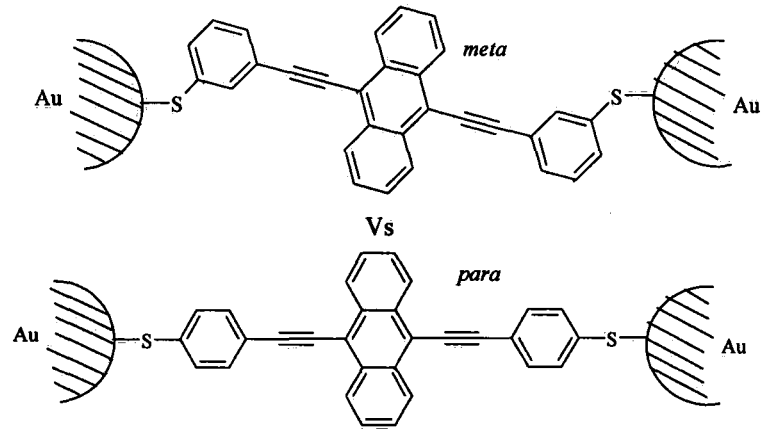


Figure I.5 Wires with *meta*- and *para*-phenylthiolate end groups.[12]

The ability to measure electrical conduction is of prime importance in the advancement of this field. With the development of scanning tunnelling microscopy (STM), it became possible to measure the electrical response of the molecular wire candidates. This was illustrated when Tour *et al* inserted an oligo (phenylene-ethynylene) wire of 2.5 nm length into an insulating layer of alkanethiol ligands, attached to a gold surface.[18] As the STM probe was passed over the surface, a significant increase in electrical current was detected when the probe contacted the OPE, as compared to the insulating layer of alkanethiol (**Fig. I.6**).

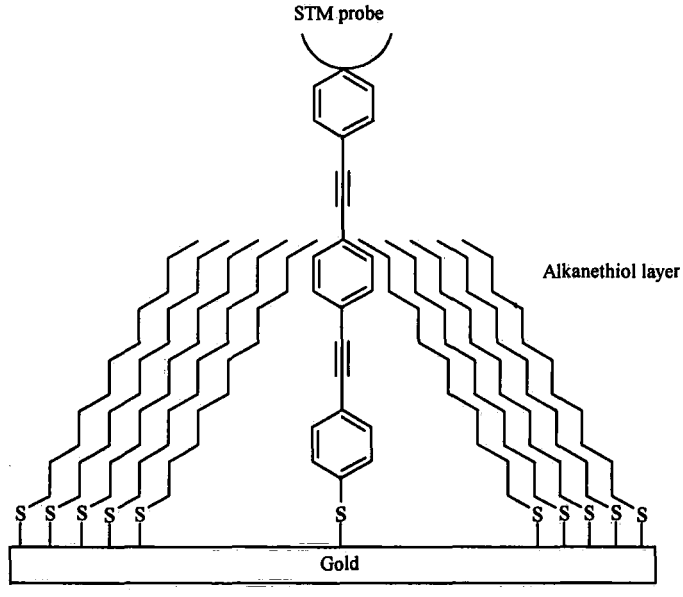
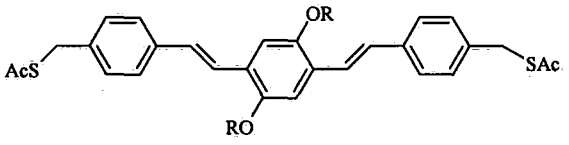


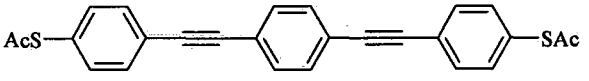
Figure I.6 Schematic drawing of an OPE system inserted into an insulating monolayer of alkanethiols.

The conductance of the wire is an extremely important characteristic, *i.e.* how well is the charge transferred, be it measured in distance or in time? The transfer of charge

appears to occur *via* a tunnelling mechanism and is measured using a tunnelling decay parameter, β. It was shown that the electron transfer displays an exponential dependence on wire length.[1] Ratner *et al* have also suggested that the bond length alternation in oligo(phenylenevinylene) (OPV) **1** offers an important contribution to charge transfer, when compared to oligo(phenyleneethynylene) (OPE) **2.** [19] For a complete and more detailed overview see references.[20-22]



OPV, **1**



OPE, **2**

Various types of molecules have been candidates for the wires, *e.g.* carbon nanotubes, porphyrin oligomers and conjugated hydrocarbons. Each of these candidates will be discussed in the following sections.

I.1.2 Carbon nanotubes

Carbon nanotubes were first discovered in 1991.[23] They consist of graphitic sheets of a hexagonal lattice, which wrap up to form a completely seamless cylinder. These entities are mechanically extremely stable, rigid and have desirable electrical properties, hence their exploitation as molecular wires. They offer very little electrical resistance and their electrical conductance can be tuned by varying their diameter or wrapping angle. The largest source of electrical resistance is the contact resistance between the nanotube and the electrode.

There are two main groups of nanotubes; single walled nanotubes (SWNTs) or multiple walled nanotubes (MWNTs), which have a thickness range between 2 and 50 layers. The individual layers in the MWNTs, however, can interact with one another and thus affect the overall properties of the nanotube. It is for this reason that SWNTs are more suited as a wire, and hence research has focused on them. By using STM measurements, it is possible to categorise nanotubes into three classes based on their electrical properties; the first class is based on metallic tubes, the second class are semi-conducting with a large band gap and the third are semiconducting with a small band gap.

Synthesis of SWNTs has greatly improved in recent years.[24,25] Nonetheless, nanotubes are still difficult to fabricate, since the wrapping angle and diameter have to be exact. Instead the actual desired tube has to be extracted from a bundle of tubes of varying sizes and diameters, which can be wasteful and not desirable on a large industrial scale.

Defects formed during the fabrication, whether due to impurities present or the presence of pentagon-heptagons, can greatly reduce the electrical conductivity of the nanotubes. The presence of metal ion impurities have served as an advantage, however; the possibility of doping the nanotube with a small amount of metal could give rise to some interesting properties. Another suggestion is to use two nanotubes in the construction of the wire; the first tube will be semi-conducting or insulating and would form a protective sheath, the second tube would be metallic and would fit inside the protecting tube. The main advantage being that the protective sheath would limit the interference from surrounding charges, emanating from external wires[9] **(Fig I.7)**.

Fig. I.7 A double walled carbon nanotube[26] and a highly organised array of nanotubes.[27]

One proposal for a nanotube device has been reported in the literature.[27] A series of parallel nanotubes was arranged on a substrate and a series of perpendicular nanotubes were suspended on a periodic array of supports. At each point in the device where two nanotubes cross is a device element, which can exist in two states. The OFF state occurs when the two tubes are separated by the gap and hence the resistance between the two tubes is large. The ON state occurs when the transient charge between the nanotubes results in an attractive force, thus resulting in the tubes moving so that they are in contact by bending, and hence conductivity between the tubes increases. This state remains (due to van der Waals forces) until the transient charge results in repulsive electrostatic forces and hence the tubes move so that they are no longer in contact. The main advantage of this design is that the circuitry only has to address the ends of each wire since this is enough to control all crossing points in the array. Calculations have

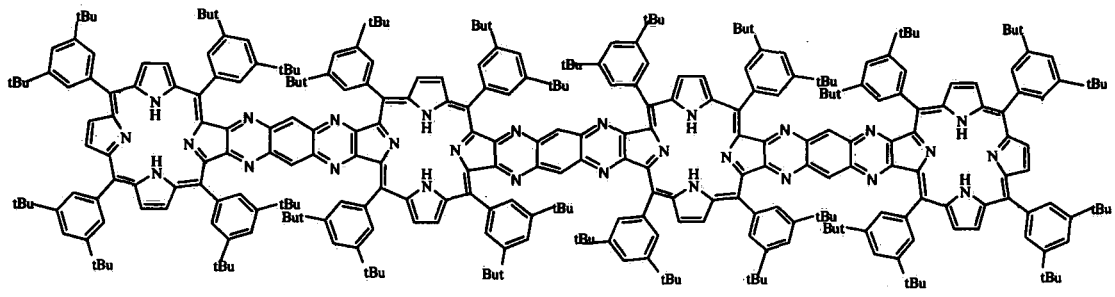
shown that the SWNTs have sufficient mechanical properties to bend (as required in the ON state), whereas most other materials do not, hence making such an array viable, **Fig I.7**. This strategy was demonstrated on an array with one cross-junction; a difference of 10 in conductivity was observed between the ON and OFF state in a device with reversible switching. This figure rose to 10^5 in a device which did not possess reversible switching.

It has been shown, hence, that carbon nanotubes are a possible candidate for use as molecular wires and may offer some unique electrical properties, as well as being extremely stable and rigid. Some working proposals have been produced, although on a very small scale. It is not certain whether such a device could, in future, be easily scaled up to form part of a molecular circuit; this may be extremely difficult if automated fabrication were to be employed.

I.1.3. Porphyrins

Porphyrins are a group of naturally occurring macrocycles. When these porphyrins are fused with other π-systems they form conjugated oligomers, which display extraordinary electrical properties. It has been suggested, that the π-systems merge to form "*giant supramolecular chromophores*".[28, 29] The HOMO and LUMO levels in a porphyrin conjugated system are separated by only 2 eV. If this gap were to be narrowed slightly (for example by chelation to a metal atom) then the system would have extremely desirable properties for use as a molecular wire.

Another main advantage of using such a system is the size; a porphyrin monomer is approximately 1.6 nm in diameter, hence exntended version of tetrakisporphyrin derivative **3** shown in **Fig I.8** could easily span bespoke gaps of *ca.* 10 nm without the problem of polymerisation, which can occur, for example, when trying to synthesise a hydrocarbon chain of 10 nm length.



3

Figure I.8 Tetrakisporphyrin system, ca. 6.5 nm length[30]

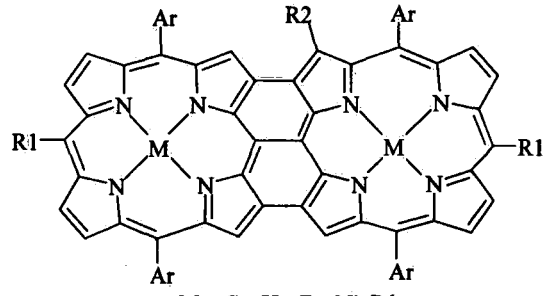
The tetrakisporphyrin system has some other interesting properties; the peripheral *tert*-butyl groups act as a "sheath", protecting the porphyrin backbone from nearby electric fields.[30] By substituting at similar positions, inherent characteristics, such as solubility, can also be greatly affected.

A large number of porphyrin systems (*ca.* 100) have been studied computationally to determine whether or not they are viable for use as a molecular wire. It was concluded that these porphyrin systems are highly tuneable and hence their characteristics depend upon substituents on the porphyrin ring and the nature of the bridging unit, which is 1,4,5,8-tetra-azaanthracene in structure **3**. The results also suggest it is the extensively delocalised π-system which results in the high degree of electron communication from one end of the system to another, a fundamental property of a potential molecular wire.

There are two main methods of linking these giant porphyrin systems. The first involves the direct fusing of the porphyrins, enforcing a coplanar geometry, which facilitates the delocalisation of the π-system. These fused systems can be either doubly or triply linked and are synthesised *via* the oxidation of a metallo-porphyrin using *tris*(4-bromophenyl)ammonium hexachloroantimonate. An example of a triply linked system is **4**; this triply linked diporphyrin exhibits a large degree of π-overlap due to the enforced co-planar geometry. This triply linked system showed strong electronic interactions and a smaller optical HOMO-LUMO gap, compared to the doubly linked diporphyrin. [29]

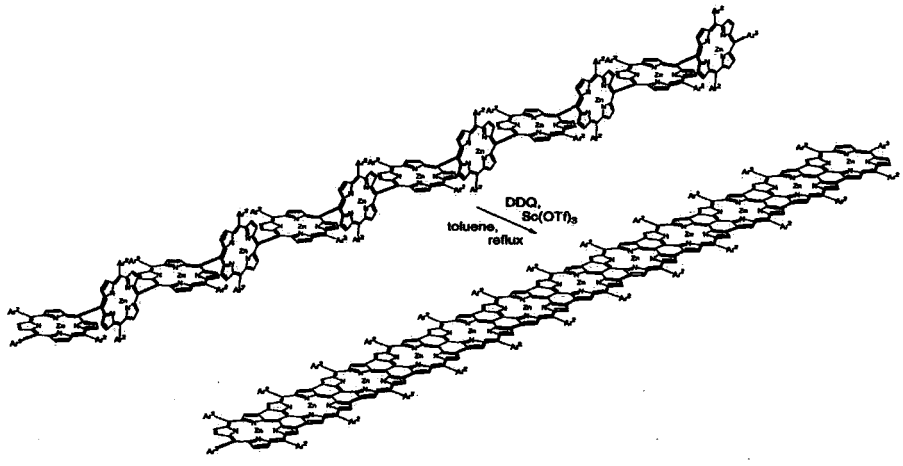
Another example of a triply linked system is the ladder-like porphyrin system **5** reported by Tsuda *et al*,[31] synthesised from the scandium catalysed oxidation of meso-meso linked zinc-porphyrin arrays (up to dodecamers, **Scheme I.1**). This molecule is extremely rigid and also will not undergo rotamerisation (spinning around bond axes),

however these molecules are extremely difficult to synthesise and therefore not practical for industrial scale-up.



M = Cu, H_2, Zn, Ni, Pd
R1 = Ar, Ph
R2 = H, Cl

4



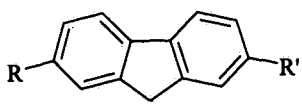
5

Scheme I.1. Triply-linked ladder like porphyrin system reported by Tsuda. [31]

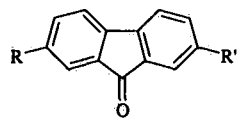
The second method of linking is using aromatic structures (delocalised and planar) or alkynes to bridge the porphyrin monomers, ensuring a discrete conjugated system is obtained.

I.1.4 Conjugated hydrocarbons

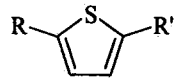
Conjugated hydrocarbons are popular molecular wire candidates. Numerous types of hydrocarbon chains have been reported in the literature. Currently there is a wide range of functionalities that have been incorporated into these chains, such as fluorene **6**, fluorenone **7**, and thiophenes **8**. Indeed, Ikemoto *et al* have reported a porphyrin-oligothiophene-fullerene triad to investigate the oligothiophene as a spacer in a long range electron system and thus incorporating the desirable electrical properties of the porphyrin system **9**.[32]



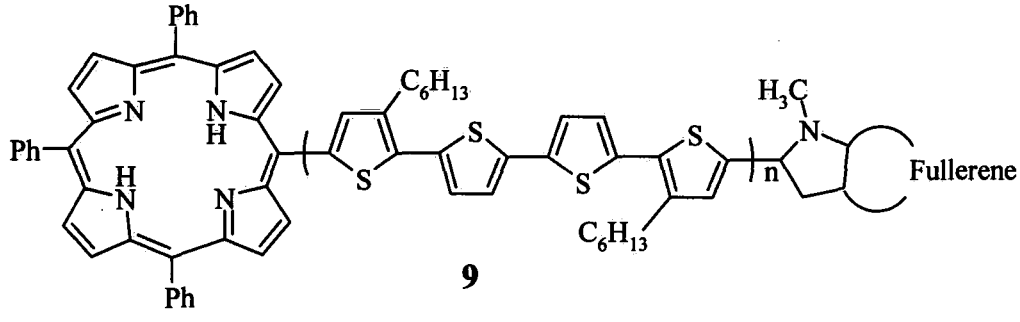
Fluorene, **6**



Fluorenone, **7**

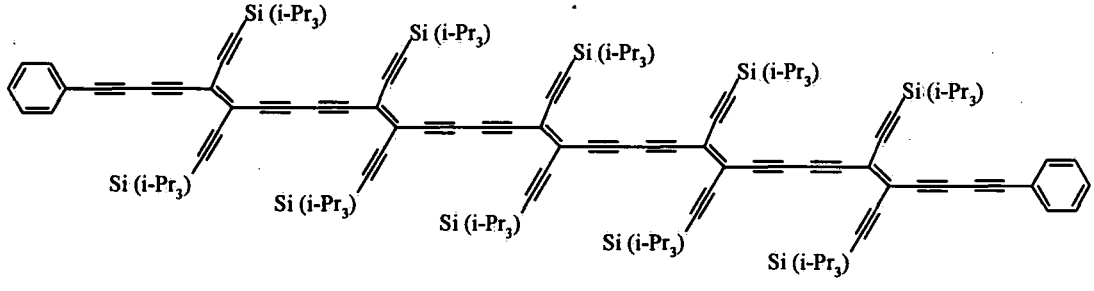


Thiophene, **8**



9

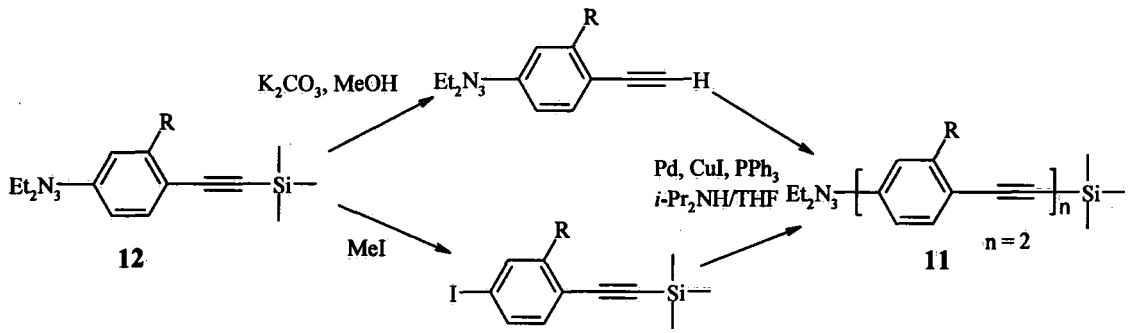
The synthesis of long molecules is not easy, especially if polymerisation is to be avoided. It can be extremely difficult to obtain a molecule of bespoke length by polymerisation; often various side products of differing lengths are obtained. One successful method is the end-capping polymerisation of *trans-bis*-(tri*iso*propylsilyl)-protected tetraethynylene to synthesise **10**.[33] The end-capping species (in this case phenylacetylene) controlled the average length of the product produced. By varying the concentration and the time at which the phenylacetylene was added, it was possible to alter the average length of the polymer obtained.



10

An interesting feature of **10** is the tetraethynylene backbone; very few examples in the literature include the use of butadiynes as linker groups in between the alkenes. There are, however, many examples in the literature of polyynes being used as linker groups in long conjugated systems. This will be discussed in more detail in a later section (I. 2. 3).

An alternative method to polymerisation is the iterative divergent/convergent approach, wherein the molecular length doubles at every iterative step, and hence results in easy purification due to the considerable difference in molecular weight.[18] It is thereby possible to obtain a molecule up to 10 nm in length involving only 3 reaction steps; iodination, deprotection and a Sonogashira coupling of terminal acetylenes with aryl halides (**Scheme I.2**).[34]



Scheme I.2 The iterative convergent/divergent approach.

The product **11** has the same protecting group as the starting material **12**, hence the same procedure can be repeated to obtain the tetramer and so on. The orthogonal protecting groups afford the opportunity of selective deprotection in high yields. This method is only suitable if an even number of monomers and a symmetrical molecule is desired. Another disadvantage is the use of the volatile and carcinogenic iodomethane; possible alternatives have been reported, such as the metal-halogen exchange of bromine and iodine.[35]

The above strategy has also been applied in solid-phase synthesis, using poly(chloromethylstyrene), also called Merrifield's resin. The last step of the scheme involves the removal of low weight by-products by filtration and washing. The resin is removed by cleaving from the oligomers, thus making purification easier.

Another possible synthetic methodology to follow is the stepwise addition approach, wherein at each step there is a continuous addition of a monomer to both ends of the growing chain which is asymmetrically protected, due to the difference in reactivity of iodines and bromines to terminal acetylenes. [36, 37]

I. 2 π-conjugated carbon backbones

The five main types of linearly conjugated carbon-rich backbones are outlined in **Fig I.9**.

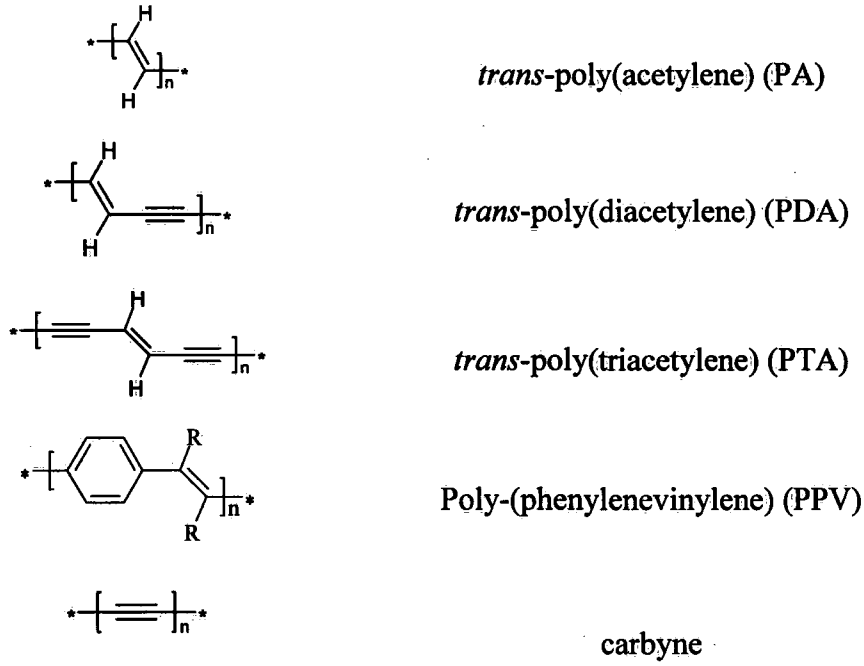
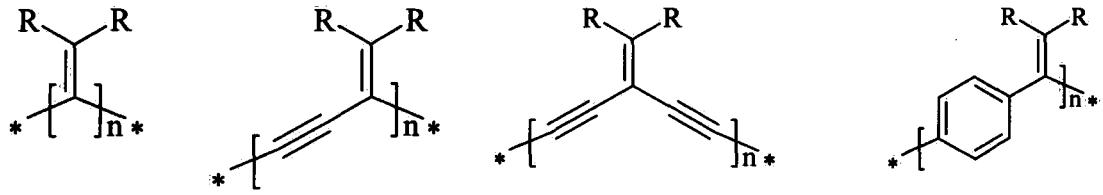


Fig. I.9; The five main types of conjugated carbon rich backbones

These compounds can then be linked using aromatic moieties, which often increases the solubility of the final product.

There are, however, alternatives to the linear-conjugated π-systems. Cross-conjugated molecules have attracted a lot of interest recently. Cross-conjugated molecules are molecules with "*three unsaturated bonds, two of which although conjugated to a third unsaturated centre are not conjugated to each other.*"[38] The π-electron density is less readily delocalised along this framework compared to the linear framework; however, electron communication is observable in such systems. **Fig I.10** shows the main cross-conjugated compounds in the literature.



Dendralene *Iso*-polydiaceylene *Iso*-polytriacetylene Poly(phenylenevinylene)

Fig I.10 The four main types of cross-conjugated carbon backbones.

This review will focus on both the linear and cross conjugated π-systems.

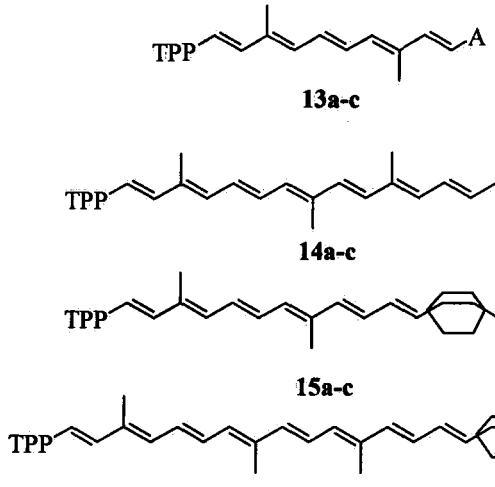
I. 2. 1 Oligo(ene)s

Trans-poly(acetylene), PA, is the simplest π-conjugated polymer not to contain any aromatic rings. It is known for its high electrical conductivity upon doping.[39] These compounds can be, however, extremely insoluble hence solubilising functionalities have been added by substitution of the ethylenic hydrogen atoms. However, this results in severe steric interactions and distortion of the conjugated backbone out of planarity, known as allylic 1,3-strain. In 2000, Heeger, MacDiarmid and Shirakawa received the Nobel Prize for Chemistry due to their work on these PA systems.

To test the electrical transfer properties of the PA systems, and hence determine whether polyacetylene systems are feasible candidates for molecular wires, various donor, acceptor and redox active groups have been added in terminal positions. Wolf *et al* synthesised cartenoid polyenes with varying end groups to study the intramolecular energy transfer, **13-16**.[40] The authors observed that the use of the bicyclo[2.2.2]alkane unit in molecules **15** and **16** did affect the conductivity, although not to a significant degree.

Müllen *et al.*[41] reported the use of the Stille cross-coupling methodology to synthesise stable analogous oligoenes, **17a-c**. These were shown to be highly redox-active, displaying up to seven successive one-electron transfer processes when studied using cyclic voltammetry.

Knoll and Schrock reported controlled Ring-Opening Metathesis Polymerisation (ROMP) to synthesise oligoenes **18a-e** with odd and even numbers of double bonds.[42]

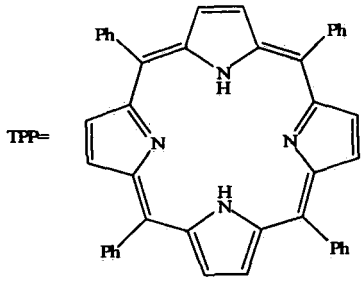


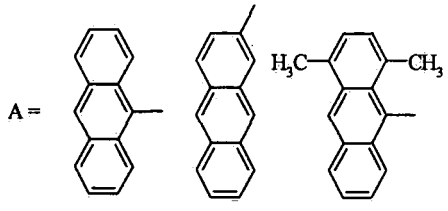
13a-c

14a-c

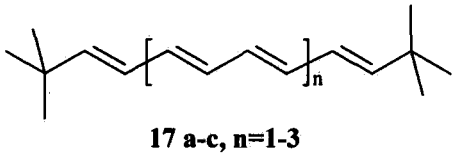
15a-c

16a-c

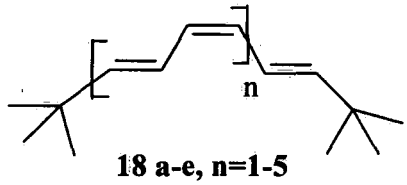




a b c

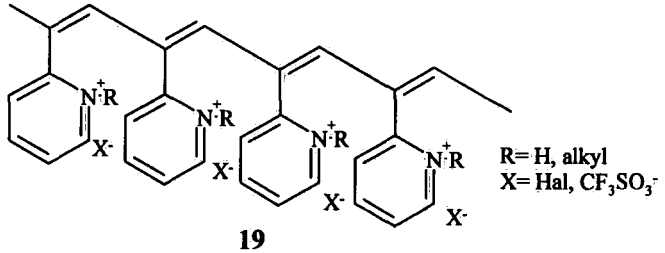


17 a-c, n=1-3



18 a-e, n=1-5

The inherent insolubility of polyenes presents difficulties for their synthesis, characterisation and use as molecular wires. Blumstein and co-workers have, however, reported the use of 2-pyridinium side-groups, which can be introduced into each repeat unit of **19**.[43] The resulting electrostatic repulsion encourages planarity in the conjugated backbone, thus resulting in a significant increase in linear π-conjugation as compared to unsubstituted PA systems. By varying the nature of the side chains R, the solubility of the system was greatly increased, *i.e.* was soluble in solvents ranging from water to non-polar solvents.

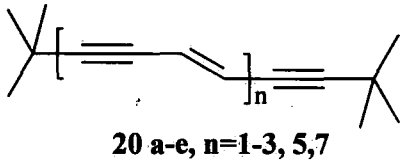


19

I. 2. 2 Oligo(eneyne)s

The second class of π-conjugated non-aromatic backbones are *trans*-poly(diacetylenes) (PDAs), which require a topically controlled synthesis usually from substituted 1,3-butadiynes, hence limiting their accessibility. These systems are, however, considerably more stable than the PA systems.

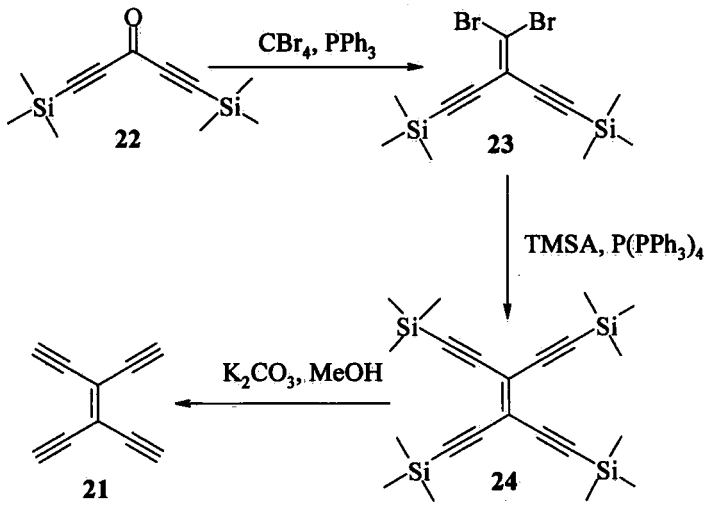
In the first series of these compounds to be synthesised, Wudl and Bitler[44] reported that for compounds **20 a-e** as chain length increased, there was a noticeable colour change, ranging from white (**20a, b**) to deep yellow (**20 e**). A difference in solubility was also observed; the compounds were decreasingly soluble in either *n*-hexane or benzene. The *tert*-butyl end groups increased thermal stability, and contrary to the general case with oligoenes, the oligomers were shown to be air and light stable, hence have more practical applications.



20 a-e, n=1-3, 5,7

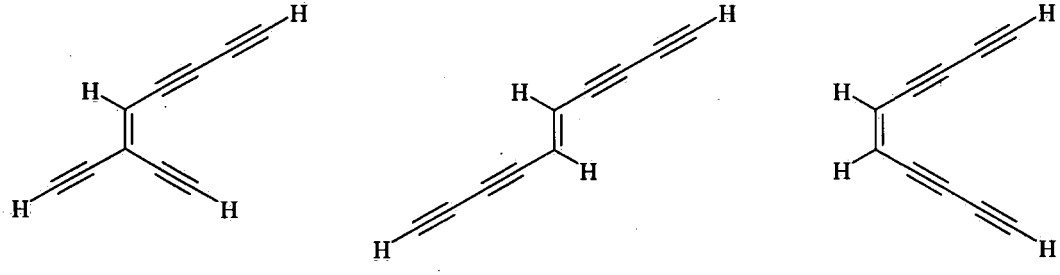
Although such non-aromatic backbones do have potential use as antitumour agents in medicinal chemistry, most work within molecular electronics includes aromatic systems either within the repeating unit or as an end-capping group, which increases π-conjugation and can also result in desirable electronic properties.

Tetraethynylethene **21** was first isolated by Diederich and co-workers in 1991. Not only is it an important example of a cross-conjugated system, it was perceived to be a direct precursor for all-carbon networks. The synthesis is relatively straightforward; 1,5-*bis*(trimethylsilyl)-1,4-pentadiyn-3-one **22** was brominated to afford **23**. Reaction with TMSA catalysed by $Pd(PPh_3)_4$ afforded the protected species **24**, which was deprotected (K_2CO_3 in methanol) to afford **21 (Scheme I.3)**. Tetraethynylethene **21** is a white solid, which decomposes rapidly at room temperature, even in the absence of oxygen. Having shown the isolation of such an elusive compound was possible, the authors further reported the isolation of a wide range of functionalised tetraethynylethene derivatives, which will be discussed in a later section.



Scheme I.3.

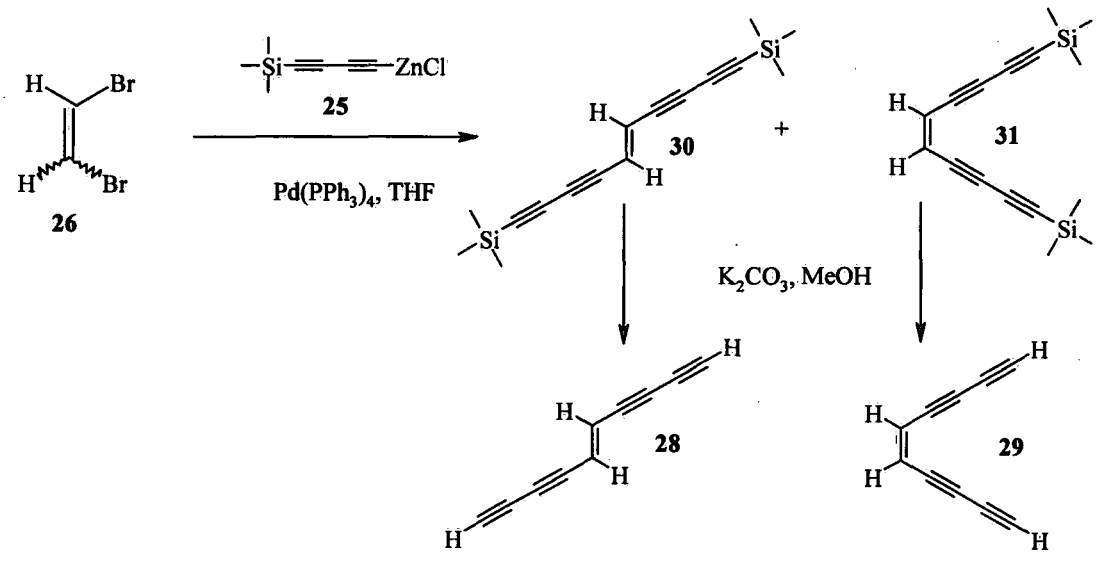
Following on from this work, Bowling *et al* reported the synthesis and isolation of enediyne isomers of tetraethynylethene.[45] Palladium catalysed Negishi coupling of a trimethylsilylbutadiynyl zinc reagent **25** with a bromoalkene **26**, followed by silyl deprotection in methanol with K_2CO_3 affords the three isomers **27**, **28** and **29** in good yield.



27 **28** **29**

The synthetic routes do vary slightly; isomers **28** and **29** were isolated separately from precursors isolated from one reaction, whereas isomer **27** was isolated separately.

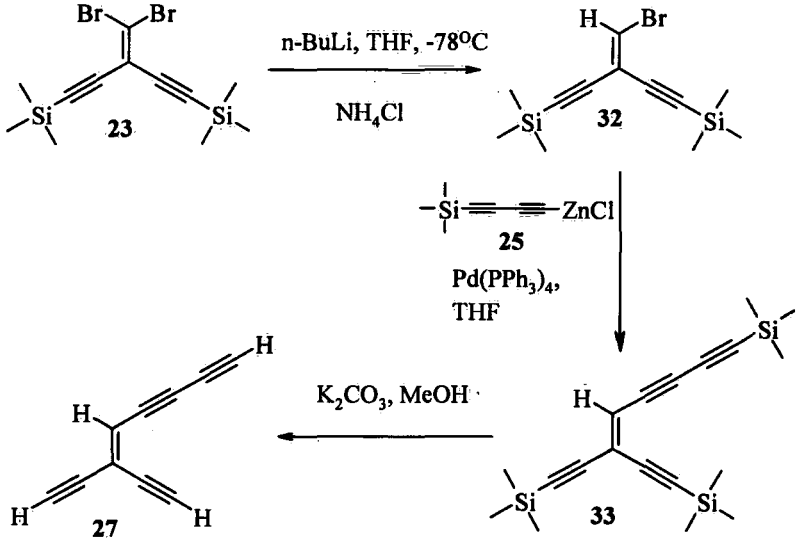
1,2-Dibromoethylene **26,** available commercially as a 2:1 mixture of *trans:cis* isomers, undergoes Negishi coupling with zinc reagent **25** in good yield to afford a mixture of **30** and **31**, which were separated by repeated flash chromatography. Basic deprotection afforded **28** and **29** as white solids at -41 °C. **Scheme I.4.** The neat enynes exhibit slow decomposition at -41 ° C, and can be stored for weeks at -20 ° C in $CDCl_3$.



Scheme I.4

The synthesis of isomer **27** is different; dibromoalkene **23** was reduced to monobromoalkene **32**,[46] which is coupled with **25** under Negishi conditions. Deprotection of **33** (K_2CO_3 in methanol) afforded **27** as a white solid at -41 ° C.

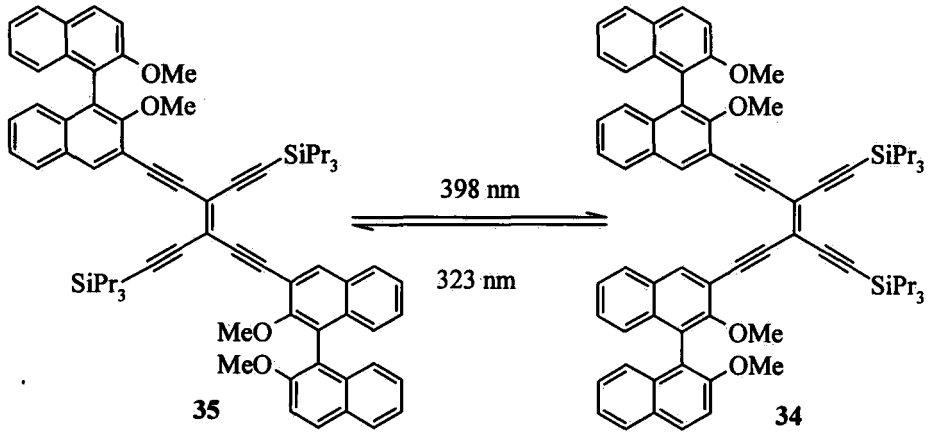
Scheme I.5



Scheme I.5.

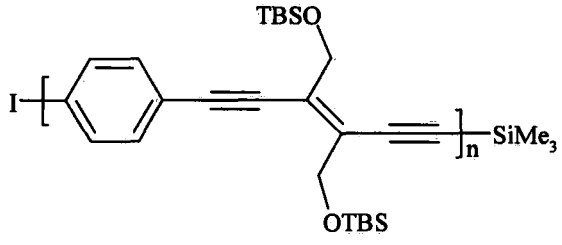
Hori and co-workers reported the synthesis of phenyl-derivatised TEE species in 1960.[47] An interesting physical property observed for the aromatic substituted TEE derivatives is the ability to undergo reversible photochemical *trans→cis* and *cis→trans* isomerisation.[48] Hence a possible application is as a photochemical molecular switch, such as that illustrated in **Scheme I.6**, based on a tetraethynylethene-1,1'-binaphthalene system. Both the *cis-* and *trans-* isomers are thermally stable and their ground state

conformations shown by X-ray analysis. Irradiation at 398 nm afforded a greater percentage of **34**, whereas irradiation at 323 nm afforded a greater percentage of **35**.[49]

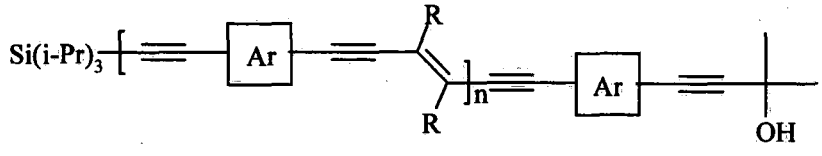


Scheme I.6 Schematic showing a photochemical molecular switch. [49]

In 2003, Diederich and co-workers reported the first synthesis of poly(triacetylene)-derived oligomers **36** by Pd(0) catalysed Sonogashira and Cadiot-Chodkiewicz cross-coupling reactions using a solid support, and thus obtained a new family of stable, highly fluorescent molecular wires.[50] Nikano and co-workers later reported a general method for the synthesis of oligo(arylene enediynes) **37**, where aryl is a phenyl, pyridyl or thienyl group. The authors reported an intense fluorescent emission and high quantum yields ($\Phi = 0.85$ where Ar = phenyl and n = 2) hence these systems are being investigated for their possible applications in organic light emitting diodes as well as their obvious uses as molecular wires. [51]



36, n=1, 2, 3, 4



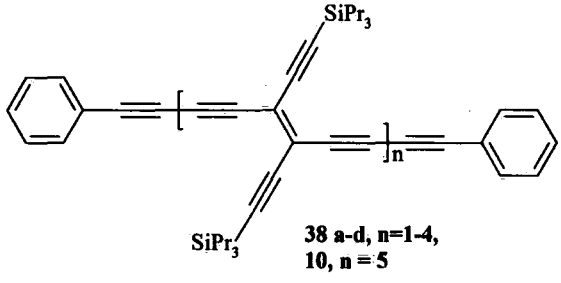
37

Ar = phenyl, pyridyl, thienyl
n =1, 2, 3

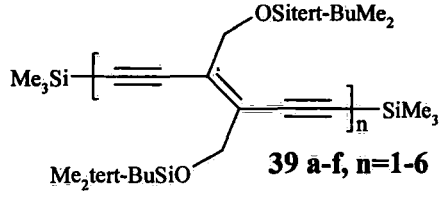
I. 2. 3 Oligo(enediyne)s

The third class of π-conjugated carbon backbones is the polytriacetylenes, which were first reported in 1994.[52] The extra acetylene unit results in an increase in spacing between side chains and hence eases steric repulsions. The PTA systems offer an attractive route into carbon-rich nanomaterials without the presence of aromatic moieties and are also a progressive step towards carbynes. Diederich *et al.* initially concentrated on the synthesis of compounds **38a-d** and **10**, which feature phenylacetylene end-capped tetraethynylethene repeat units. These compounds showed high kinetic stability, even at 5 nm in length with high melting points. They subsequently studied the effective conjugative length in these new PTA systems by preparing a series of analogous PTA oligomers, which varied only in length. **39**.[53] Cyclic voltammetric studies showed that all the oligomers underwent a reversible one-electron transfer reduction, which was facilitated by an increase in length of conjugated backbone; however they could not be oxidised below a potential of +1.0 V in THF.

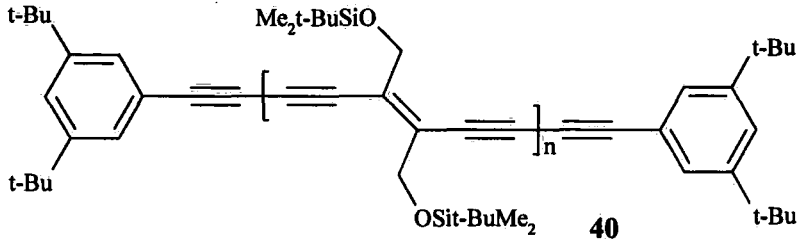
Research in this area has been intense over the past 10 years. The first longer chain PTA system, **40**, has been reported by Diederich *et al.* The authors described a synthetically variable route *via* oxidative acetylenic coupling which tolerates a range of functionality. The inherent physical properties of the system can be changed by varying the side-chains and many substituents were attached by using a different end-capping reagent.[54]



38 a-d, n=1-4,
10, n = 5



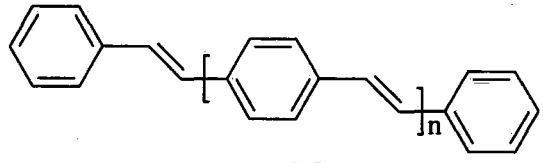
39 a-f, n=1-6



40

1. 2. 4 Oligo(phenylenevinylene)

This class of compound has been extensively studied since Friend and co-workers showed that light emitting devices can be made utilising PPVs as the emissive layer.[55] The physical and electronic properties have been extensively studied, as has the fine-tuning of the HOMO-LUMO energy gap by chemical modification of the basic structure, **41**. Such compounds have significantly contributed to the understanding of the optical properties of PPVs.



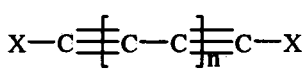
n = 0-2

41

I. 2. 5 Oligo(yne)s

The simplest all-carbon chain would consist of carbon atoms which are all *sp*-hybridised, *i.e.* a chain of alternating single and triple bonds of the formula R-$(C{\equiv}C)_n$-R. This polymeric *sp* allotrope, often called "carbyne" has conceptual importance; it is the *sp* allotrope of carbon, (*cf.* graphite is an sp^2 allotrope and diamond is an sp^3 polymeric allotrope). There is continuing research into carbynes and extensive literature, both older and modern. [56, 57]

It is worth noting that different valence structures are possible. The first features alternating single and triple bonds with *sp* carbon termini bonding to one end group, **42**. The second structure, a cummulene derivative, involves an sp^2 carbon backbone, with sp^2 carbon termini bonding to two end groups, **43**. The third valence structure has sp^3 carbon termini bonded to three end groups, **44**. The valence structure depends upon the nature of the end group and whether it is capable of forming one, two or three bonds to carbon.



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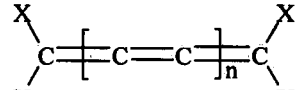
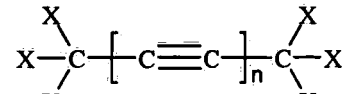
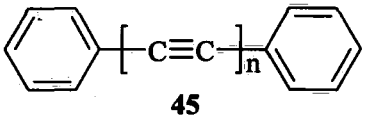


43



44

Recent studies have focused primarily on i) extending the polyyne length and fully characterising longer systems and, ii) exploring the wide range of end groups. An excellent overview of end-capped stabilised oligoynes has been published. [58] These end groups fall into two families; non metal, such as phenyl derivatives **45**,[59] cyano moieties **46**,[60] trialkylsilyl and bulky dendrimers **47**, [61] and metal containing end-caps, such as, ferrocenes **48, 49** ruthenium complexes **50** and platinum species **51**.[62] Recently, Gladysz and co-workers reported the synthesis and isolation of polyynediyl chains of up to C_{28} length (14 C≡C bonds) spanning two platinum atoms. [63]



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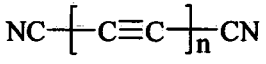

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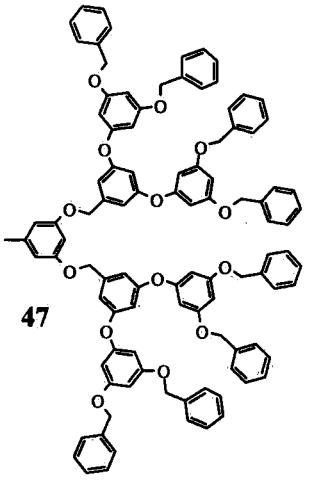

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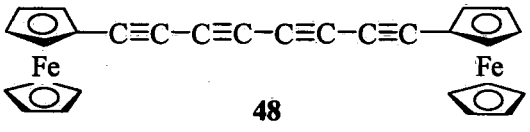

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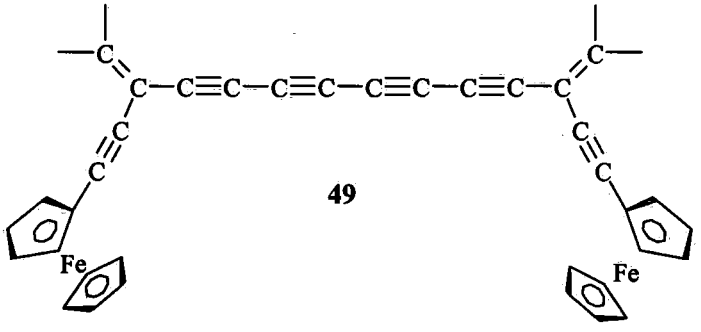

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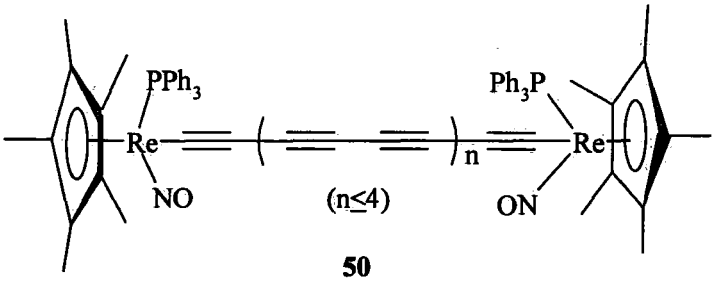

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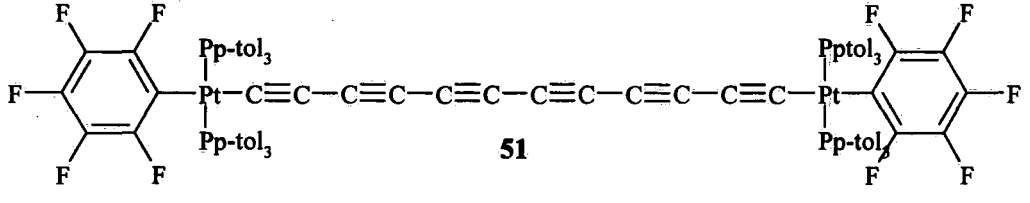
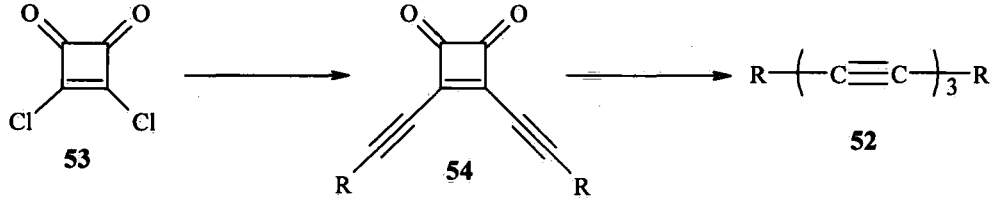


51

Polyynes offer inherently attractive properties as molecular wires, due to their rigidity and efficient electron transfer properties.

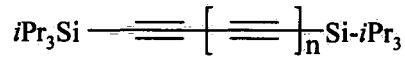
The commonest way to assemble polyyne chains remains a Cu-catalysed oxidative homo-coupling, such as the Glaser[64] or Hay reaction.[65] The main detraction from such a protocol is that it only allows the synthesis of even-numbers of triple bonds. Usually the silyl protected alkyne is deprotected *in situ* and then oxidatively homocoupled in a one-pot synthesis. Walton *et al*, even isolated $H(C{\equiv}C)_{12}H$ in solution from a desilylation reaction, the only characterisation being UV-Vis data. There is a slight blue shift of the deprotected species (λ_{max} = 375 nm) compared to the protected silylated species (λ_{max} = 388 nm).[66] However, the main problem of how to synthesise and isolate a large quantity of the longer polyynes still remains. Another problem encountered with these systems, if they are to be considered as potential candidates for molecular wires, is the attachment of the terminus to the electrodes. This would require the deprotection of the polyyne system, hence result in the formation of a potentially unstable species.

The formation of polyynes with an odd number of C≡C bonds remained elusive for a long time, since oxidative homocouplings usually afford even-numbers of C≡C. In 1991, Rubin *et al* reported the synthesis of symmetric and asymmetric substituted polyynes **52** from 3,4-dichloro-3-cyclobutene-1,2-dione **53** via an alkyne precursor **54**, **Scheme I.7** [59, 67]



Scheme I.7

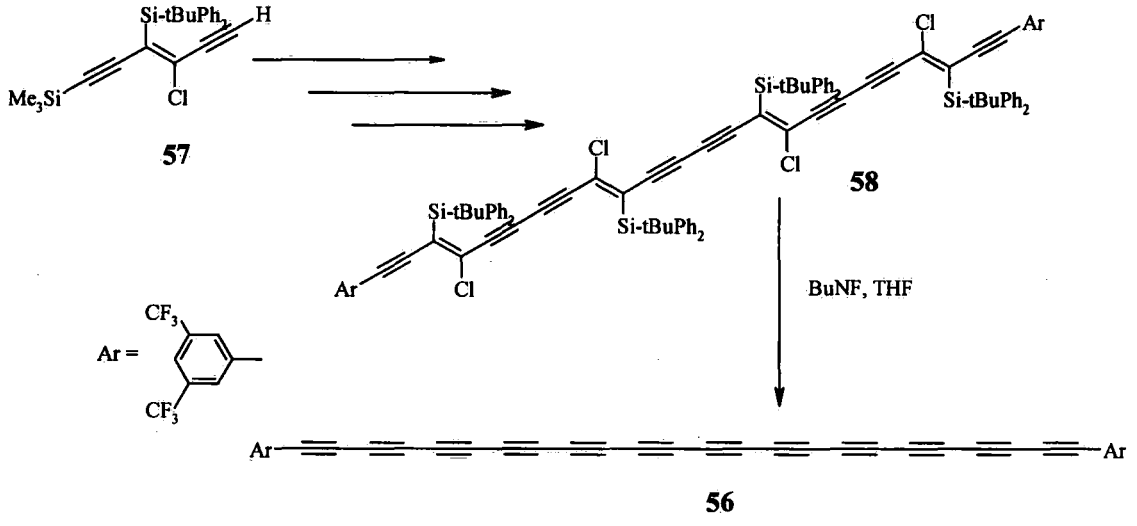
A one-pot synthesis and functionalisation of polyynes has recently been published by Tykwinski and co-workers.[68] The authors have also reported the synthesis of polyynes as a model for "*carbyne, the hypothetical linear form of carbon consisting entirely of sp-hybridized carbon atoms*". [69] A series of tri*iso*propylsilyl (TIPS) end-capped polyynes was synthesised *via* the Fritsch-Buttenburg-Wiechell rearrangement and oxidative homocouplings, **55**.



n = 1-7, **55**

Very recently, the synthesis of the first aryl-end-capped dodecayne **56** was reported by Simpkins *et al*, [70] starting from the masked triyne **57**.[71] A 5-step synthesis afforded masked dodecyne **58**, which underwent dechlorosilylation with 4 eq. fluoride to afford

56 (**Scheme I.8**). The species was very unstable, however, decaying before UV-Vis spectra could be recorded. To prove isolation, the authors monitored the unmasking reaction by UV-Vis spectroscopy, since masked and un-masked dodecyne differ significantly in the UV-Vis spectrum, **Fig I.11**.



Scheme I.8

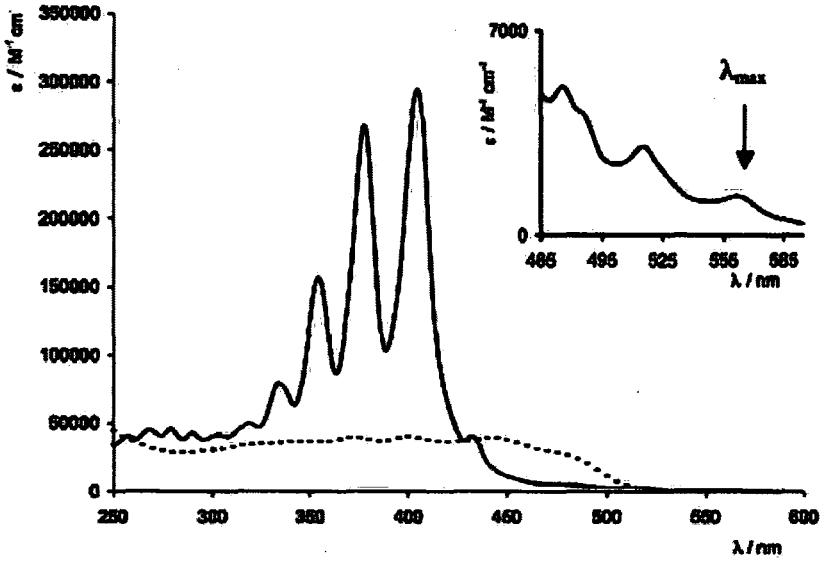


Fig. I.11 A UV-Vis spectrum of masked dodecayne 58 (dashed line) and dodecayne 56.[70]

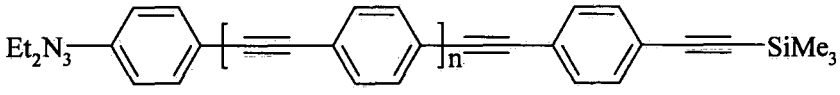
The stability of these long compounds has historically been an associated problem. Recent work published by Sugiyama *et al*, reports the use of complexation with α-cyclodextrin to stabilise and solubilise the oligoynes formed. [72]

To conclude, therefore, there is large amount of research at present on the potential use of polyyne systems as molecular wire candidates. However, until the difficulty of attachment to electrodes has been addressed the systems will not find applications in device architectures.

I. 2. 6 Oligo(aryleneethynylene)s

Oligo(aryleneethynylene)s comprise alternating aromatic or heteroaromatic moieties and alkyne bonds; unlike PPVs, they do not have alkenic sp^2 bonds. The lack of such bonding gives rise to a rigid oligomer, which cannot undergo *cis/trans* isomerisation. The linear structure of these molecules should minimise conformational movement and the end-capping aromatic systems can be easily functionalised, *e.g.* by addition of thioacetyl groups to enable attachment to nanoelectrodes. Their photoluminescence properties have already been demonstrated, as have their electrical transfer properties. [73]

In 1994, Tour and co-workers published an oligo(aryleneethynylene), containing 16 benzene rings and 16 C≡C bonds **59** with a length of 12.8 nm, thus showing these systems can be isolated and characterised. [74]

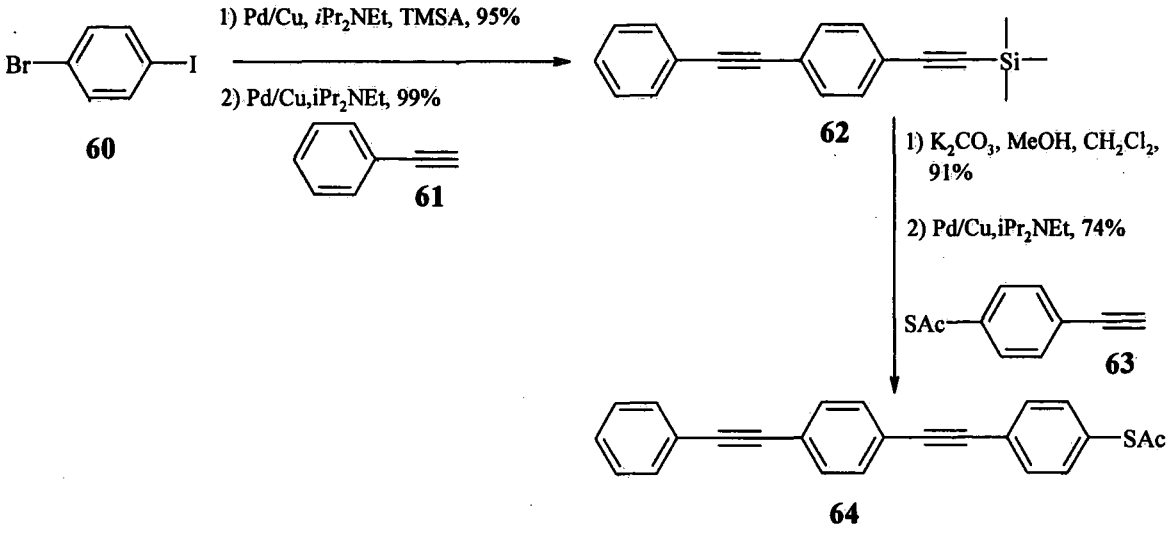


59, n=14

There have been a wide range of syntheses reported for these systems mostly utilising the convergent/divergent or stepwise approaches, yielding conjugated oligomers of precise length.

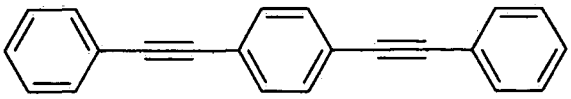
Molecules which exhibit nearly-linear I(V) curves are well represented in the literature. These incorporate at least one thioacetyl end group which is required for self-assembly on a gold surface. The synthesis of a mono-protected simple wire is shown in **Scheme I.9.** [75]

A two step reaction is shown; in the first step trimethylsilylacetylene (TMSA) reacts selectively at the iodo site on **60** at room temperature, followed by reacting with **61** to afford **62**, which occurs in high yield. Deprotection followed by coupling with 1-iodo-4-thioacetylbenzene **63** affords the simple wire **64**.



Scheme I.9 [75]

X-ray crystallography of the thiol-derived compound shows the phenyl rings to be co-planar and hence the conjugated system is nearly planar in the solid state. It is hypothesised that this planarity results in maximum π-orbital overlap, hence high conductivity. The cylindrical symmetry of the alkyne bond maintains conductivity regardless of the orientation of the aromatic moiety, as compared to an alkenic bond. There have been photophysical studies on 1,4-bis(phenylethynyl)benzene **65** (**Fig I.12**), with conflicting theories as to why the first study by Levitus *et al.* [76] suggested the co-existence of two configurational isomers (both the planar and twisted forms). Since the barrier to rotation of the aryl-alkynyl bond is very low (estimated to be 1 kcal/mol) then it is feasible that such rotomers could exist as discrete species.[77,78] If this were the case, however, it could have serious implications in the use of such compounds in a wide range of settings. The authors report spectral abnormalities which they conclude must be due to the presence of two rotamers in the excited state. However, studies by Beeby *et al.* have found no evidence to suggest the existence of such species, instead suggesting the observed spectral changes had arisen from the presence of "*a second chemically distinct species*". [79] Indeed, Beeby *et al.* did synthesise **65** by Sonogashira coupling of 1,4-diiodobenzene with phenylacetylene **61**, to afford analytically pure product. Levitus *et al*, however, bought the substance from Aldrich. Purification *via* column chromatography and recrystallisation was undertaken, however there is no mention whether the substance was analytically pure.



65

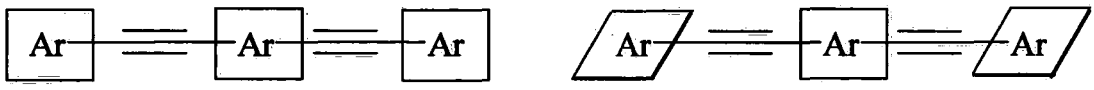
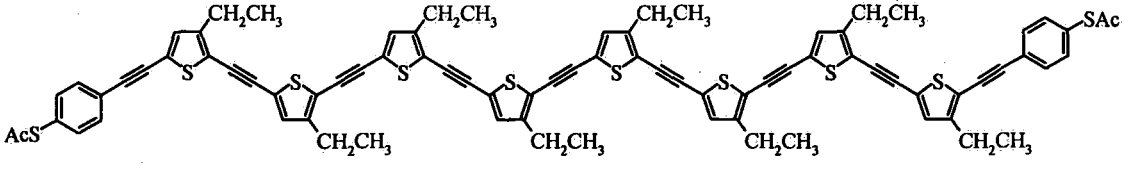


Fig I.12 Compound 65, and a schematic representing its coplanar and twisted forms.

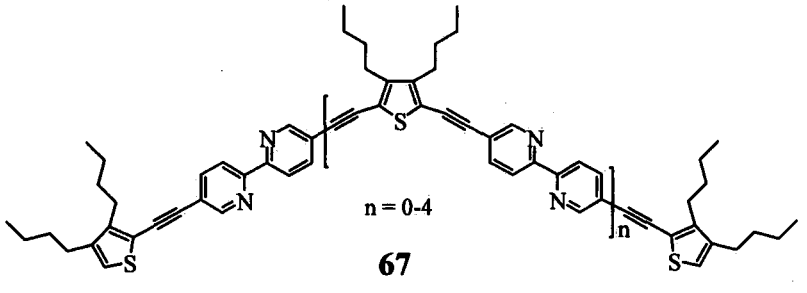
From a practical perspective the solubility of such compounds is important and hence alkyl chains are sometimes incorporated, however these can inhibit ordered formation of the monolayer.

A wide range of π-conjugated systems have been inserted between the triple bonds. For example, the Tour group reported the synthesis of octa-(α-thienylethynylene) **66** with protected thiol end groups,[80] whereas Goeb and co-workers have synthesised ligands incorporating both bipyridine and thiophene derivatives **67**.[81]

Wang *et al.* in our laboratory, have reported the synthesis and electrochemistry of a fluorenone containing wire **68** of 7 nm length.[82] The wire is comprised of a rigid acetylene backbone with alternate fluorenone and solubilising dialkoxyphenyl moieties. The oligomers show reversible solution electrochemistry and hence are attractive candidates for use as a molecular wire. Our group has also developed cyanoethylthiol end groups as alternatives to thioacetyl end groups.[82]



66



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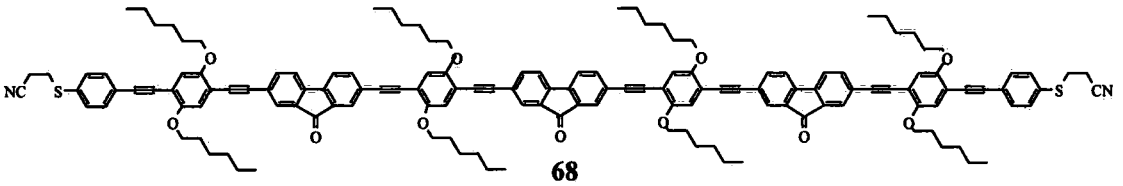
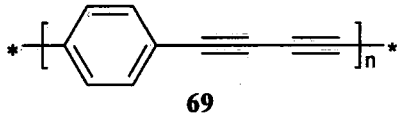


68

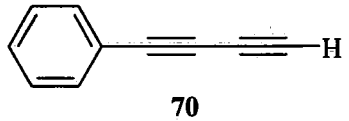
II. 3. Diacetylene linkages

There are notably few reports in the literature of aryl units inserted into polyyne systems, although such wire molecules should possess attractive structural and electronic features. Hay was the first to report the synthesis of *poly*-(*p*-phenylenebutadiynylene) (PPB) **69**, followed by work by Bunz *et al* .[83]



69

***poly*-(*p*-phenylenebutadiynylene), PPB**



70

Phenylbutadiyne

One reason for the limited amount of research in this area is the presumed instability of the precursors. Phenylbutadiyne **70**, for example, was noted by Brandsma to be unstable and can only be stored at -20 °C.[84] The reactivity of the phenylbutadiynes has also been described by Haley *et al*, who report the formation of "intractable polymeric gums" when trying to react unprotected phenylbutadiynes in alkynylation reactions.[85] Indeed, in most of the examples of polyynes reported in the literature, isolation of the butadiyne derivative does not occur. A long-held view is that the isolation of such species is not possible, indeed in 2006 Tykwinski *et al* stated:

"*kinetic stability of terminal alkynes decreases dramatically as the number of carbon-carbon triple bonds increases. For example, aryl butadiynes are unstable to isolation, which has necessitated the development of in situ techniques.*"[86]

The stability of phenylbutadiynes and any 1,3-butadiynes in general is thus questioned. Why are the phenyl derivatives not stable and to what extent are other 1,3-butadiynes stable?

The relative instability of phenylbutadiynes is due to the molecules' tendency to polymerise. A general trend is that a larger aryl group results in a more stable compound. Indeed, at the outset of this project a few crystal structures of terminal

arylbutadiynes were known, such as a 2,5-diphenyl-1,3,4-oxadiazole bearing a butadiynyl substituent **71** reported by the Bryce group **Fig I.13**. [87,88]

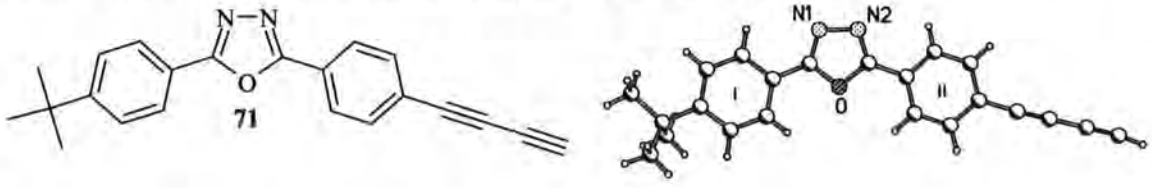


Figure I.13 X-ray molecular structure of 71,[88]

It has been suggested that a crystalline lattice can stabilise chemically labile aryl butadiynes, and thus prevent polymerisation, if it is outside the guidelines published for topochemical polymerisation.[89] The general guidelines are that the vector distance between two diyne rods, in parallel, is between 4.7-5.2 Å (d), which form an angle of *ca* 45 ° (Φ), as illustrated in **Fig I.14** (*N.B.* This is a theoretical model; the planar aryl system is shown in black and the butadiyne moiety in red).

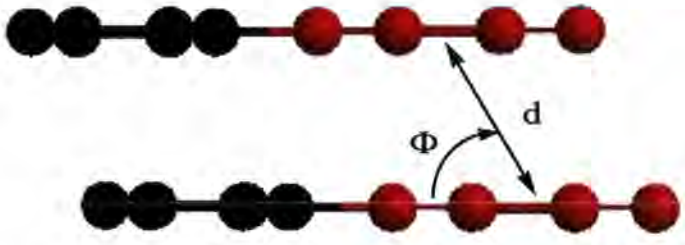
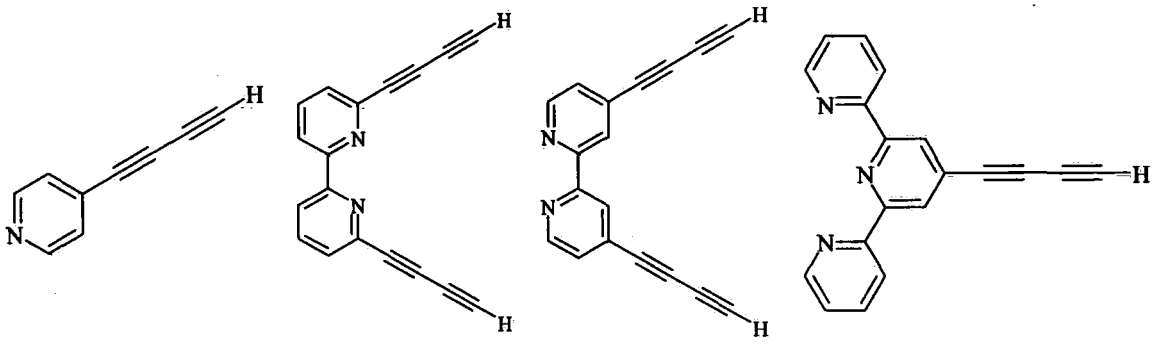


Fig I.14 A schematic diagram of a stacked arylbutadiyne, illustrating vector distance (*d*) and angle Φ .

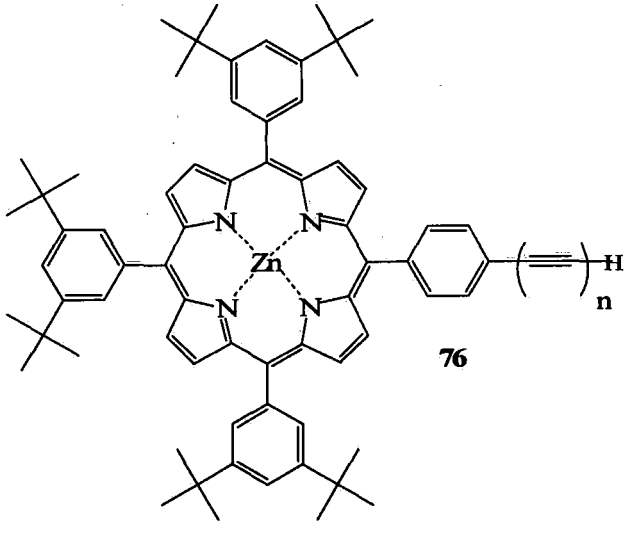
Another possible explanation for the instability of such compounds is the synthesis and isolation techniques employed. The much-quoted work by Brandsma, for example, details phenylbutadiyne as being isolated as a neat oil; the free movement of the molecules in the liquid state might result in close-contact between the diacetylene rods and be causing the observed polymerisation.

The few arylbutadiynes which have been reported in the literature have been synthesised by various routes. These include desilylation of trialkylsilylated precursors (Ar–C≡C–C≡C–SiR_3), as utilised by Ziessel and Suffert in the isolation of a range of mono or disubstituted pyridines **72-75** for use as chelating ligands.[90]



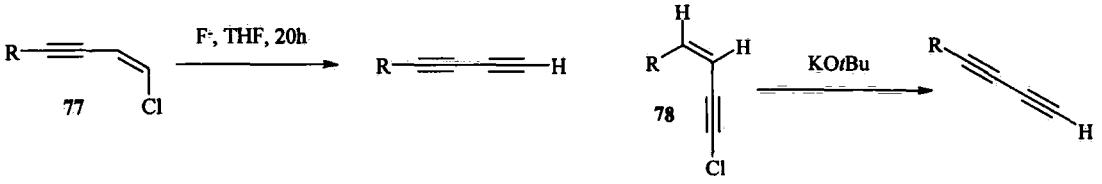
72 **73** **74** **75**

The desilylation route has also been utilised in the synthesis and isolation of a porphyrinbutadiyne and triyne.[91] It is predicted that the huge steric bulk of the porphyrin moiety is preventing a close-proximity between neighbouring butadiyne rods.



76

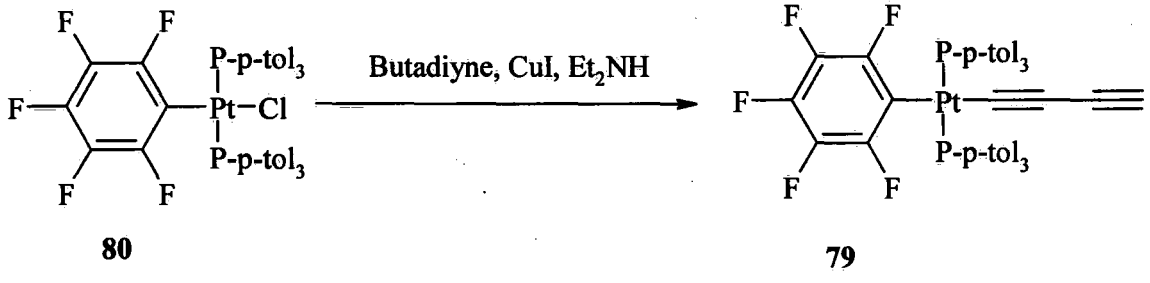
Very often the terminal butadiyne is not actually isolated; instead it is generated and reacted *in situ*, avoiding the potentially difficult isolation and purification steps. For example, Haley *et al* have exploited this *in situ* method in the isolation of carbon networks (**Section I.3.1**). Dehydrohalogenation of haloene-yne (R–C≡C–CH=CHCl) **77** [92] or ene-haloyne (R–CH=CH–C≡CCl) **78** [93] derivatives has also been utilised to synthesise such elusive compounds (**Scheme I.10**).



Dehydrohalogenation of haloene-yne, **77** Dehydrohalogenation of ene-haloyne, **78**

Scheme I.10

In work on platinum end-capped polyynes, Gladysz *et al* isolated **79** from **80** in high yield (**Scheme I.11**). Although there is no mention of the stability of the product, it is assumed is it stable.[62] Indeed, the authors report microanalysis, along with ^{1}H, ^{13}C and ^{31}P NMR; such stability is probably due to the steric bulk of the phosphine ligands.



80 **79**

Scheme I.11.

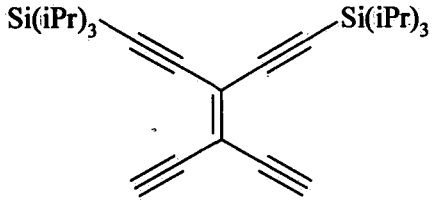
I. 3. 1 Carbon-rich networks containing butadiyne linkages

One area where butadiynes (both terminal and protected) have been exploited is in the synthesis of all-carbon networks. Until the relatively recent discovery and isolation of the fullerenes, graphite and diamond were the only well characterised carbon allotropes. Both compounds are of high importance; graphite is used as a solid lubricant and has good electrical conductivity, whereas diamond has high thermal conductivity and is extremely hard. It has been the objective of many chemists, therefore, to synthesise carbon-rich cross-linked organic solids which could, macroscopically, display similar desirable properties of both graphite and diamond.

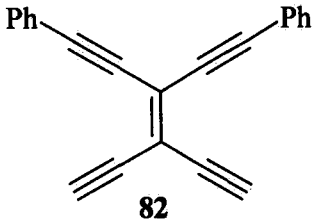
In this context, annulenes and dehydroannulenes have long been the subject of much interest. The synthesis and isolation of tetraethynylethene, TEE **21**, by Rubin *et al* in the early 1990s,[94] paved the way to new carbon networks. This followed work by Hori in

1969 and Hauptmann in 1975, who both synthesised and isolated derivatives of TEE.[95,96]

Unsurprisingly, **21** was found to decompose rapidly at room temperature, to "*a black solid with metallic lustre*". Derivatised species **81** and **82** similarly decomposed at 25 °C; indeed **82** was found to be the least stable of the series: "*the neat oil polymerizes to a black hard mass in a matter of seconds*".[94]

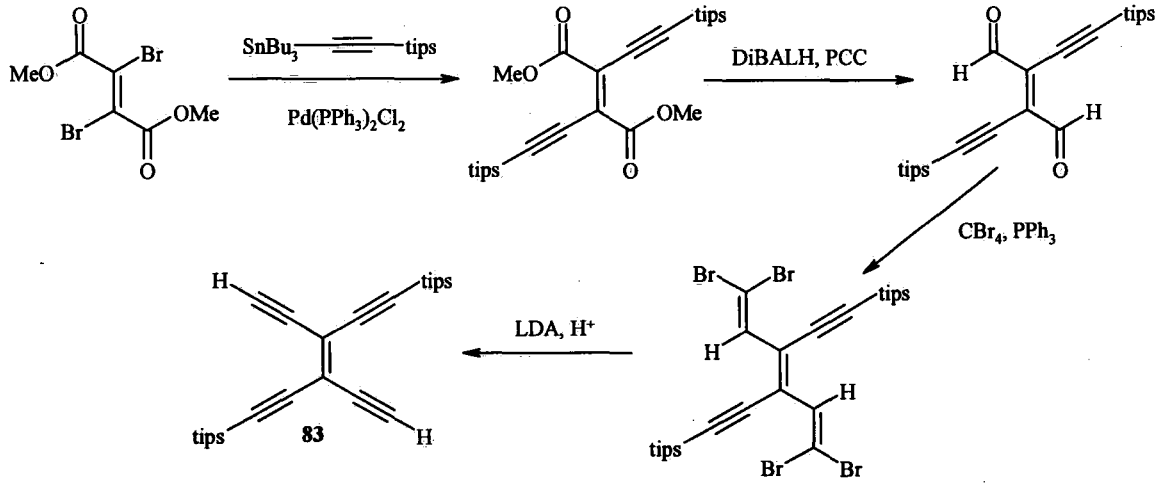


81



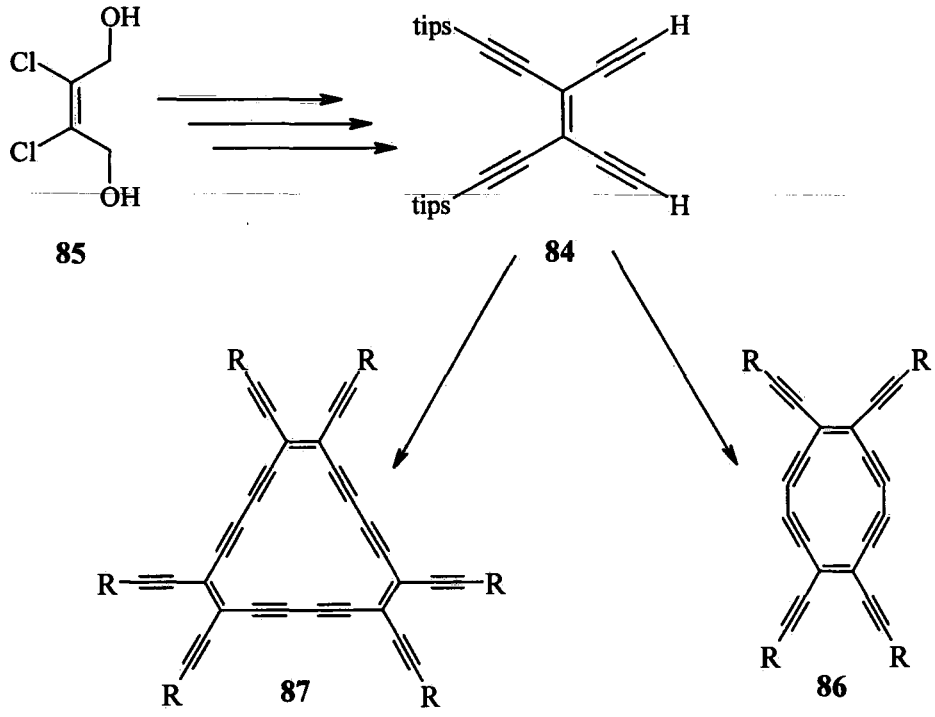
82

The authors further reported the synthesis and isolation of *cis-* and *trans-* bis-deprotected species: the *trans* isomer **83** is shown in Scheme **I.12.**[97] The resulting conjugated carbon rods have been illustrated previously (Section 2.1).

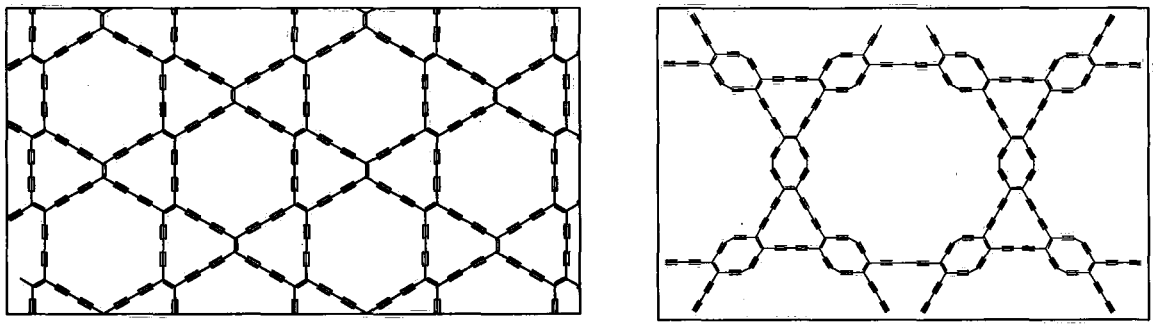


Scheme I.12.

The *cis-bis*-deprotected species **84** was more difficult to synthesise, requiring a 7-step synthesis, in 13% overall yield from starting material **85**.[98] The efforts were worthwhile, however, since oxidative homo-coupling of **84** afforded the [12]annulene **86** and [18]annulene **87** in 28% and 12% yields, respectively (**Scheme I.13**). Deprotection of **87** could, in theory, result in the formation of the all-carbon network **88**, whereas **86** could afford the lattice **89** (**Fig 1.15**).



Scheme I.13



88 **89**

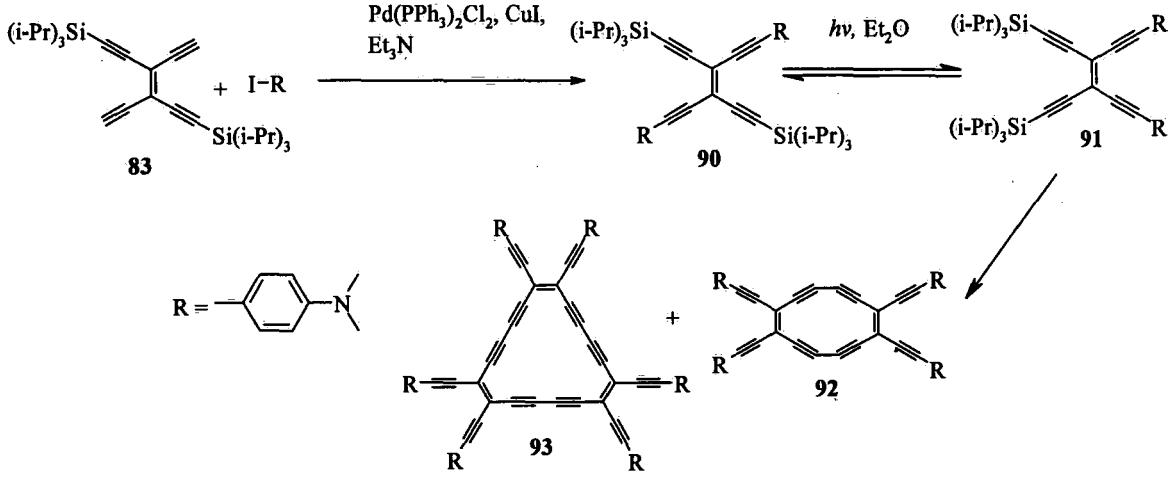
Fig I.15 Theoretical all-carbon networks 88 and 89 from the deprotection and coupling of annulenes 87 and 86.

The [18]annulene **87** was found to have aromatic character, whereas [12]annulene **86** is antiaromatic; the red shifted end-absorption in the electronic absorption spectra of **86** (λ_{end} 660 nm) implies a smaller HOMO-LUMO gap (*cf.* **87** (λ_{end} 480 nm) which the authors propose "*can be explained by the smaller HOMO-LUMO gap in an antiaromatic system*".[98]

The same authors sought to determine whether intramolecular charge transfer effects were influenced by the aromaticity/antiaromaticity as observed in **87** and **86**, respectively. It was necessary, therefore, to functionalise the *cis*-deprotected species

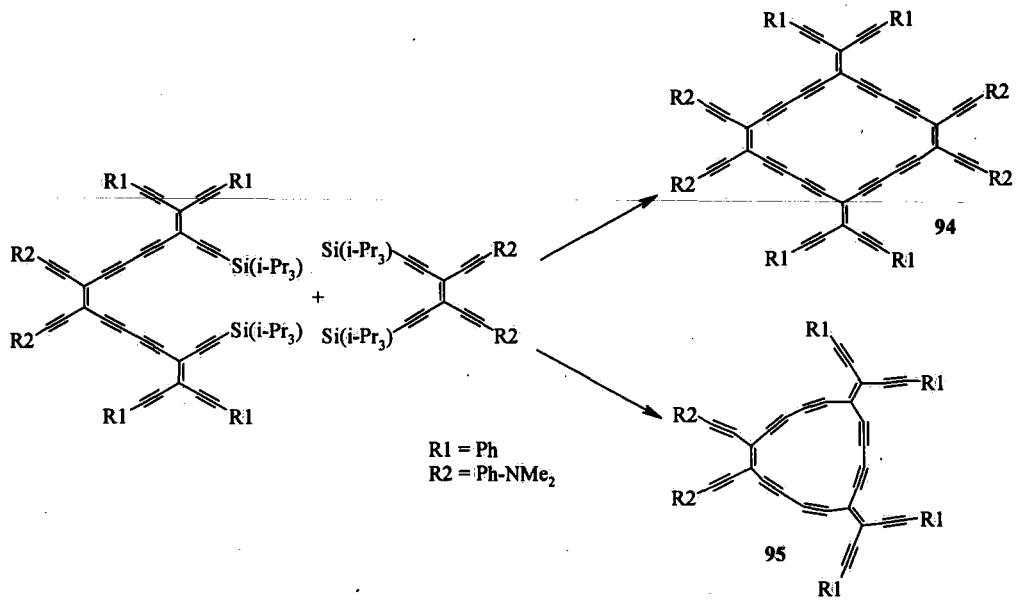
with donor groups before oxidative homo-coupling, since the all-carbon cores are electron accepting.[99]

By starting with *trans*-bis-deprotected species **83** (which is far easier to isolate than the *cis* analogue) and functionalising with the required donor groups to afford **90**, Mitzel *et al* reported the facile conversion to the protected *cis*-species **91** by UV irradiation.[100] Fluoride deprotection followed by oxidative homocoupling afforded the aniline-derivatised [12]- and [18]-annulenes (**92** and **93**, respectively), both of which were sparingly soluble in organic solvents, **Scheme I.14**. Changes in UV-Vis spectra were observed upon acidification (with toluene-4-sulfonic acid) followed by neutralisation (with triethylamine), thus confirming intramolecular charge transfer.



Scheme I.14

The same paper reports the isolation of a novel class of all-carbon macrocycle a "radiaannulene" a structural hybrid of a dehydroannulene and an expanded radialene, **Scheme I.15**. The intramolecular charge transfer properties of compounds **94** and **95** were then studied in detail in a later publication, which also reports the crystal structure of **95, Fig I.16**. [101]



Scheme I.15

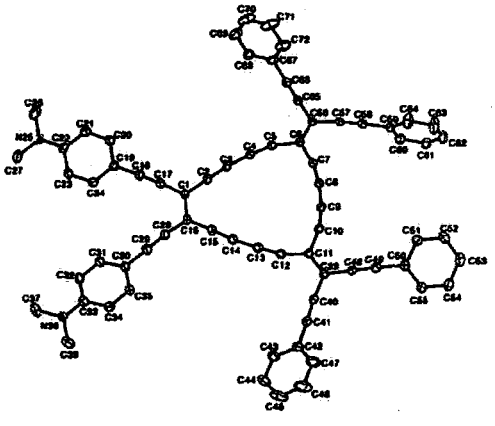


Fig I.16 Crystal structure of compound 95. [101]

An expanded radialene comprises the insertion of either ethynyl or butadiynyl moieties into a cyclic framework, thus resulting in a change of molecular formulae, as outlined in **Fig I.17.**[99]

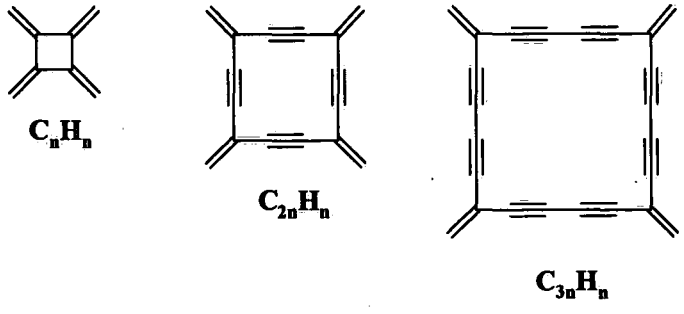
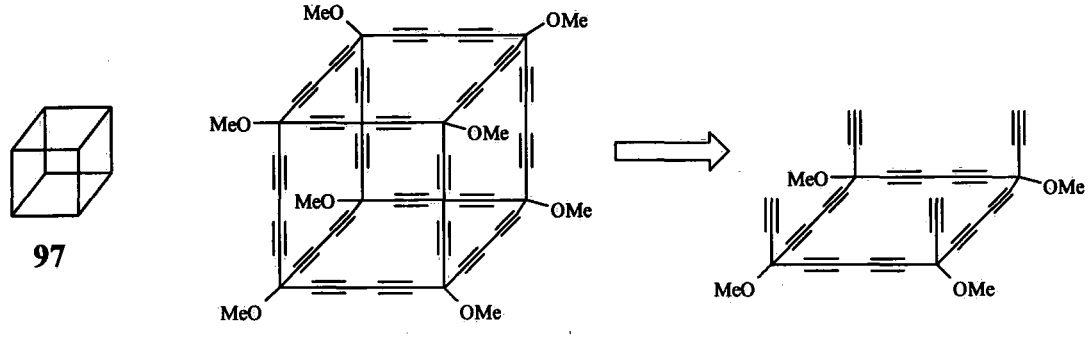


Fig I.17.

In the same fashion, the synthesis of expanded cubane **96**, a three-dimensional structure, was achieved by the Diederich group. Cubane **97** was first isolated by Eaton

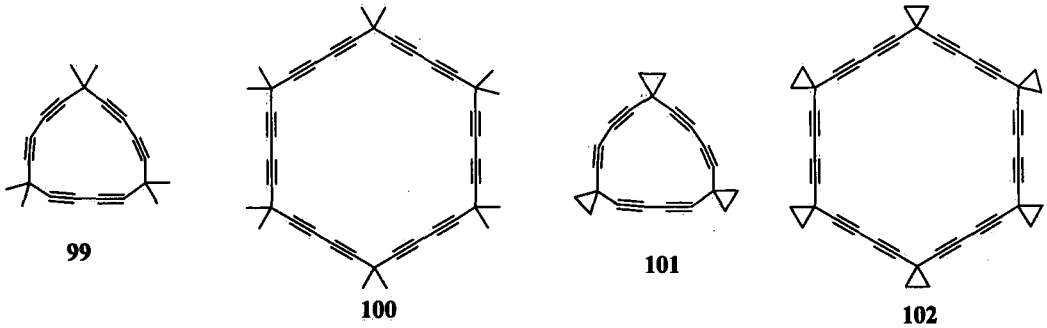
and Cole Jr., in 1964.[102] Despite its highly strained conformation, the compound was very stable. By inserting butadiynyl moieties between the carbon-carbon single bonds, an expanded cubane is attained.[103] The synthetic protocol involved the formation of corners, edges and faces, the latter **98** being homo-coupled to afford **96** in a straightforward, if synthetically difficult, method, **Scheme 1.16**.



97 **96** **98**

Scheme I.16

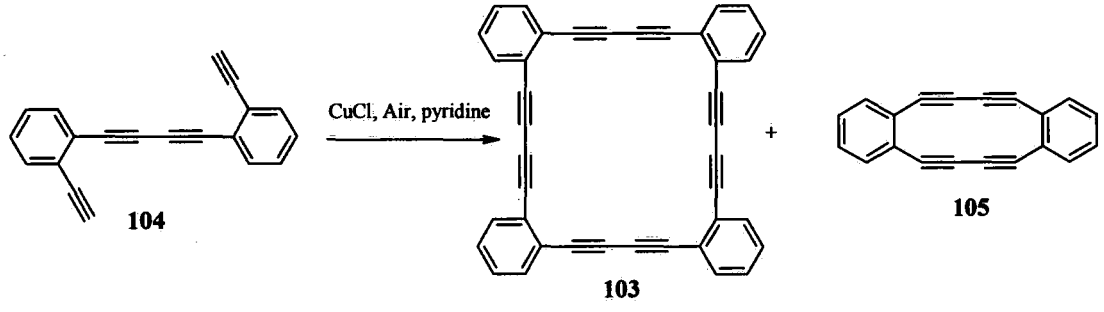
Another example of the butadiyne moiety being utilised in the synthesis of carbon-rich backbones, is the synthesis of alkylydiynyls **99** and **100**.[104] de Meijere *et al* proposed by replacing the *gem*-dimethyl groups in **99** and **100** with a cyclopropane ring, there would be a smaller HOMO-LUMO gap and hence "*stronger homoconjugative effects*", would arise.[105] The syntheses of **101** and **102** were reported in 1994.



99 **100** **101** **102**

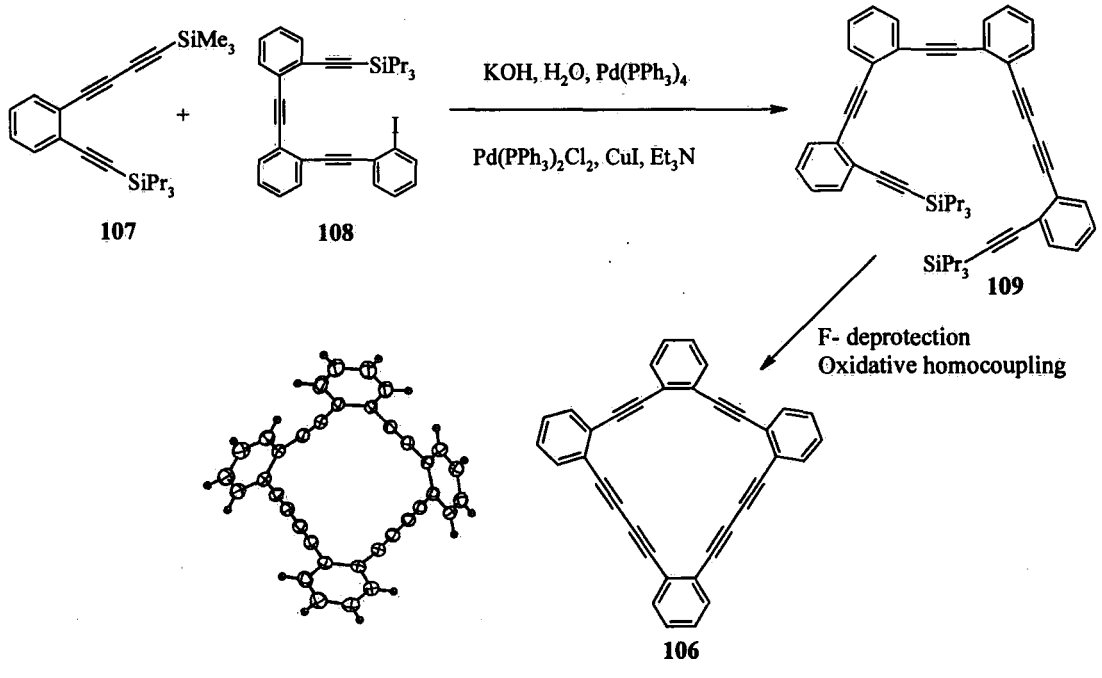
X-Ray analysis of **102** indicated that the 30-membered ring adopts a chair conformation. The authors found **102** to be extremely unstable to external force: "*when a sample was struck hard with a spatula, a pestle or a falling metal ball, it flared and turned into black soot*". [105] This behaviour was ascribed to the presence of the cyclopropane rings, since the same was not observed for the gem-dimethyl analogue **100**.

The synthesis of dehydrobenzoannulenes and benzannelated analogues has also been extensively explored in the past; however, it has recently been rejuvenated by a one-pot desilylation/dimerisation approach. Previous approaches utilised the dimerisation of α,ω-diacetylenes, which often afforded a messy reaction mixture and many products. For example, Guo *et al* reported the synthesis of QBCO **103** from the Glaser homocoupling of **104** in only 20% yield. The major product was the dimer **105**, isolated in 50% yield (**Scheme I.17**).[106]



Scheme I.17.

By using the one-pot procedure, Haley *et al.* reported the synthesis in good yields and crystal structures of novel dehydrobenzoannulenes including compound **106**.[107] (**Scheme I.18**).

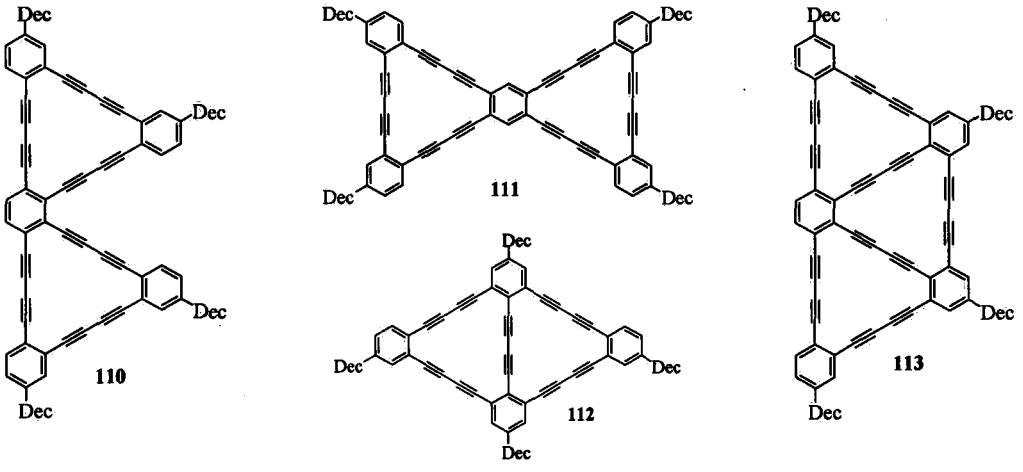


Scheme I.18 Synthesis and X-ray structure of compound 106.[107]

Compound **107** underwent deprotection of the trimethylsilyl group followed by *in situ* Sonogashira coupling with iodoarene **108** to afford **109** in good yield. Compound

109 was further deprotected, this time using a fluoride deprotecting agent, and homocoupled using standard conditions to afford **106** in good yield.

Subsequently Haley *et al.* reported the synthesis of larger, all-carbon network substructures **110-113**.[108]



These carbon frameworks were important at the time as the largest known substructures of graphdiyne; a planar network of butadiyne linked benzene rings (**Fig I.18**).[108] Historically graphdiyne has been just one of the many proposed natural, and non-natural, carbon rich networks which could exhibit important properties such as chemical inertness, thermal stability, hardness and possibly display nonlinear optical (NLO) behaviour. Many of the other proposed structures incorporate strained ring systems which can result in graphitisation; the rearrangement of the network affording a more stable conformation, which often resembles graphite. Graphdiyne is thought to be the most synthetically viable all-carbon allotrope, hence the great interest in the synthesis of its fragments.

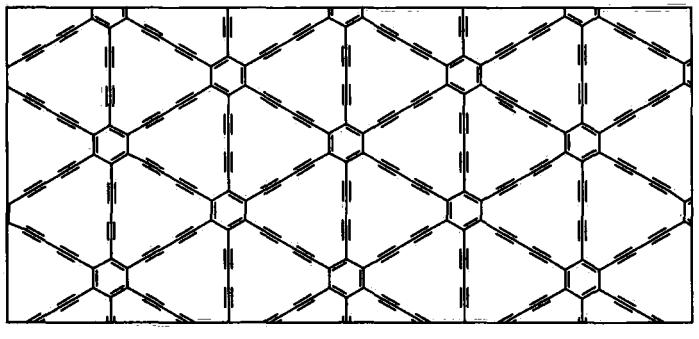


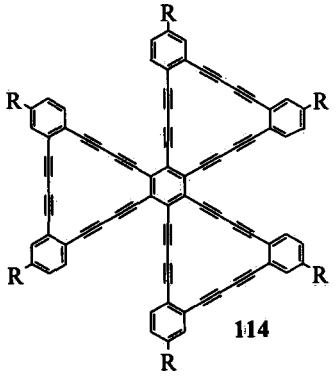
Fig I.18. A schematic diagram of hypothetical all-carbon network graphdiyne.

The graphdiyne fragment **114** was synthesised by Haley's group in 2001.[109] In the same paper the authors report the attempted synthesis of **115**, was unsuccessful.

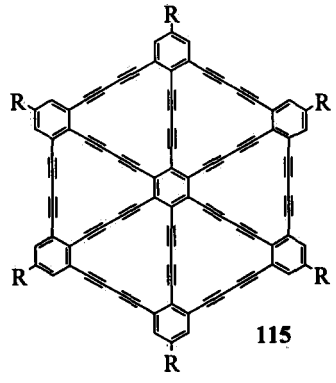
However, they isolated functionalised phenylbutadiynes, such as *t*-butyl-phenylbutadiyne **116**:

"A significant amount of crystalline material was obtained, which upon further inspection proved to be pure, stable crystals of diyne. This result was surprising given the reported instability problems of other phenylbutadiyne derivatives".[109]

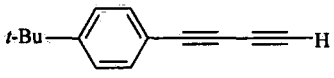
The crystallinity of the compound is perhaps not a surprise as *t*-butyl groups are often incorporated to facilitate crystal growth; the observed stability is surprising, however. The same paper reports the isolation of *n*-decyl- **117** and methoxy- **118** functionalised phenylbutadiynes. However, these were "found to be considerably less stable".



114



115



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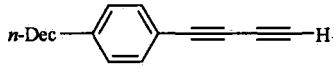
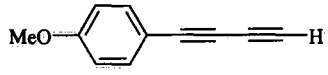
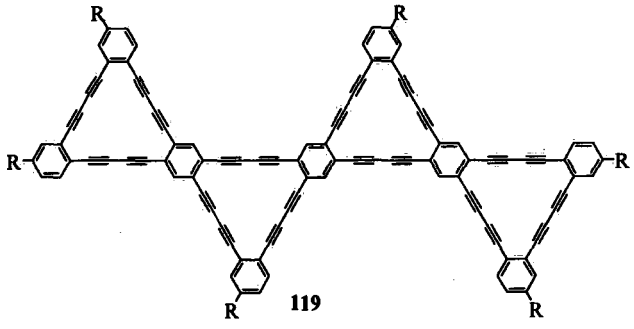


117



118

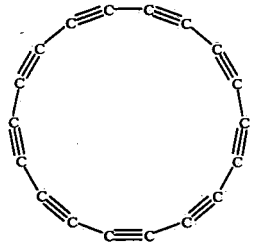
In 2005 Haley *et al.* reported the synthesis and isolation of the largest graphdiyne fragment **119** to date.[110]



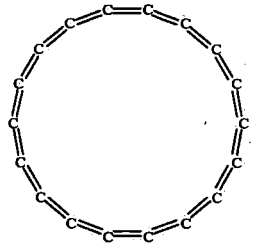
119

I. 3. 3 Cyclo[n]carbons

The synthesis of cyclic polyynes has also attracted much attention; **120** was one of the first synthetic targets, although it was not clear whether the species would exist as a cummulene **121.**

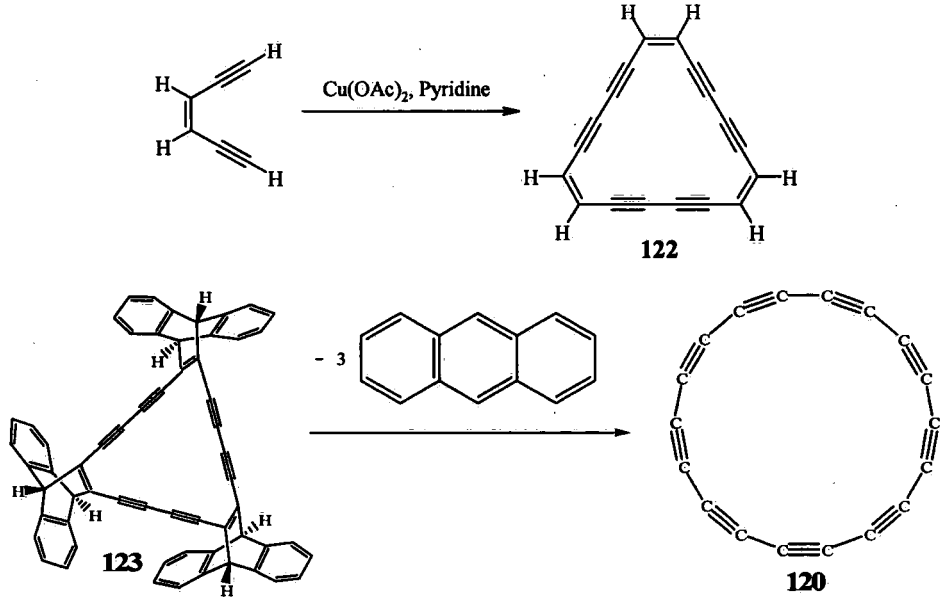


120



121

The approach was to functionalise the hexadehydro[18]annulene **122**, first reported by Sondheimer *et al.* in 1967,[111] by replacing the six peripheral hydrogen atoms with "leaving groups". Four routes have been pursued, none of which has afforded the synthesis of **120** on a preparative scale.[112] The formation of *cyclo*-C_{18} **120** by laser flash heating of **123**, in a retro Diels-Alder fashion (**Scheme I.19**), was reported by Diederich *et al.*[113]



Scheme I.19

I. 4 Kinetic Stability of 1,3-butadiynes

Recently, there have been a few studies regarding the conjugation stabilisation energy of 1,3-butadiynes, which has been reported as being, rather interestingly, zero. The heats of hydrogenation of the polyynes have never been measured, mainly because diynes are known for detonating in oxygen, thus making this data virtually impossible to obtain in the laboratory. It was supposed that polyynes would follow a similar pattern to polyenes; the enthalpy of hydrogenation of 1,3-butadiene is smaller than that measured for 1-butene. This discrepancy has been ascribed to "*conjugation stabilisation*" and follows work in the 1930s by the thermodynamicist Kistiakowsky.[114]

Triple bonds were assumed to follow this pattern by considering a triple bond as two superimposed π bonds on an inert σ bond, hence the stabilisation energy of 1,3-butadiyne would be twice that measured for 1,3-butadiene. However, Rogers and Zatisas have reported that the conjugation stabilisation of 1,3-butadiene is zero, using established computational methods.[115] The authors report there to be "*no conjugation stabilisation at all*". The group then extended the range of oligoynes studied, and found the same lack of conjugation stabilisation.[116] The same results were obtained by another research group headed by Houk and Schleyer.[117] These authors reported essentially the same values, obtained *via* different computational methods; however, they gave a different interpretation of the results.

I. 5 Conclusions

To conclude, therefore, there are many different types of molecules currently being investigated for use as molecular wires in the much-researched area of molecular electronics. At present, conjugated hydrocarbon systems currently offer the greatest potential, since their integration into systems is solved by carbon-rich backbones reported in the literature

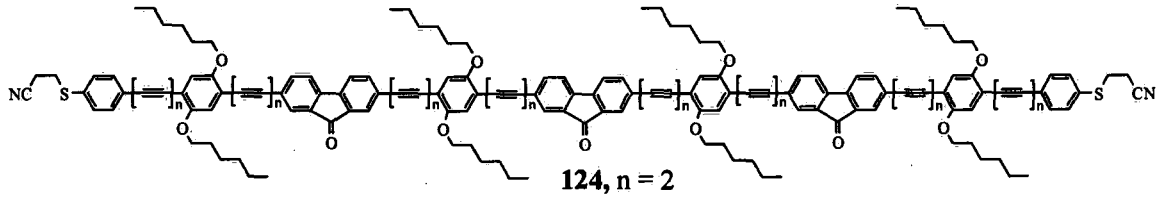
From this viewpoint we decided, therefore, to investigate the potential use of arylbutadiyne derivatives as synthons for new conjugated systems and as potential precursors to longer molecular wire candidates.

The investigation of oligoynes, specifically 1,3-butadiynes, between aromatic moieties was recognised as an under-explored topic and our contribution will be described in the following chapters.

Chapter II; Arylbutadiynes

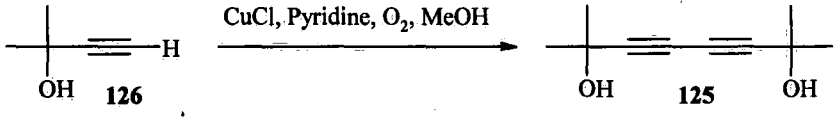
II. 1 Towards molecular wire synthesis

At the outset we envisaged the synthesis of very long molecular wires with butadiyne linkages, as analogues of previously reported mono-acetylene systems, *e.g.* **124**, as an analogue of **68**. [82]



124, n = 2

An important starting material was **125** which was readily obtained by the copper-catalysed oxidative homocoupling of methyl-*tert*-butyn-2-ol, **126** following Hay coupling conditions (**Scheme II.1**).[65]



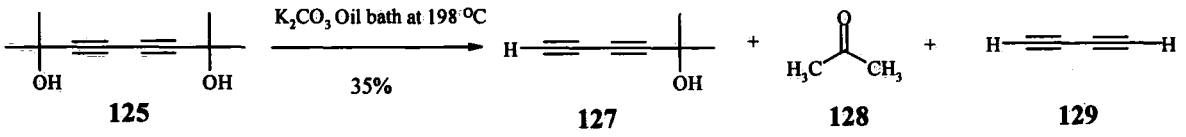
Scheme II.1

The yields were typically 50-80% depending on the oxidant used and the reaction time.

The reaction mechanism is not thoroughly understood, but is thought to proceed *via* a copper-complex of the terminal acetylide. The initial step is probably deprotonation by the base (pyridine) to form a carbanion. The cuprous ion is thought to chelate in some fashion to the triple bond. The last step is considered to be the coupling of two radicals to form the homo-coupled product.[118] Other alternatives suggest oxidative addition of acetylides onto copper, reductive elimination resulting in the formation of the homocoupled species.

The next step was the mono-deprotection of the diacetylene **125** to afford the terminal butadiyne derivative of 2-methyl-hexa,3,5-diyn-2-ol **127**.[119] The reaction proceeded under basic conditions (stirring with a catalytic amount of potassium carbonate), at high temperature and reduced pressure to yield a mixture of product **127** and acetone **128, Scheme II.2**. The latter was removed under reduced pressure to yield the yellow oil of **127** in 30-40% yield. However, as the starting material **126** is

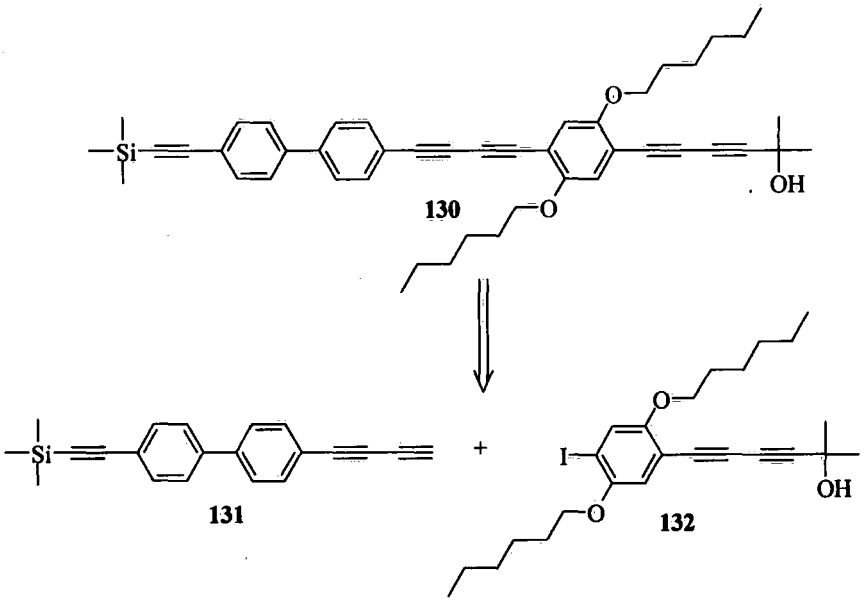
extremely cheap, this procedure is economically viable. The formation of the di-deprotected species **129** probably also occurs; however **129** is gaseous so does not contaminate any of the desired product.



125 **127** **128** **129**

Scheme II.2

Our first target oligomer was **130**. We reasoned that deprotection of the 2-hydroxyl-2-propyl protecting group and further cross-coupling could afford rods of considerable length. The retrosynthetic analysis of **130** from **131** and **132** is illustrated in **Scheme II.3**.

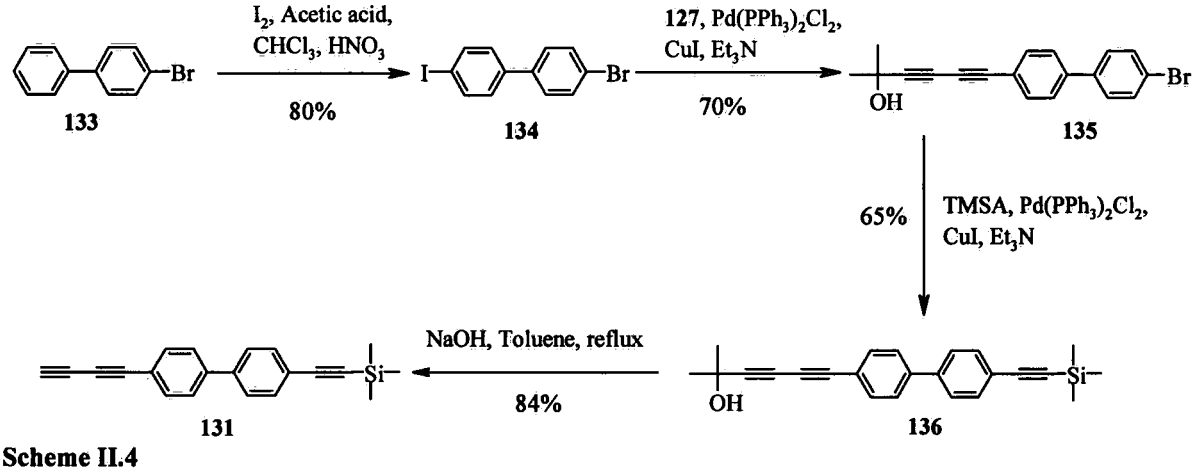


130 **131** **132**

Scheme II.3

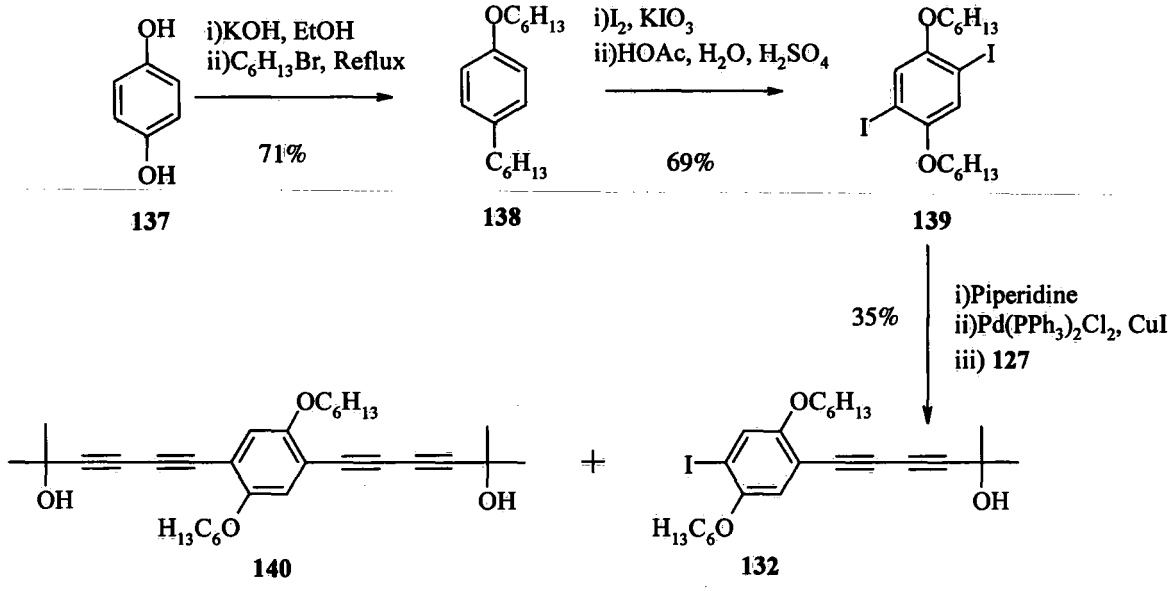
The synthesis of **131** is shown in Scheme **II.4**. Iodination of bromobiphenyl **133** proceeded in 80% yield following the literature procedure.[120] The Sonogashira[34] reaction between **134** and **127** under standard conditions, using triethylamine as both base and solvent gave **135** in 70% yield. The next step, the Sonogashira coupling reaction between the bromide moiety **135** and TMSA was slightly more difficult. Aryl bromides are not as reactive towards Sonogashira coupling as their iodide counterparts, hence higher temperatures are often required. To overcome the loss of TMSA, due to its volatility, the reaction flask was tightly stoppered. All reagents were handled as though air-sensitive and all glassware flame-dried and purged with argon prior to use. Thereby

136 was obtained in 65% yield. Basic deprotection of **136** under anhydrous conditions afforded the terminal butadiyne species **131** in high yield, which to our surprise was relatively stable. Standard NMR and ms characterisation was obtained confirming the structure. A dilute solution of **131** could be stored at room temperature in the column eluent (DCM/hexane) for weeks without significant darkening of the solution.



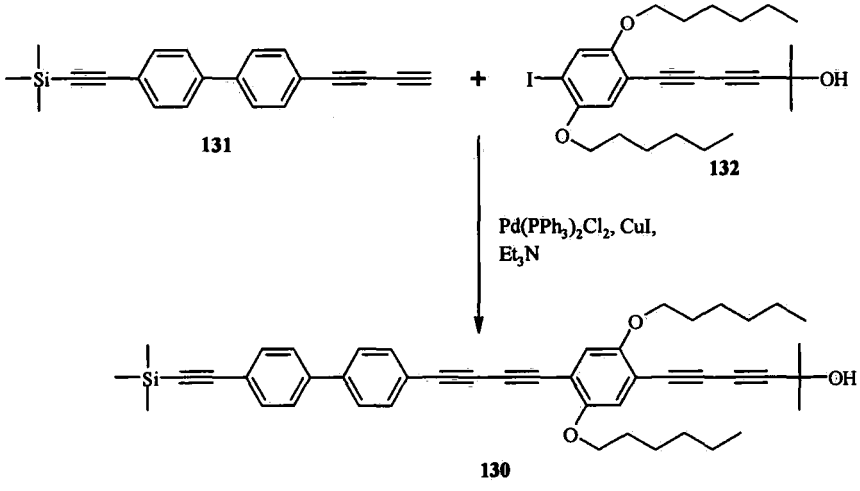
Scheme II.4

The synthesis of **132** is outlined in **Scheme II.5**. Hydroquinone **137**, was dihexylated with bromohexane under basic conditions at reflux to yield **138** in 71% yield. Diiodination of **138** afforded **139** in good yield as described in the literature. [121] In this reaction, potassium iodate acts as an oxidizing agent, converting iodine to a better electrophile, which is necessary since iodine is the least reactive halogen in aromatic substitution, **Scheme II.5**. The Sonogashira coupling reaction was again employed in the next step; the reaction of **139** with **127** (1 equiv.) gave the mono-coupled product **132** in 35 % yield which was analytically pure even as a brown oil. The most common side product was the di-coupled species, **140**, (see Chapter III for an optimised synthesis of **140**) which could be a useful product if asymmetric protection is not desired. Separation by column chromatography was relatively facile, due to the difference in polarity between **132** and **140**.

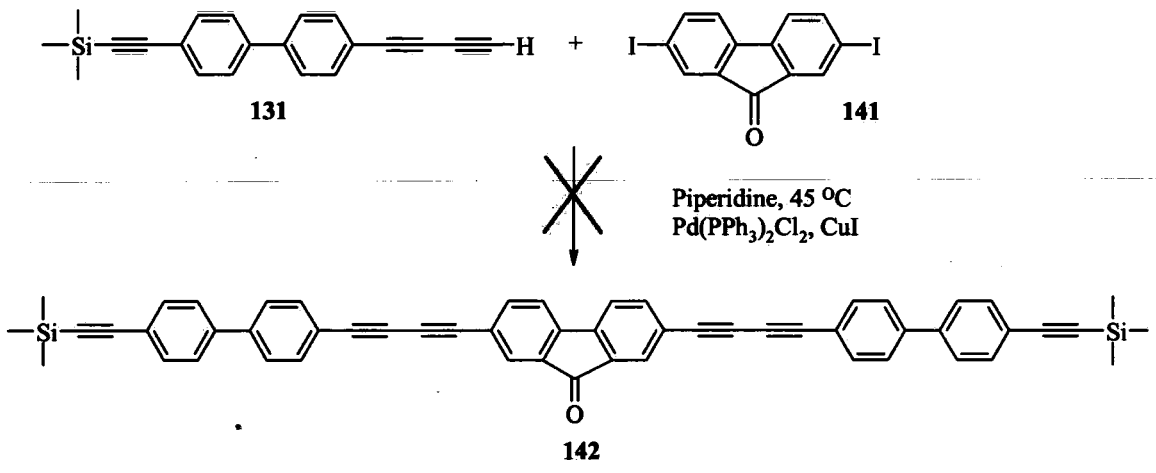


Scheme II.5

The reaction between **131** and **132** proceeded well under standard Sonogashira conditions; using triethylamine as both solvent and base, $Pd(PPh_3)_2Cl_2$ and CuI catalysts, to afford **130** as a bright yellow solid in 65% yield after stirring at 45 °C for 6 h. A recrystallisation from cyclohexane afforded spectroscopically and analytically pure compound **130**. Unfortunately it was not possible to obtain X-ray crystallographic data since the crystals formed were not of appropriate size.



Having thus shown the reactivity of species **131**, the next Sonogashira cross-coupling reaction attempted was between **131** and diiodofluorenone **141** to afford **142**. However, the reaction was unsuccessful; a multi-component product mixture was obtained (tlc evidence) with a significant amount of baseline material, **Scheme II.6**.



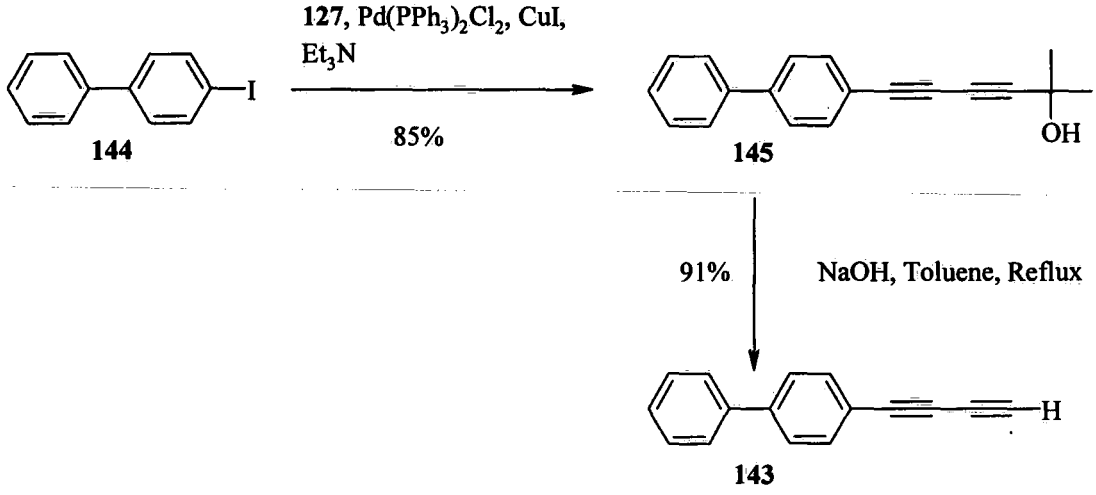
Scheme II.6.

Having thus synthesised a functionalised terminal arylbutadiyne **131**, it was decided to investigate the synthesis and stability of a series of simpler aryl- and heteroarylbutadiynes, since there are only very few examples reported in the literature, as noted in Chapter 1 (**Section I.3**).[88,90,92,93]

We surmised the dihedral twist of the biphenyl moiety in **131** could provide some steric hindrance which was retarding the usual polymerisation of the butadiyne unit. The trimethylsilyl group could possibly also be sterically contributing to the observed stability. Crystals for X-ray analysis could not be obtained – it was an amorphous solid. It was decided, hence, to attempt the synthesis of 4-(buta-1,3-diynyl)biphenyl **143** to determine its relative stability.

II. 2 Simple aryl butadiynes

Accordingly, 4-iodo-1,1'-biphenyl **144** and 2-methyl-3,5-hexadiyn-2-ol **127** were coupled using standard Sonogashira conditions to afford 4-(5-hydroxy-5-methylhexa-1,3-diynyl)-1,1'-biphenyl **145** as a white solid in 85% yield. Basic deprotection in refluxing anhydrous toluene under an argon blanket afforded the desired product **143**, in 91% yield after column chromatography (**Scheme II.7**).



Scheme II.7.

To our delight the compound was isolated as a stable white solid, characterised by ^{1}H and ^{13}C NMR, GC-MS, high resolution mass spectrometry and its X-ray crystal structure was solved. There are two independent molecules (A and B) in the unit cell. The packing diagram (**Fig II.1**) shows the structure contains separate AB pairs of nearly parallel molecules, which pack in antiparallel (biphenyl to diyne) fashion. Therefore, there are no continuous chains which are pre-aligned for polymerisation. Every diyne group donates a weak hydrogen bond, accepted by a π-system of either a benzene ring (molecule A) or a C≡C bond (molecule B), thus explaining the observed stability. The dihedral angles were measure to be 45.6 ° for molecule A and 42.6 ° for molecule B.

"A hydrogen bond, X – H••••A, is an interaction wherein a hydrogen atom is attached to two atoms, X and A, rather than just one, and so acts as a bridge between them."[122] The hydrogen bonding interaction is not a simple one, instead a wide range of interaction types are involved, such as electrostatics, van der Waals, covalency and polarization. There are also many different types of X – H••••A hydrogen bonds, with dissociation energies varying from 0.2-40 kcal mol^{-1},[123] which is dependent on the strength of the hydrogen bonding interaction, ranging from very strong (40 kcal mol^{-1}) to weak (0.2 kcal mol^{-1}). This area of research is a very controversial one with regard to alkyne C-H interactions and a fuller discussion is considered to be outside the scope of this thesis. For more detailed debate, the reader is referred to references [122-124].

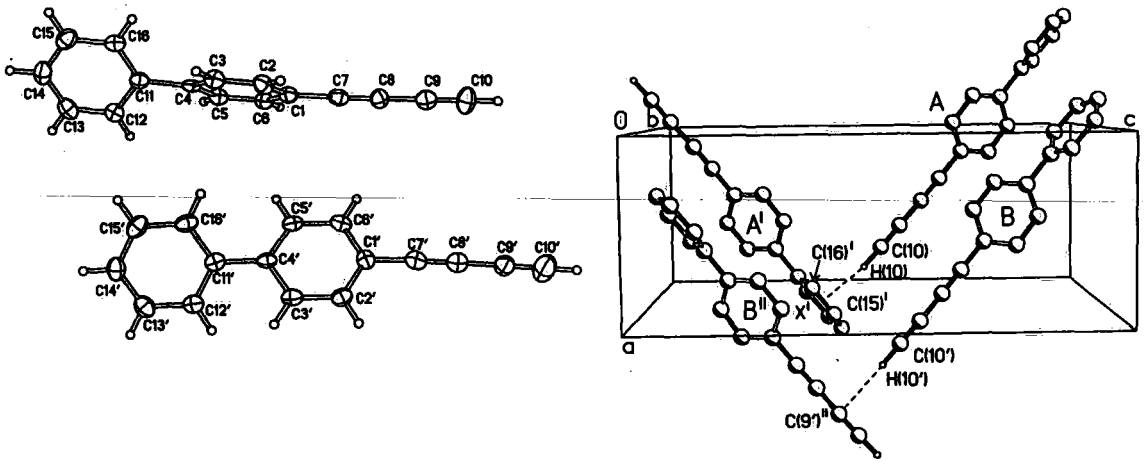


Fig II.1.

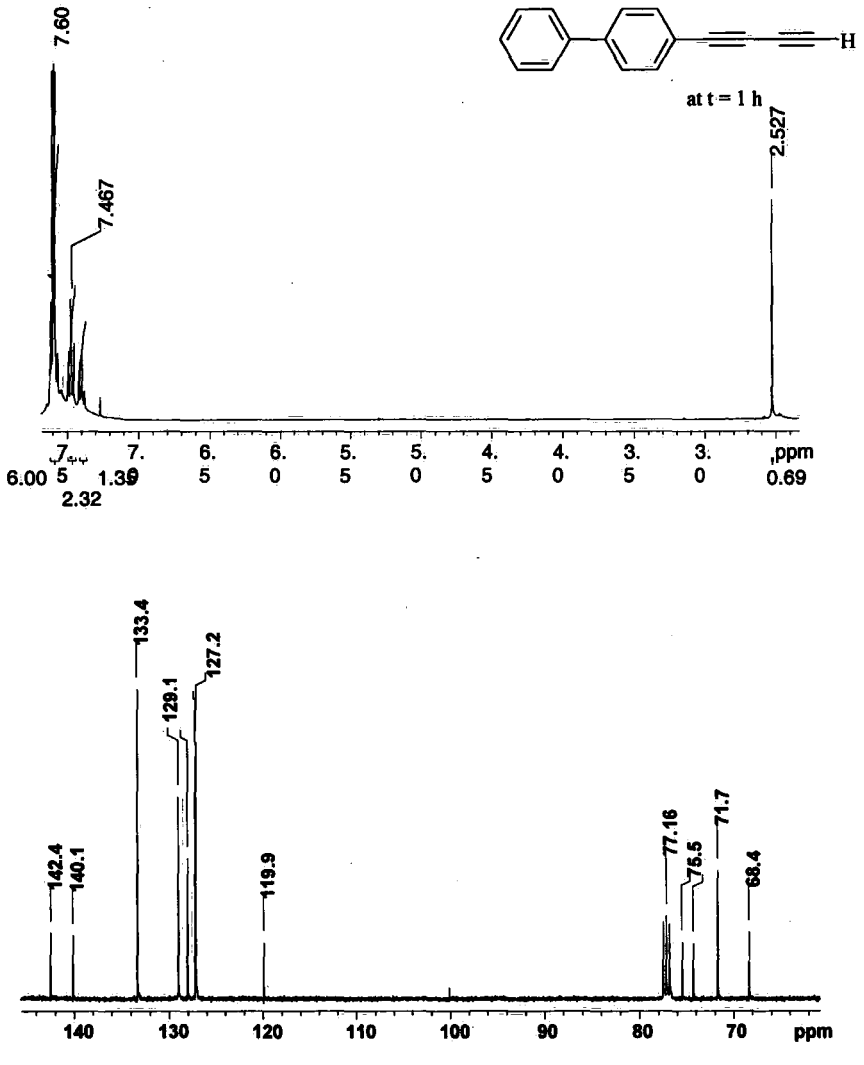


Fig II.2 NMR data of 143 at t = 1 h in $CDCl_3$ at 400 MHz and 100 MHz

Fig II.2 shows the ^{1}H and ^{13}C NMR of **143.** Refluxing a 5×10^{-2} M solution of **143** in either toluene, cyclohexane or 1,4-dioxane in daylight for 10 min resulted in a slight

darkening of the solution and recovery of 60-70% of unchanged **143.** A trace amount of dark insoluble precipitate formed and was removed before evaporation of the toluene and dissolution of the residue in $CDCl_3$ to obtain the spectra. Integration of the aromatic protons against the alkyne proton (δ 2.516) (theory 9:1; experiment 13.7:1) is consistent with the sample being *ca.* 65% unchanged **143**. The survival in such harsh conditions is remarkable (both during its formation from **145** and during subsequent heating). The NMR spectrum after reflux is shown in **Figure II.3**.

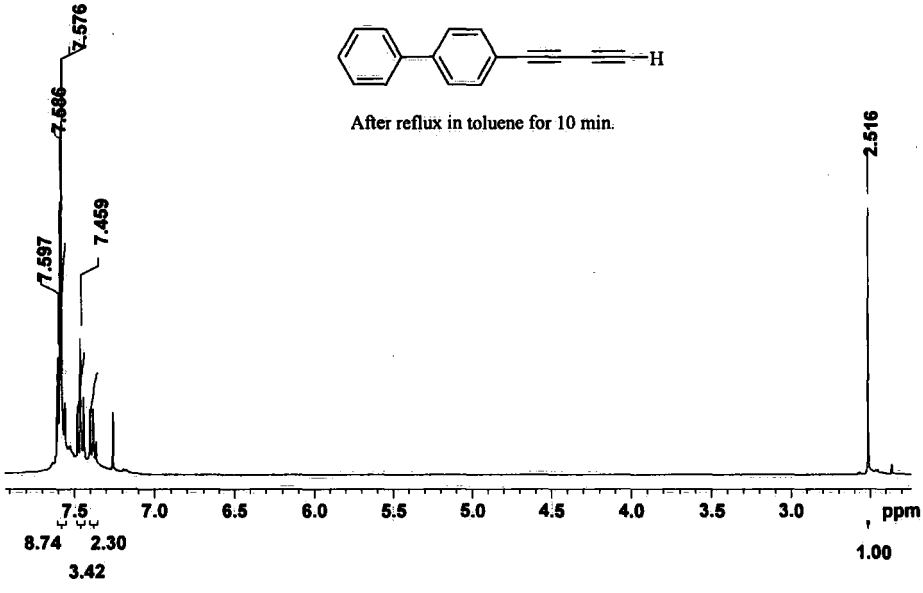
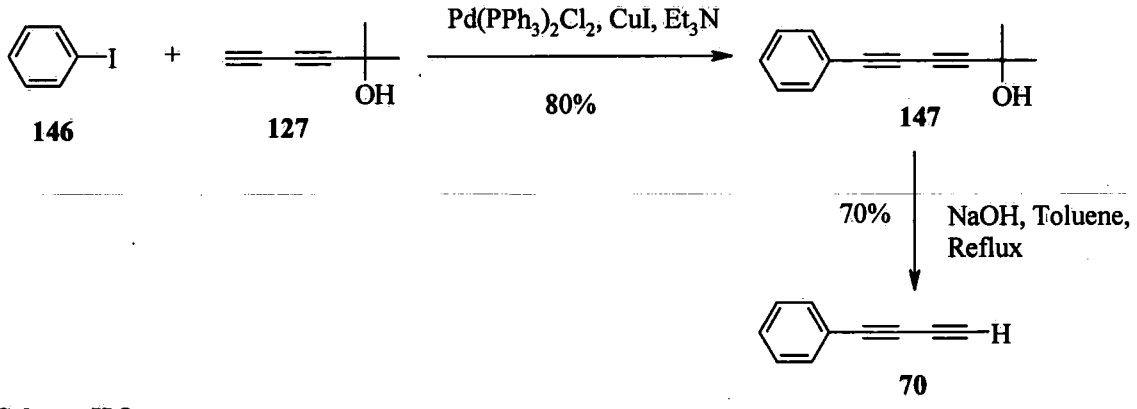


Fig II.3 NMR data of 143 after reflux in toluene for 10 min at 400 MHz in $CDCl_3$.

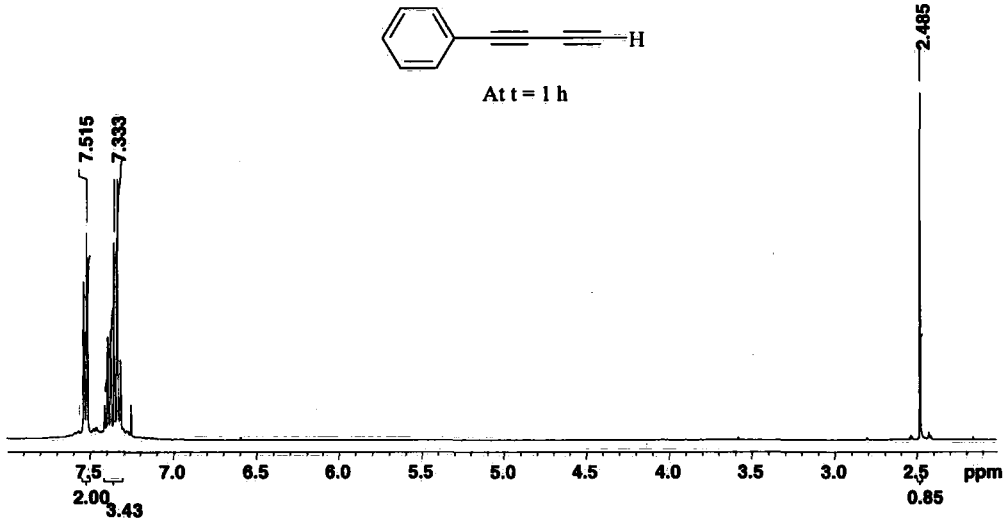
It was decided, therefore, to concentrate on monocyclic aryl and heteroaryl systems, and hence the synthesis of phenylbutadiyne **70** was attempted. Historically, **70** has been reported as unstable (**Section I.3**). [84]

Iodobenzene **146** and **127** afforded 2-methyl-6-phenylhexa-3,5-diyn-2-ol **147** as a white solid in 80% yield. Deprotection gave phenylbutadiyne **70** as a colourless oil in 70% yield (**Scheme II.8**). There were no signs of degradation on drying, hence, it was possible to obtain ^{1}H and ^{13}C NMR, GC-MS and a high resolution mass spectrum.



Scheme II.8

Since **70** was an oil it was not possible to grow a crystal using standard techniques. A sample was stored at -20 °C in solution, since storage of the neat oil resulted in significant darkening and degradation. It is remarkable, however, that an NMR spectrum of a sample of **70** which had been stored in $CDCl_3$ for 2 weeks at 20 °C in ambient light conditions under air showed no signs of decomposition (**Fig II.4** and **Fig II.5**). It was thus shown that contrary to literature precedents, the isolation of phenylbutadiyne **70** is possible. Admittedly, careful handling was required, but this is not problematic.



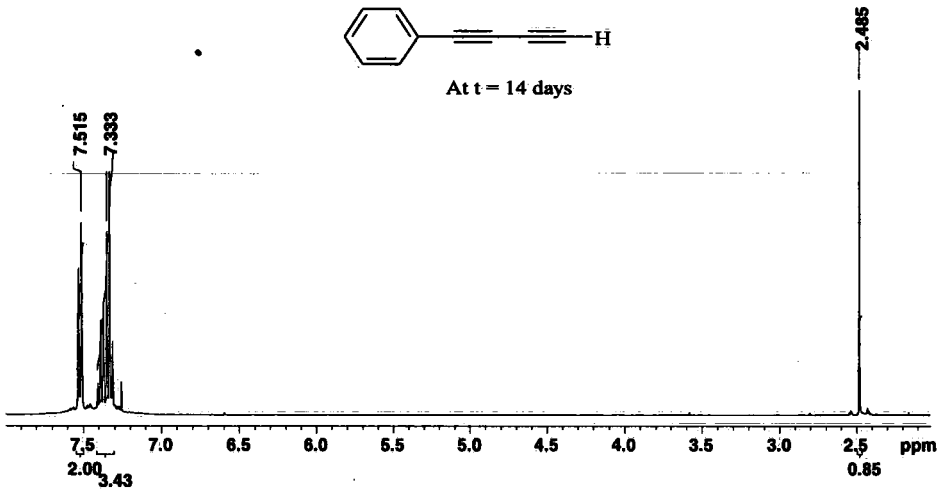
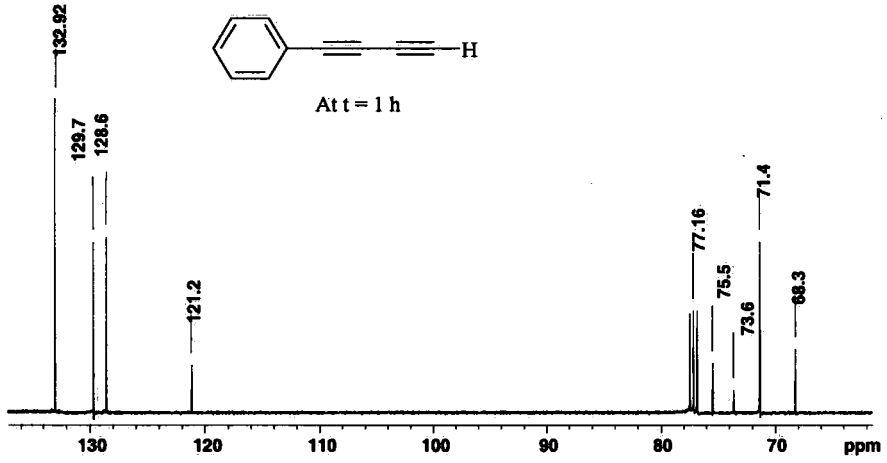


Fig. II.4; ^{1}H NMR spectra of terminal phenylbutadiyne 70 after t = 1 h and t = 2 weeks in $CDCl_3$ at 400 MHz



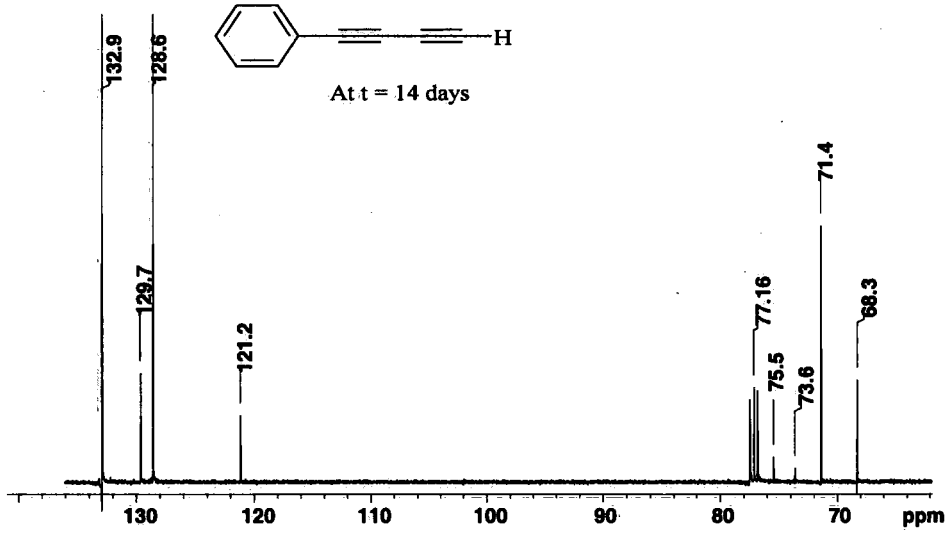
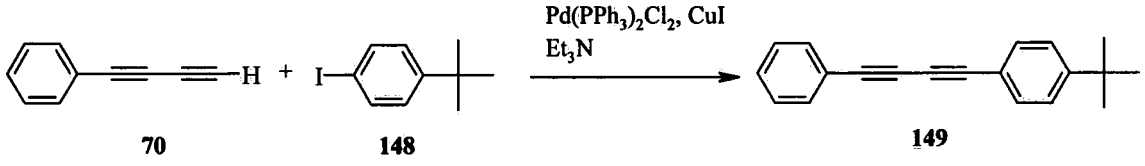


Fig. II.5; ^{13}C NMR spectra of terminal phenylbutadiyne 70 after t = 1 h and t = 2 weeks in $CDCl_3$ at 100 MHz

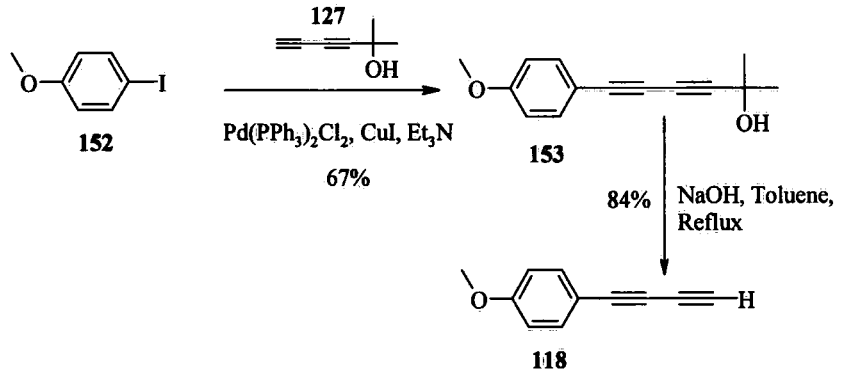
To confirm that isolated **70** is a viable precursor to unsymmetrical 1,4-diarylbutadiynes, it was cross-coupled with *p*-*t*butyl-iodobenzene **148**, to afford the expected product **149**. (The 9-proton singlet peak was a useful marker in the ^{1}H NMR spectrum). The reaction was accomplished in two steps; deprotection of **147** afforded **70** (as in **Scheme II.8**) which was isolated from the reaction mixture by column chromatography. Solvent was removed *in vacuo* and without delay the residual oil of **70**, **148**, $Pd(PPh_3)_2Cl_2$, CuI, and triethylamine were mixed and stirred at 45 °C for 18 h to give a 75% yield of **149** (based on **147**). **Scheme II.9**.



Scheme II.9

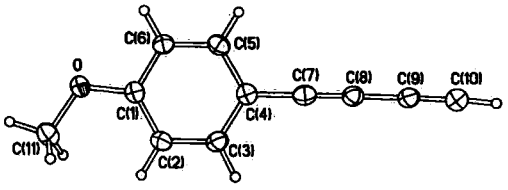
In further attempts to obtain crystalline arylbutadiyne derivatives, and probe the effect of substituents on stability, we explored the synthesis of 2- **150**, 3- **151**, and 4- **118** methoxyphenylbutadiyne derivatives.

4-Iodoanisole, **152** underwent Sonogashira coupling conditions with **127** to afford **153** in 67% yield as a white solid. Basic deprotection in refluxing toluene afforded **118** as a white solid, **Scheme II.10.**



Scheme II.10

Crystals suitable for X-ray analysis were grown and the structure is shown in **Figure II.6.**



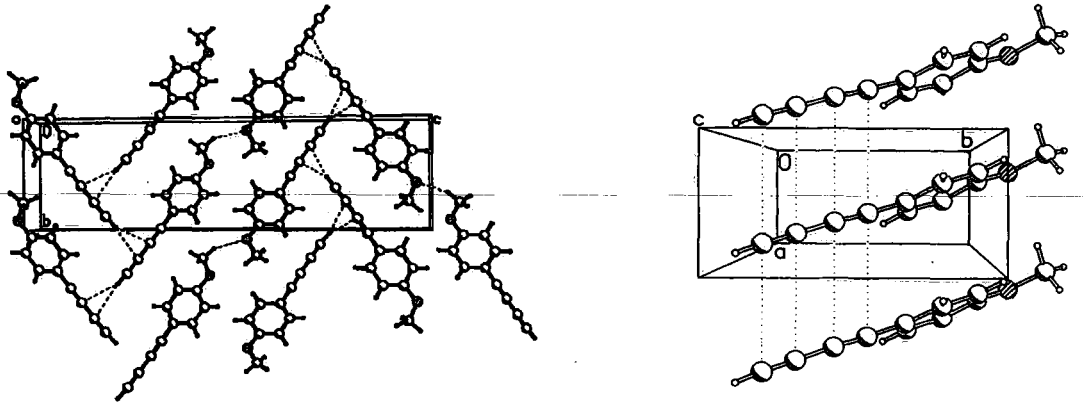
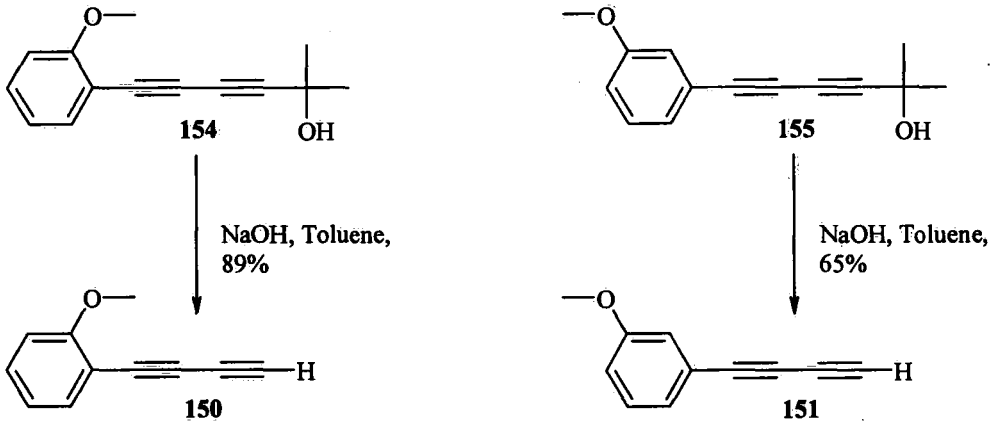


Fig. II.6 Crystal structure and packing diagrams of 118.

The 2- and 3- methoxy analogues **154** and **155**, respectively, were synthesised by directly comparable methodology in 75% and 50% yields from the iodoanisole starting material, **Scheme II.11**. Deprotection afforded **150** and **151** in 89% and 65% respectively. However, they were both oils and found to be considerably less stable than the crystalline isomer **118**. It is not clear why these isomers of crystalline **118** are both oils, indeed their precursors **154** and **155** were also oils, even though their purity has been confirmed by elemental analysis.



Scheme II.11.

It was decided to extend our methodology to a range of nitrogen-containing heterocyclic systems, which would hopefully be stable solids (and even crystalline) due to the possibility of hydrogen bonding interactions between the terminal butadiyne proton and a nitrogen atom in the ring. **Table II.1** lists the structures and isolated yields of both protected and deprotected heterocyclic butadiynes .

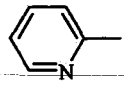
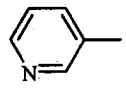
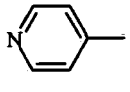
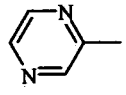
N-heterocycle	Isolated yield of protected product	Isolated yield of butadiyne derivative
 *o*-pyridyl,	**156**, 80%	**157**, 66%
 *m*-pyridyl,	**158**, 82%	**159**, 65%
 *p*-pyridyl,	**160**, 80%	**72**, 64%
 Pyrazine,	**161**, 78%	**162**, 64%

Table II.1. Heteroaryl butadiynes synthesised.

The X-ray crystal structure was obtained for the protected derivative **156**. The packing diagram confirms that, in the crystal, there is a hydrogen bonding interaction between the pyridyl N-atom and the hydroxyl proton of the protecting group of an adjacent molecule (indicated by the dashed line) leading to dimer pairs (**Figure II.7**).

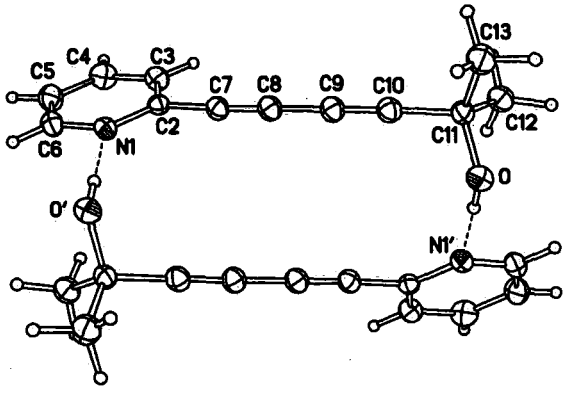


Fig II.7.

As predicted, white solids of the deprotected butadiyne derivatives were isolated for all these heterocyclic systems and the crystal structures were solved by X-ray analyses for compounds **157**, **72** and **162.** In all cases, intermolecular hydrogen bonding interactions were observed which would enhance their stability in the solid state. In the crystalline state the compounds were stable at room temperature for a matter of days,

long enough for X-ray crystallography submission and associated handling. Dilute solutions could be kept for weeks at room temperature, whereas solutions stored in the freezer (-20 °C) have remained for over a year unchanged (without visible signs of decomposition).

The herringbone packing motif in the crystal of **157** is stabilised by a ≡C–H···N hydrogen bonding interaction as shown in **Figure II.8**.

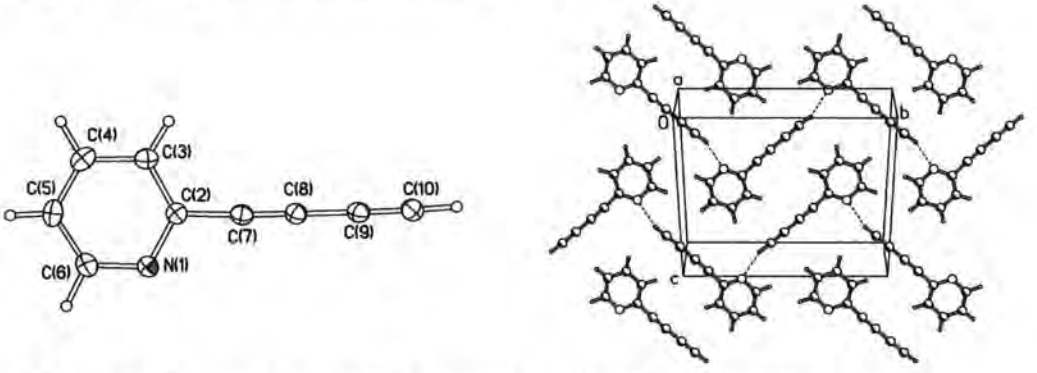


Fig II.8. Crystal structure and packing diagram of 2-(buta-1,3-diynyl)pyridine, 157

For crystals of **72** a ≡C–H···N hydrogen bonding interaction is also observed, thus forming a continuous ribbon structure (**Figure II.9**). The vector distance between the diyne rods, *d*, was measured to be 3.82 Å, whereas the angle formed between them, Φ, was 68.9 °.

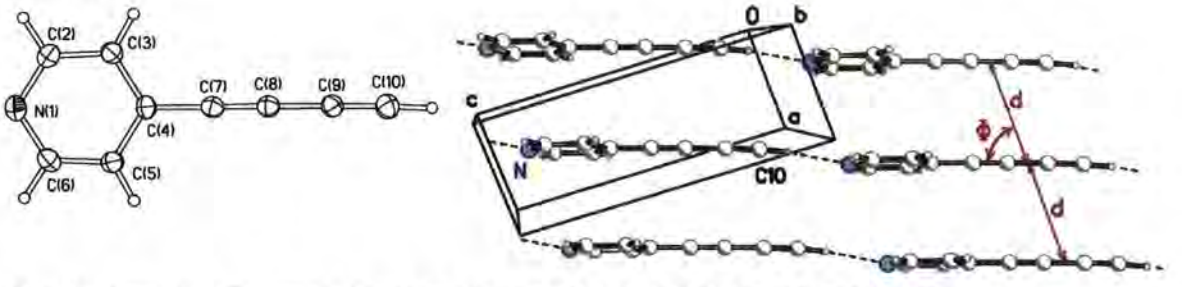


Fig II.9. Crystal structure and packing diagram of 4-(buta-1,3-diynyl)pyridine, 72

X-ray analysis of the pyrazyl-butadiyne **162** was more complicated due to two independent molecules in the unit cell, one ordered, and the other disordered. There is a pseudo-inversion centre (×) relating the ordered molecule with the *mean* position of the disordered molecule. The packing diagram shows both ordered and disordered chains of hydrogen-bonded molecules (**Figure II.10**).

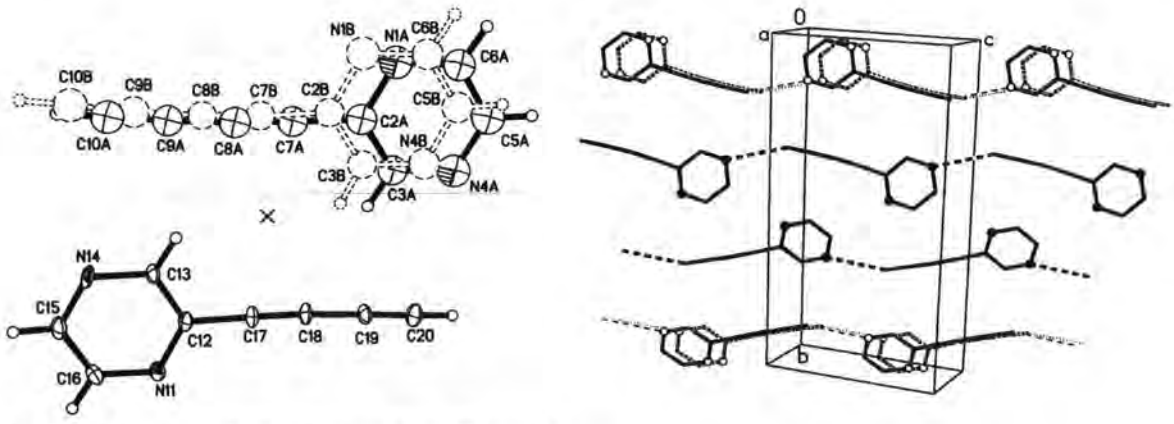
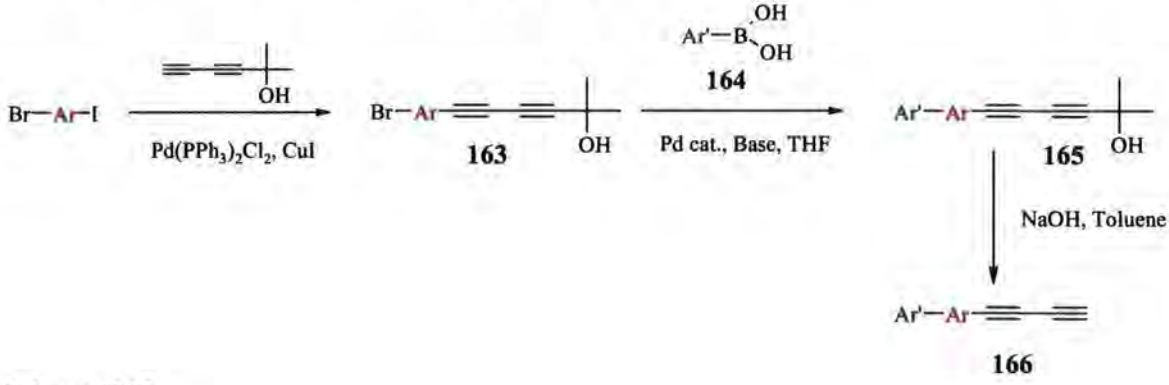


Fig II.10 X-ray analysis of pyrazylbutadiyne 162.

Following on from the successful isolation, and structural analysis, of *N*-heterocyclic and biphenyl butadiynes, it was decided to attempt the synthesis of bi-aryl- and heteroaryl-butadiynes.

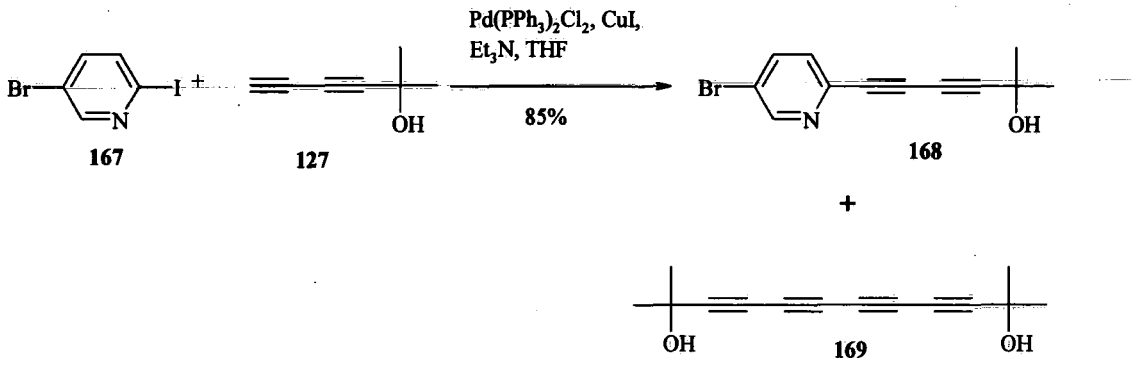
II. 3 Biaryl/heteroaryl butadiynes

The introduction of a bromo or iodo substituent on a phenylbutadiyne derivative **163** afforded the opportunity for further cross-coupling by standard Suzuki-Miyaura protocols (**Scheme II.12**).[125] Parts of this work were done with the assistance of Laura Hayward, a 4th year MChem student within our group. Accordingly bromo-substituted compound **163** was synthesised following our standard procedures. It was not obvious whether or not the protecting group would withstand the basic conditions of the Suzuki reaction between **163** and **164** to afford **165**. By varying the aryl groups Ar and Ar', in principle it could be possible to synthesise a whole range of biaryl/heteroaryl butadiynes from **166**. The incorporation of sites for hydrogen bonding (*e.g.* N atoms) might afford new crystalline solids suitable for X-ray analysis.



Scheme II.12

5-Bromo-2-iodopyridine (commercially available), **167**, was coupled with **127**, yielding **168**, in high yield, **Scheme II.13**.

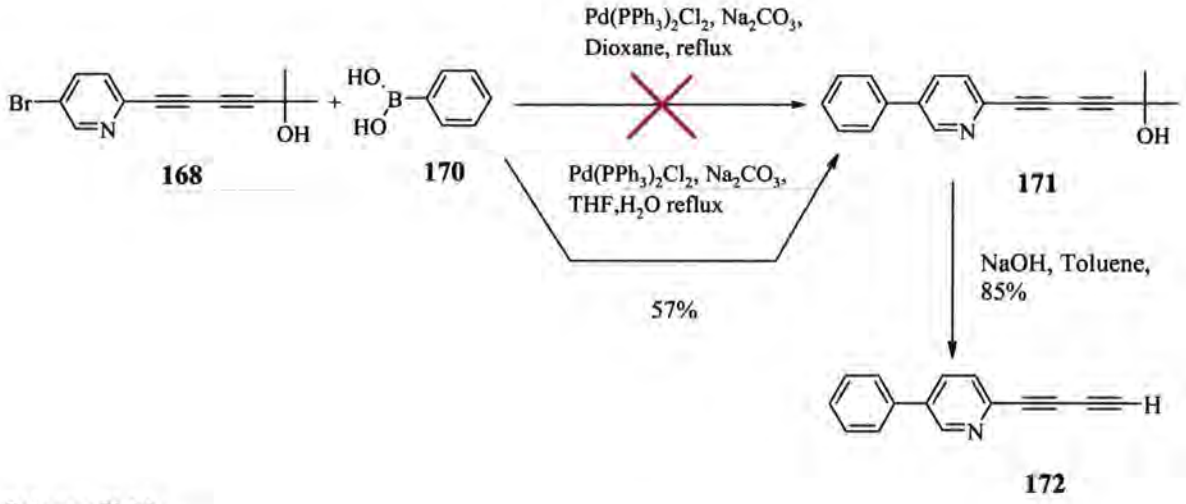


Scheme II.13

Optimum conditions for this reaction were 1 eq. of aryl halide **167**, 1.25 eq. of alkyne **127**, with 3% by mol of catalyst (based on aryl halide) and reaction times of 3 hours; tlc analysis showed that longer reaction times (e.g. 5 h) can favour formation of homocoupled species **169** (^{1}H NMR evidence). The formation of **169** was not optimised.

The first Suzuki coupling attempted was between **168** and phenylboronic acid **170**, in the presence of Na_2CO_3, with $Pd(PPh_3)_2Cl_2$ catalyst and dioxane solvent at reflux. The reaction was unsuccessful; analysis by TLC showed a dark base line spot. It was assumed that the slightly basic conditions, together with the high reaction temperature might result in the deprotection of **168**. Terminal arylbutadiynes bearing bromo derivatives were found to be less stable than their analogues (see later section), and hence if deprotection is occurring it is highly likely the resulting product is not stable and is thus polymerising. By changing the solvent to THF (with a small amount of water to ensure homogeneity), the reaction proceeded in 57% yield to afford **171**, thus showing that Suzuki couplings do proceed in the presence of this protecting group (**Scheme II.14**).

Deprotection of **171** afforded the terminal butadiyne **172** in 85% yield. Crystals suitable for X-ray structural analysis were obtained, shown in **Figure II.11**



Scheme II.14

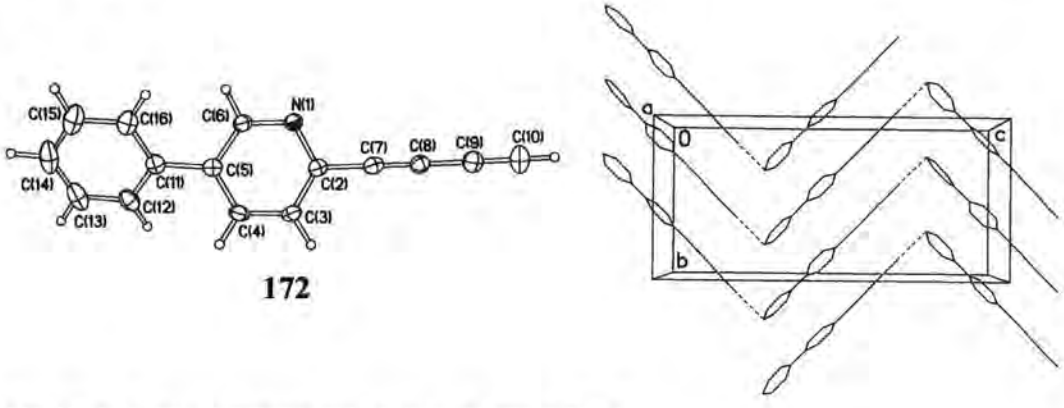
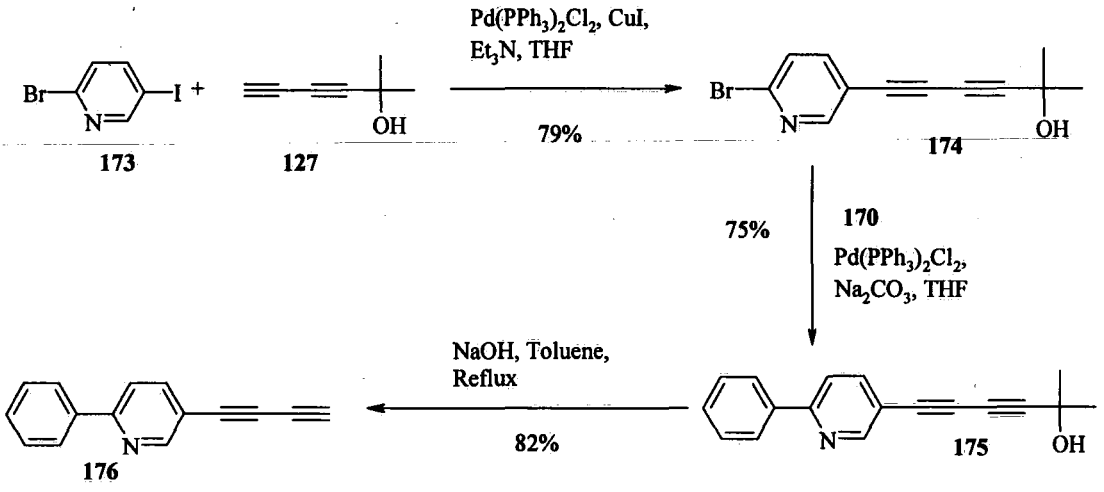


Fig. II.11; X-ray structure and packing diagram of 172

Interestingly, the packing diagram showed no hydrogen bonding interaction between the terminal acetylenic proton and the pyridyl nitrogen atom. Instead, the herringbone-type formation shows a weak hydrogen bonding interaction with C14. The dihedral angle of **172** was measured to be 32.2 °, which is smaller than the dihedral angle of biphenyl **143**, which had a dihedral angle of 45.6 °.

The same synthetic protocol was adopted using 2-bromo-5-iodopyridine **173** to afford the protected species **174** in good yield (**Scheme II.15**). Although the bromo substituent is in an activated position (*ortho* to the nitrogen atom), Sonogashira coupling still occurs selectively at the iodo-position, when 1.3 equivalents of **127** were used. This further corroborates previous observations that reagent **127** is reactive only with aryl iodides and not bromides.

Suzuki Coupling of **174** with phenylboronic acid **170** in THF under standard conditions afforded the cross-coupled species **175** in 75% yield, which underwent standard basic deprotection in toluene to afford **176** as a crystalline solid in 82% yield, **Scheme II.15**.

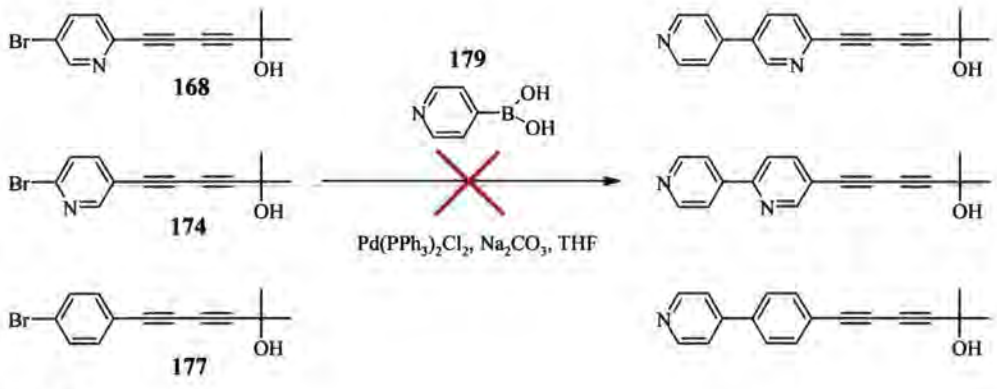


Scheme II.15.

By growing crystals for structural information it would be possible to determine whether there is a hydrogen bonding interaction with the nitrogen in the ring, or whether the packing is the same as seen for **172**. It is predicted the dihedral angle would not be as great as observed with biphenylbutadiyne **143** or **172**, since **176** has one less *peri*-proton. Disappointingly, crystals of **176** suitable for X-ray analysis could not be grown, despite its crystallinity. It is predicted that **175** or **176** could be a useful ligand for cyclometallation with a chosen heavy metal atom, *e.g.* iridium.

The stability of both **172** and **176** are much the same and are very similar to the N-heterocycle butadiynes discussed earlier; compounds are stable in the solid state for a matter of days, thereafter significant darkening occurs. These compounds are normally stored in dilute solutions in the freezer as an act of precaution.

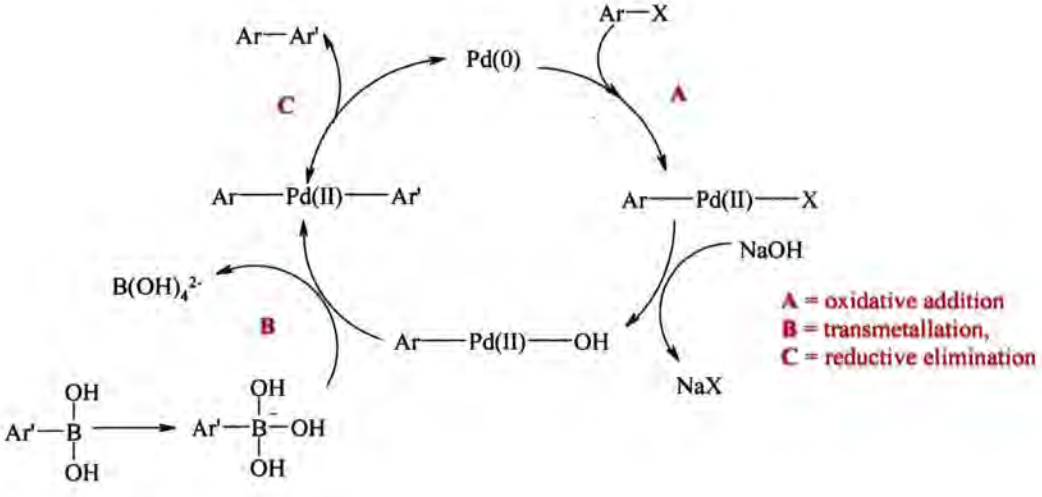
Coupling species **168**, **174** and **177** (synthesised from 1-bromo-4-iodobenzene **178**) with 4-pyridylboronic acid **179** (**Scheme II.16**) would result in the incorporation of a nitrogen site into the outer aryl ring with potentially interesting structural consequences (*c.f.* the hydrogen-bonded ribbon structure of **72**, Figure II.9).



Scheme II.16

Unfortunately, all attempted cross-couplings of **168**, **174** and **177** with 4-pyridylboronic acid **179** were unsuccessful (**Scheme II.16**). Analysis by TLC indicated only unreacted starting material in the reaction mixture. Similarly, the attempted coupling of **177** with 3-pyridylboronic acid was unsuccessful. By replacing solvent THF with 1,4-dioxane, and gradual heating to 105 °C, it was hoped the reaction would proceed; however, this was not the case. Tris(*t*-butyl)phosphine ligand was also added to the reaction mixture, with the hope that the bulky, strongly electron donating phosphine would increase the electron density on the Pd atom, thus improving the rate of oxidative addition. However, again, there was with no observable product formation.

The Suzuki couplings between compounds **168**, **174** and **177** with both 3-, and 4-pyridylboronic acid were not successful. The Suzuki-Miyaura mechanism is outlined in **Scheme II.17**. There are three basic steps; oxidative addition, transmetallation and reductive elimination on cycle.



Scheme II.17

Pyridylboronic acids have long been problematic with proto-deboronation as a particular issue, [126]affording pyridine and $B(OH)_3$, which is lost in the aqueous layer. The lack of spots on the TLC plate in our reactions suggests this process could be occurring, as pyridine would not be observed. The rate of proto-deboronation could be quicker than other steps in the catalytic cycle, hence the Suzuki reaction is not proceeding. To increase the chance of reaction, a higher reaction temperature is probably necessary, but this could result in deprotection of the butadiyne unit.

To conclude, the synthesis of aryl-, heteroaryl and biaryl- butadiynes has so far been shown. **Table II.2** presents the bond distances i-v, measured in Å, along with lattice vector *d* (Å) and Φ (°), which is the angle formed between the lattice vector, *d*, and the diyne rod.

	i	ii	iii	iv	v	*d*	Φ (°)
118	1.435(3)	1.203(3)	1.380(3)	1.187(3)	0.97(3)	3.93	76.0
143	1.441(4)	1.200(4)	1.381(4)	1.180(4)	0.95		
157	1.4345(16)	1.2012(16)	1.3768(16)	1.1949(17)	0.976(16)	3.82	69.3
72	1.433(2)	1.202(2)	1.381(2)	1.194(2)	0.987(18)	3.82	68.9
162	1.428(3)	1.220(3)	1.367(3)	1.215(4)	0.95	3.82	68.4
172	1.436(2)	1.200(2)	1.371(2)	1.187(2)	0.91(2)		

Table II.2 Crystal structure data showing bond lengths in aryl- and heteroaryl-butadiynes.[127]

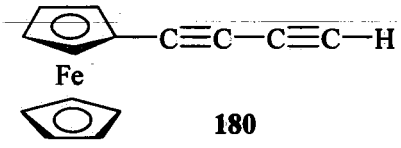
It is difficult to comment whether or not the nature of the aryl group is affecting the butadiyne bond-lengths, since the observed hydrogen bonding interactions might also influence these bond distances.

II. 4 Stability

Presently, it is not possible to determine conclusively the factors which determine the stability of these simple butadiyne compounds. A general trend is that the greater the steric bulk, the more stable the arylbutadiyne, *e.g.* the diaryloxadiazole derivative **71** and the biphenyl derivative **143** are among the most stable we have synthesised in our laboratory.

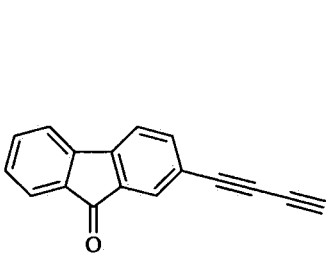
A ferrocene butadiyne **180** was reported as early as 1993 by Marder *et al.* as being "*stored as a solid in a refrigerator under air for several months.*"[128] Since the authors

did not obtain structural analysis, it is difficult to determine the reason for such relative stability. It is presumed, therefore, the steric bulk of the ferrocene moiety is not allowing close contact of the diyne rods, therefore the compound is not decomposing.



180

Another stable butadiyne derivative, from the Bryce research group, is the fluorenone **181** prepared by Dr Changsheng Wang. [127] Crystals suitable for X-ray analysis were obtained. The crystal packing diagram in **Fig II.12** indicates a hydrogen bonding interaction between the terminal acetylenic proton and the oxygen atom doubly bonded at the C9.



181

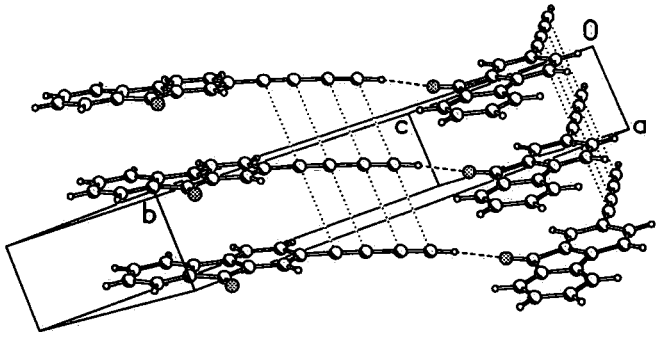


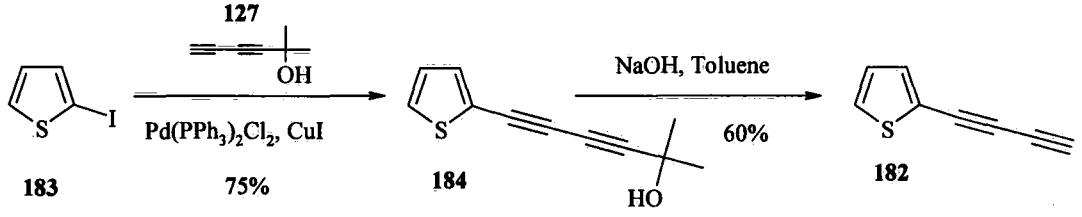
Fig II.12 Crystal packing diagram of fluorenone butadiyne 181.[127]

The hydrogen bonding interaction as seen in various compounds discussed within this chapter is thought to be a stabilising factor. It is hypothesised that the crystallinity of the compound, aided by the observed hydrogen bonding interaction, is thus enforcing a solid state arrangement which is not favourable to polymerisation.

It is presumed that the electronic properties of the ring are also affecting the stabilities of the compounds, however, it is extremely difficult to determine this because any substituent affecting the electron density on the ring will also give rise to a possible site for hydrogen bonding. For example, a nitro group on a phenylbutadiyne will result in the ring being electron deficient; however, it would also introduce sites for hydrogen bonding between the nitro group and the terminal alkyne proton.

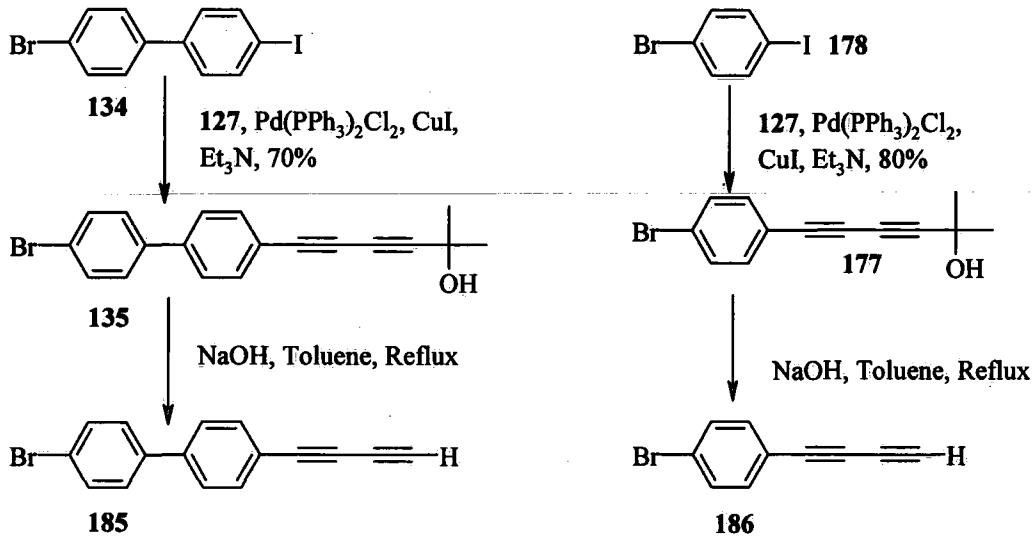
Thiophene is an electron-rich system, therefore the synthesis of a thienylbutadiyne was attempted. It was predicted that the species would be an oil and not be stable as there are neither sites for possible hydrogen bonding (as in the pyridyl systems), nor is there any steric bulk (as in the biphenylbutadiyne, **143**). It was not obvious, however, whether the electron-rich aromatic system would affect the stability of the butadiyne derivative **182**.

2-Iodothiophene **183** was coupled with **127** to afford **184** in 75% yield. Basic deprotection afforded the deprotected target 2-(buta-1,3-diynyl)thiophene **182** in *ca.* 60% yield (**Scheme II.18**). This species was volatile, hence careful handling was required during isolation and characterisation. ^{1}H NMR spectra, GC-MS and high resolution mass spectrometry were entirely consistent with the structure **182**. Its volatility meant that solvents could not be completely removed for NMR analysis, thus ^{13}C NMR spectra were inconclusive.



Scheme II.18.

The syntheses of bromobiphenyl **185** and *p*-bromophenyl **186** terminal butadiynes were attempted (**Scheme II.19**). The bromo-substituent is electron withdrawing, thus resulting in less electron density on the biphenyl and phenyl rings, respectively. However, bromines are also soft sites of electron density and can encourage close packing in the solid state. If, as a result of this, the diyne rods come into too close contact, polymerisation could readily occur. **134** and **178** underwent Sonogashira couplings to afford **135** and **177** in good yield. The synthesis of **185** and **186** from their protected precursors **135** and **177** respectively, was next attempted. Both terminal compounds were extremely unstable, however; significant darkening of crude residue before loading onto the column was observed, and upon isolation after column. Black solids of **185** and **186** were afforded, hence characterisation and yields were not obtained. Analysis by TLC did, however, indicate a quantitative reaction.

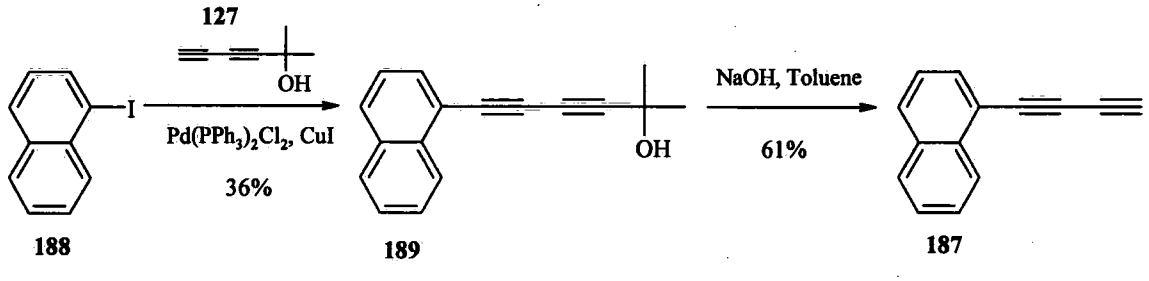


Scheme II.19.

II. 5 Fused-Ring Systems

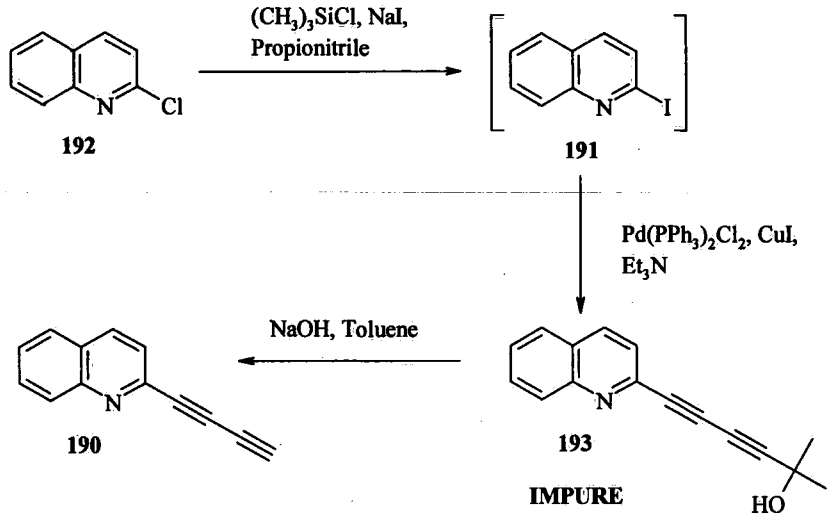
We also explored the synthesis of fused-ring planar aromatic butadiynes. For example by comparing naphthalene and biphenyl derivatives **187** and **143** it might be possible to determine whether, larger planar systems afford greater or lesser stability.

1-Iodonaphthalene (commercially available) **188,** was coupled with **127** to yield **189**. Deprotection under basic conditions at reflux afforded **187** as a brown, unstable oil which was identified by ^{1}H NMR, ^{13}C NMR and mass spectrometry (**Scheme II.20**). Possibly π–π stacking of the naphthalene rings could bring the butadiyne rods into close contact, thus resulting in polymerisation.



Scheme II.20

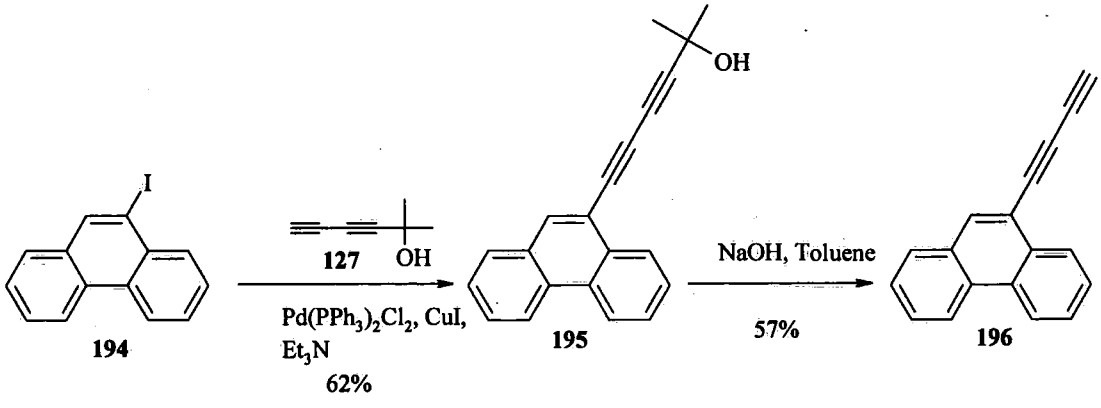
It was hoped that a quinolyl analogue **190** might be more stable due to hydrogen bonding to the nitrogen atom as observed in the pyridyl series (see section II.2). Iodoquinoline **191** is not commercially available, requiring synthesis from chloroquinoline **192 (Scheme II.21)**.



Scheme II.21.

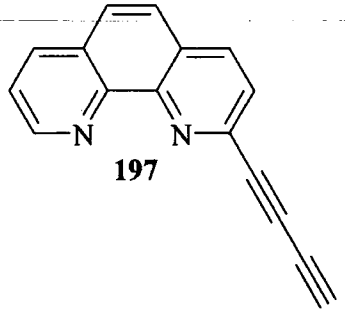
TMSiCl, sodium iodide and 2-chloroquinoline **192** were stirred in propionitrile to afford **191** after recrystallisation.[129] The presence of any unreacted **192** should not be a problem, since it will not react in the next step. Unfortunately, product **190** was a brown oil, implying impurities being present. Analysis by NMR indicated the presence of two butadiyne moieties, most likely due to iodination of **191** occurring at another position on the ring. At this point, it was decided not to continue further with this system to concentrate on other fused ring systems, hence the synthesis of a phenanthrylbutadiyne was next attempted.

9-Iodophenathrene **194** is commercially available, hence was bought and used without further purification. The preparation of **195** proceeded in 62% yield under standard Sonogashira conditions. Deprotection to afford **196** was successful, (^{1}H NMR evidence) however, **196** was extremely unstable and darkened within a few minutes of isolation, **Scheme II.22.**



Scheme II.22.

Phenanthrolene analogue **197** would be an interesting target which could also serve as a bidentate ligand. A promising approach could be a copper-free Sonogashira reaction (to avoid chelation with Cu) on readily available 2-iodophenanthrolene.[130]

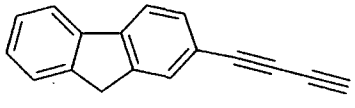


197

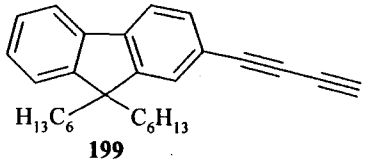
It was concluded, therefore, that whilst the fused-ring butadiynes are fundamentally and theoretically important, they are very challenging targets and this avenue of work was not pursued further.

II.6 Future work

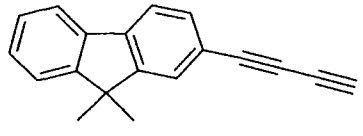
To determine whether the dihedral twist is playing an important role in the stabilisation of **143**, the synthesis of a fluorene butadiyne **198** was predicted to be important. It was predicted fluorene butadiyne would not be able to withstand the deprotection conditions, since the protons at the C9 positions are relatively acidic. By functionalising at the C9-postion, it might be possible to overcome such a problem. It was predicted the hexylated-fluorenebutadiyne **199** would be an oil, hence the dimethyl fluorenebutadiyne **200** was thought to be the most promising.



198

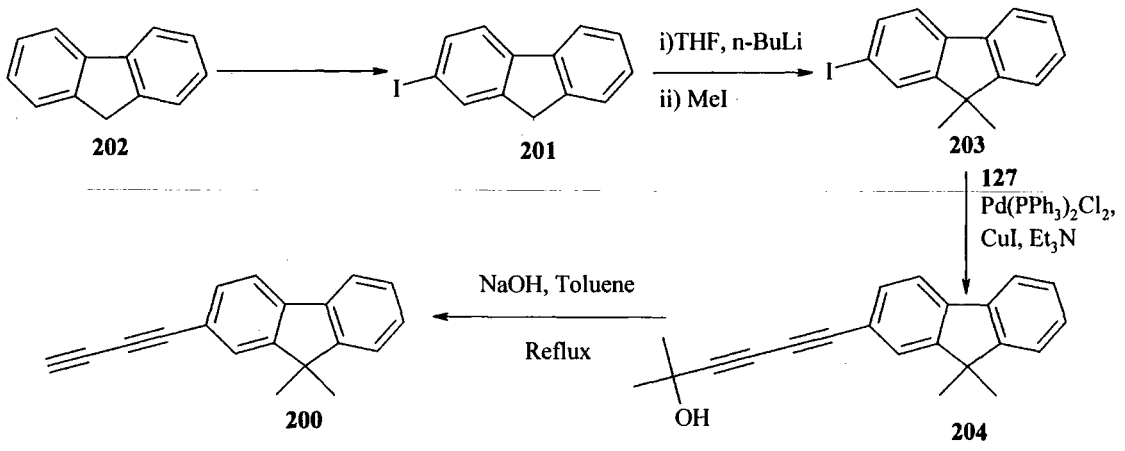


199



200

Due to time restraints, the dimethyl analogue **200** has not been synthesised to date. The mono-iodinated fluorene **201** is not readily available, requiring synthesis from fluorene **202**. Treatment with two equivalents of *n*-BuLi followed by quenching with MeI, should afford **203**. Sonogashira coupling with **127** to afford **204**, followed by basic deprotection in toluene would afford **200**, **Scheme II.23**.



Scheme II.23

II. 7 Conclusions

In summary, the synthesis, isolation and characterisation of a wide range of terminal aryl and heteroarylbutadiynes has been successfully achieved in good to excellent yields. Many of these species are considerably more stable than previously predicted; indeed the parent phenylbutadiyne **70**, which has traditionally been considered to be too unstable to characterise, can be stored in dilute solution for several months at -15 °C with very little decomposition. An important feature of the synthetic methodology we have developed is the use of the 2-hydroxy-2-propyl protecting group which being highly polar facilitates purification of the precursors before deprotection to the target arylbutadiynes. Structural analysis by X-ray crystallography indicates, in most cases, stabilisation by a hydrogen bonding interaction between terminal acetylenic proton and a heteroatom.

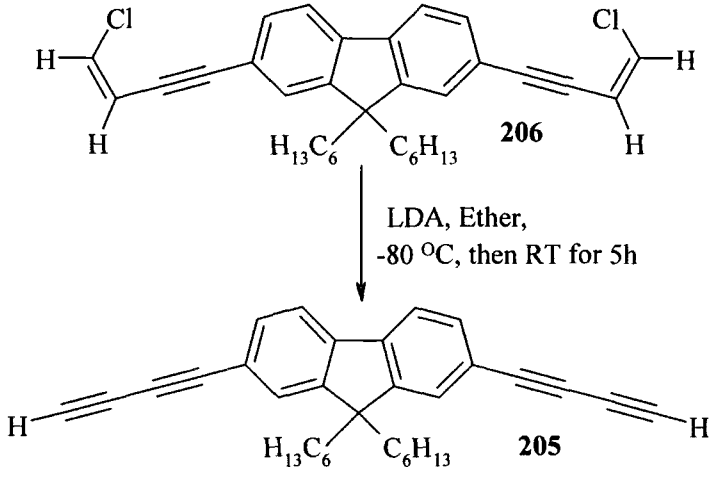
The Suzuki coupling of phenylboronic acid in the presence of the 2-hydroxy-2-propyl protecting group has also been shown to proceed in good yield. Unfortunately, Suzuki couplings with pyridylboronic acids were not successful.

The reactions and functionalisation of aryl and heteroarylbutadiynes will be detailed in Chapter IV.

Chapter III Aryl bis-butadiynes

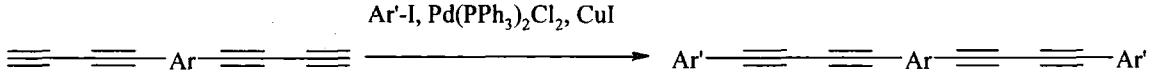
III. 1 Introduction

Chapter II explored the isolation and characterisation of terminal aryl- and heteroarylbutadiynes, along with several of their X-ray crystal structures. This work prompted us to extend our methodology to the synthesis of terminal aryl bis-butadiynes, a relatively unexplored research area. During the course of this our work, 9,9-dihexylfluorene bis-butadiyne **205** has been reported in the literature, synthesised by the dehydrohalogenation of precursor **206**, **Scheme III.1.**[131]



Scheme III.1

If we could obtain terminal bis-butadiynes, subsequent end-capping reactions would yield symmetrical highly conjugated systems bearing the bis-butadiyne motif (**Scheme III.2**)



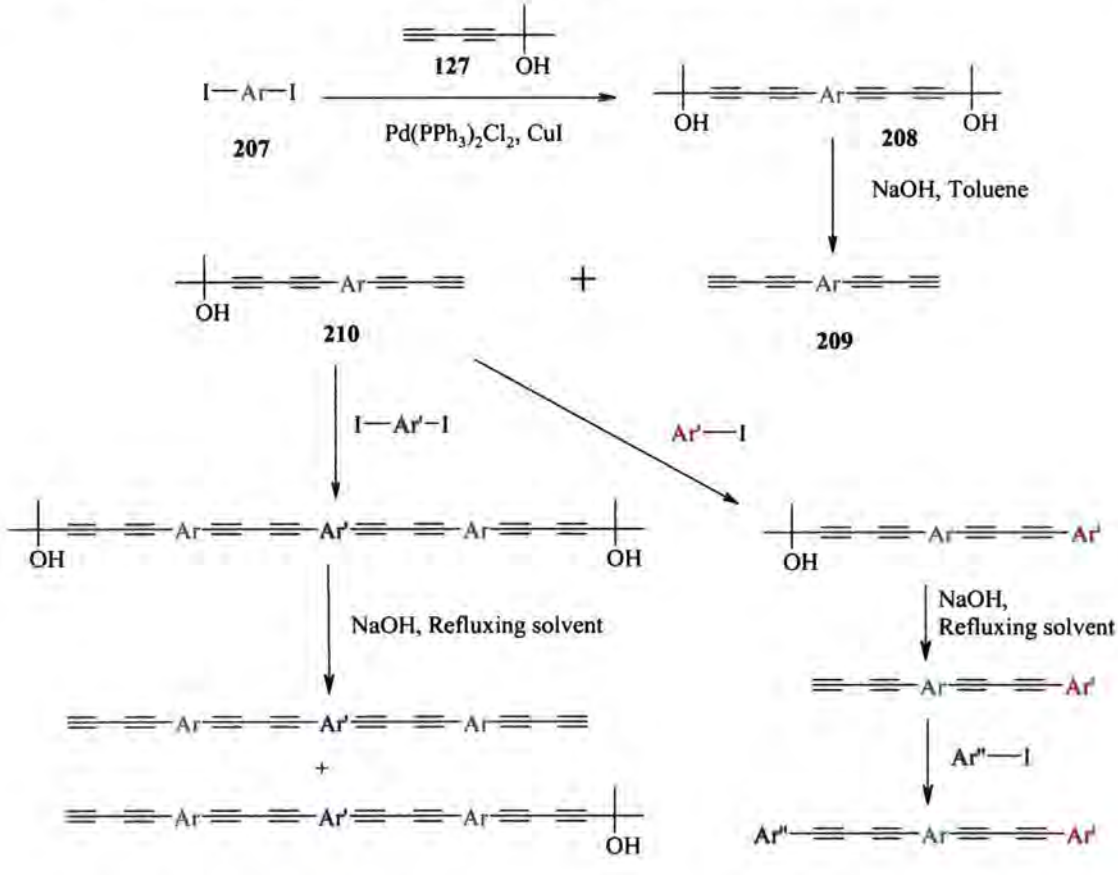
Scheme III.2.

The stability of such compounds is, however, questionable: Will the bis-butadiynes be sufficiently stable in their solid state, for isolation and full characterisation? The hexylatedfluorene species **205** was reported as a yellow/brown solid and characterisation by ^1H and ^{13}C NMR, along with MS data, obtained.

III. 2 Bis-butadiyne synthesis

The protocol adopted was the same as previously utilised. An overview is presented in **Scheme III.3**. Two-fold Sonogashira coupling between a diiodo-arene **207** and 2-methyl-3,5-hexadiyn-2-ol **127** afforded the di-coupled species **208**. Deprotection in basic conditions gave the di-deprotected bis-butadiyne **209**. The deprotection was not quantitative and some mono-deprotected bis-butadiyne **210** was also isolated from the reaction mixture. The large difference in polarity between **208, 209** and **210** means that purification by column chromatography is relatively facile. This easy purification is essential; such compounds may not be stable if left for a long period of time on the column.

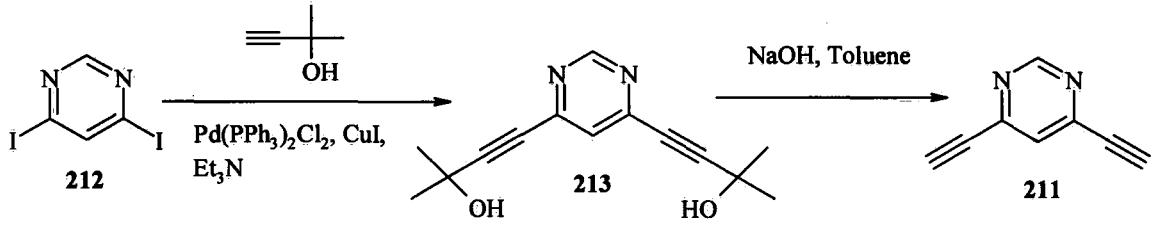
Side-product **210**, however, is an extremely useful precursor for both symmetrical and unsymmetrical molecular wire synthesis by iterative procedures. Cross-coupling of **210** with diiodo-arene, I-Ar'-I, would afford a long protected species which could be further deprotected. Cross-coupling of **210** with Ar'-I, deprotection and further reacting with Ar''-I would afford an asymmetrically capped system (**Scheme III.3**).



Scheme III.3.

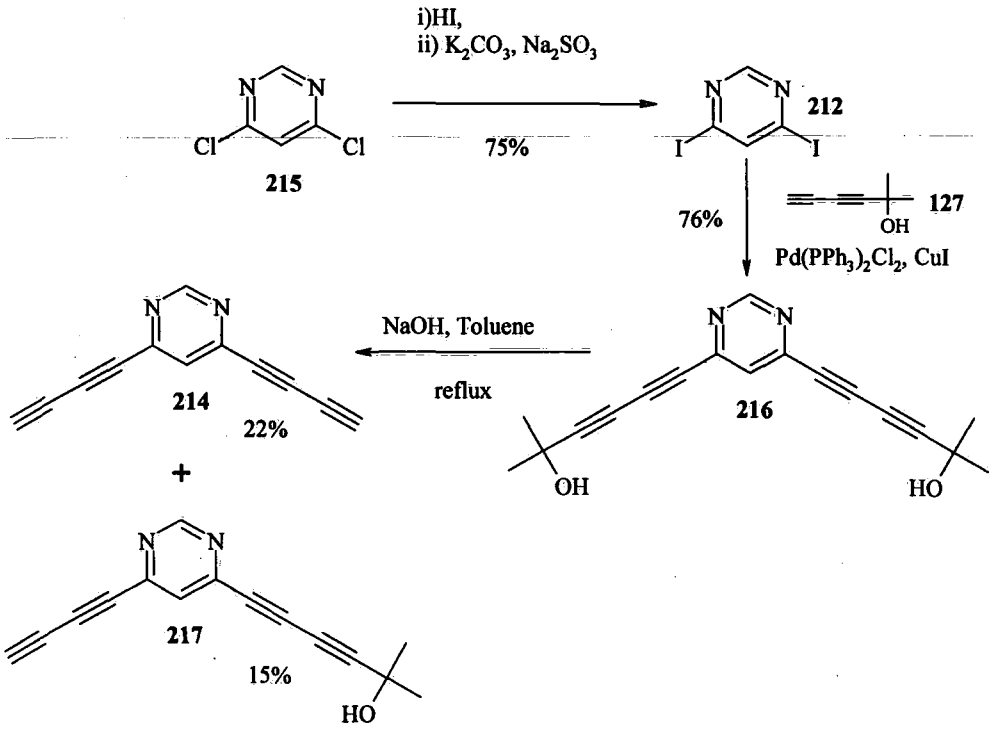
It is worth noting that the synthesis and isolation of mono-deprotected products would probably not be possible if a silyl protecting group had been utilised, since silyl deprotection is usually quantitative. Silyl deprotection usually proceeds at room temperature under relatively mild conditions, whereas 2-hydroxy-2-propyl deprotection usually requires refluxing at high temperatures (80-110 °C). Nonetheless, we favour the 2-hydroxy-2-propyl protecting group due to the easy product purification noted above.

Previous studies in Chapter II have shown that simple terminal arylbutadiynes are stabilised in the solid state by hydrogen bonding interactions of the acetylenic proton. For our first attempted bis-butadiyne isolation we chose a system with sites for hydrogen bonding within the aromatic system. Dr Türksoy in our group had previously synthesised 4,6-diethynylpyrimidine **211** in high yield from 4,6-diiodopyrimidine **212** *via* **213** (**Scheme III.4**).[132] This success led us to explore the possibility of synthesising the analogous pyrimidyl bis-butadiyne **214** which would have two possible nitrogen sites for hydrogen bonding interactions.



Scheme III.4.

4,6-Diiodopyrimidine **212** was isolated in good yield following literature precedent from reaction of 4,6-dichloropyrimidine **215** with hydroiodic acid, HI.[133] Compound **212** was then coupled with 2-methyl-3,5-hexadiyn-2-ol **127** (3.0 equiv.) under standard Sonogashira conditions to afford the di-coupled species **216** in 76% yield, **Scheme III.5**. Deprotection of **216** in refluxing toluene, catalysed by powdered sodium hydroxide, gave a mixture of the di-deprotected **214**, mono-deprotected product **217** and unreacted **216**. The brown residue was purified by column chromatography. Predictably, the first compound to elute was the least polar species **214**, which was isolated as a white crystalline solid in 22% yield. This was followed by **217** (15% yield) and finally unreacted starting material **216** (*ca.* 50% yield). The clean recovery of **216** meant this compound could be re-used and thus, in spite of low yields of **214** and **217**, it is a viable synthetic route to these novel compounds.



Scheme III.5.

The NMR spectra confirmed the structures of both products; the ratio of acetylenic to aromatic protons aided the assignment, **Fig III.1**.

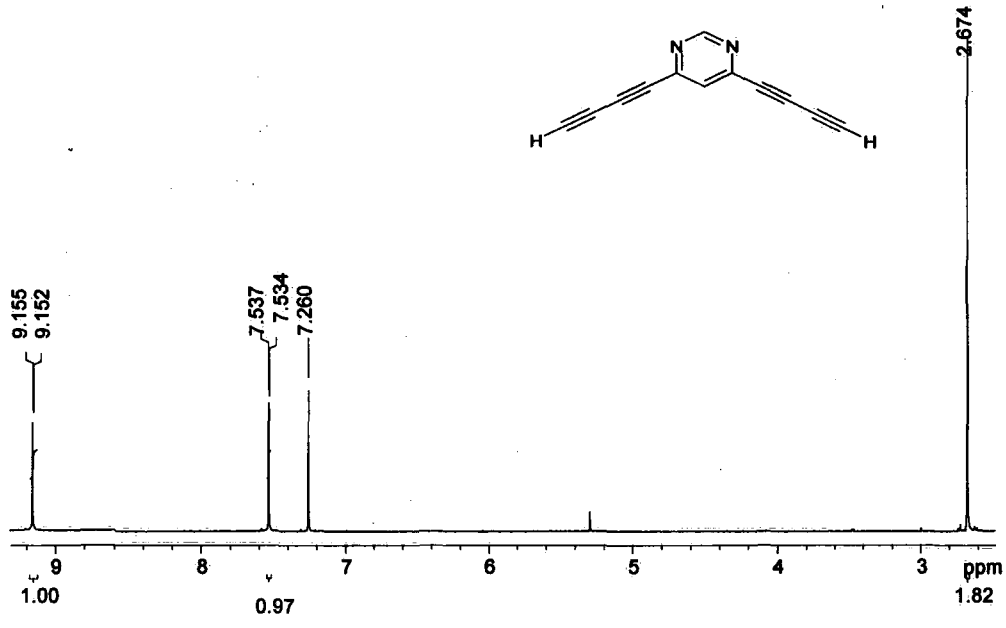
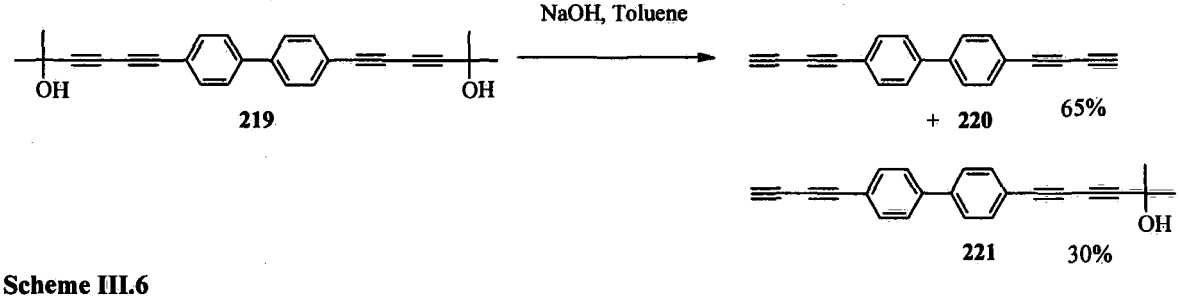


Fig III.1 1H NMR spectra of compound 214 in $CDCl_3$ at 400 MHz.

The successful synthesis of **214** prompted further exploration of terminal bis-butadiynes based on commercially available diiodo-arenes. Biphenylbutadiyne **143** is a relatively stable crystalline solid reported in Chapter II. Hence, a biphenyl bis-butadiyne was a logical target.

4,4'-Diiodobiphenyl **218** was coupled with **127** to afford **219** in 64% yield. Basic deprotection in toluene gave both di-deprotected **220** and mono-deprotected bis-butadiyne **221** in 65% and 30% yields, respectively (**Scheme III.6**).



Scheme III.6

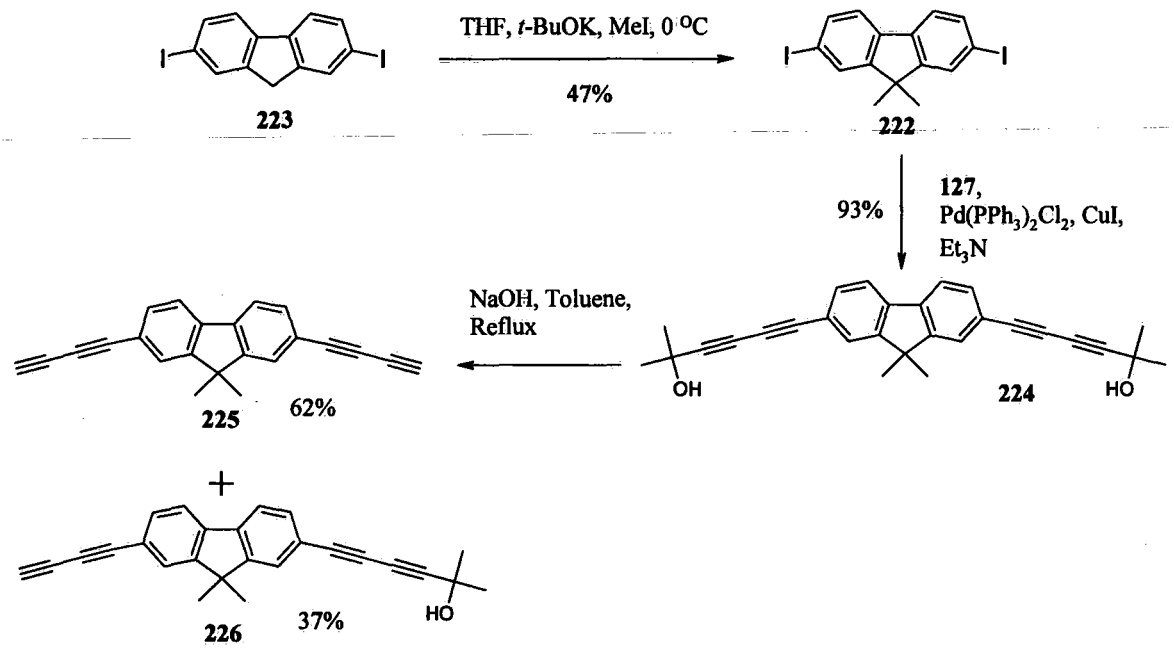
The optimum time for deprotection reaction was *ca.* 10 minutes at reflux. With a longer reaction time an increased amount of black solid was produced.

Both **220** and **221** were characterised by ^{1}H NMR, ^{13}C NMR and mass spectrometry.

It was originally predicted that the dihedral twist angle in a biphenyl moiety might give rise to the observed stability. To determine whether this was the case, it was decided to synthesise a bis-butadiyne based on the fluorene core. 9,9-Dihexylfluorene bis-butadiyne **205** has previously been reported,[131] hence there was no point in repeating this published compound. Our aim at this point was to obtain the first X-ray crystal structure of an aryl bis-butadiyne, and we judged the 9,9-dimethylfluorene derivative to be a possible candidate – it should withstand the basic deprotection and be a crystalline solid.

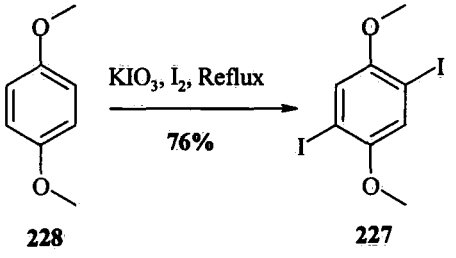
2,7-Diiodo-9,9-dimethyl-9*H*-fluorene **222** was synthesized in moderate yield from 2,7-diiodofluorene **223** as shown in **Scheme III.7**. Coupling of **222** with **127** under standard Sonogashira conditions afforded **224** in 93% yield. Basic deprotection afforded **225** and **226** in 62 and 37% yields, respectively.

There was no notable difference in stability between the biphenyl **220** and 9,9-dimethylfluorenyl bis-butadiynes **225**. Both compounds could be stored at -15 °C for several months without observable decomposition. Neither compounds gave crystals suitable for X-ray analysis.



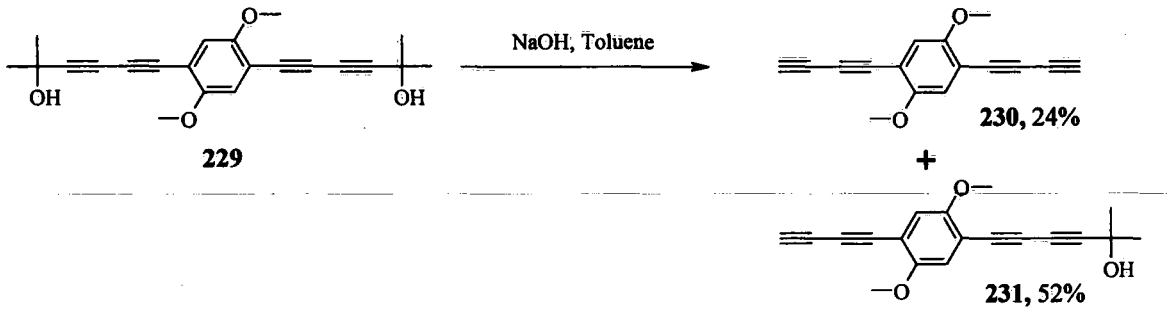
Scheme III.7

We had learnt from our experience with arylbutadiynes (Chapter 2) that derivatives which crystallise are more stable out of solution, *e.g.* 4-methoxyphenylbutadiyne **118** for which a crystal structure had been obtained (Chapter II, **Fig II.6**). To obtain a monocyclic phenyl bis-butadiyne, methoxy substituents would seem to be beneficial. 1,4-Diiodo-2,5-dimethoxybenzene **227** is not commercially available; it was synthesized from 1,4-dimethoxybenzene **228** following the literature route (**Scheme III.8**).[134]



Scheme III.8

Sonogashira cross-coupling of **227** with **127** afforded the expected cross-coupled species **229** in 64% yield. Deprotection in toluene afforded both **230** and **231** in 24% and 52% yields respectively, **Scheme III.9**.



Scheme III.9

Both compounds were characterised by ^{1}H NMR, ^{13}C NMR and mass spectrometry. Compound **230** was an amorphous powder, but, gratifyingly, mono-deprotected species **231** afforded crystals suitable for X-ray structural analysis, **Fig III.2**.

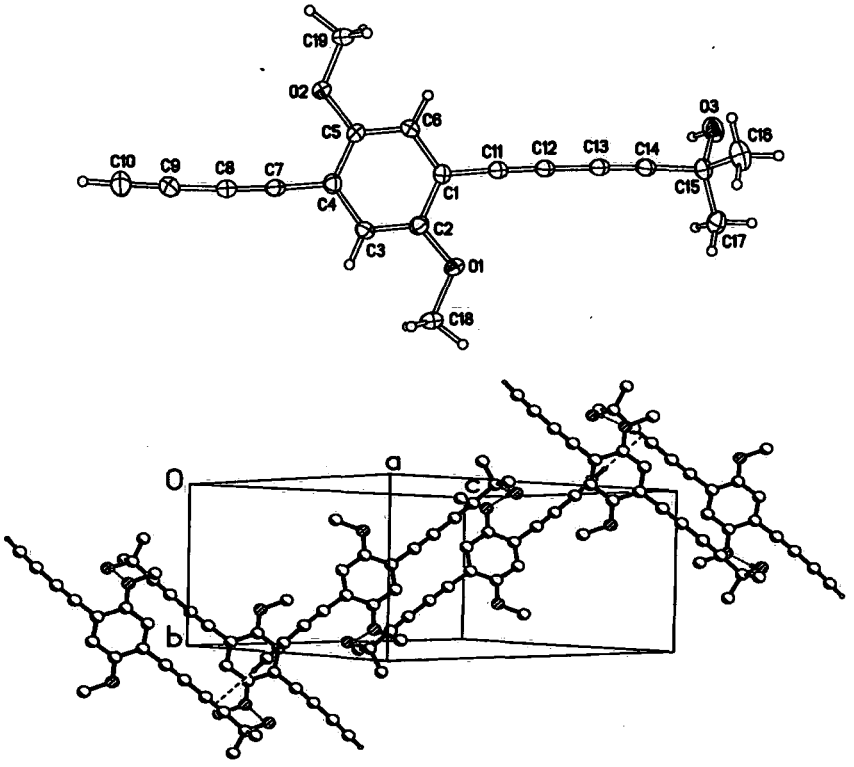


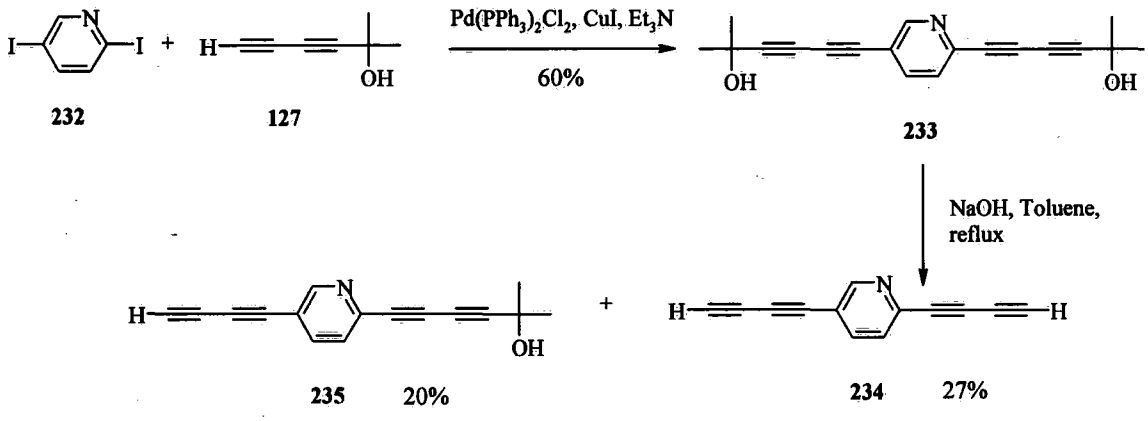
Fig III.2 X-ray crystal structure and packing diagram of 231.

The herringbone packing motif indicates a hydrogen bonding O-H····O interaction involving the 2-hydroxy-2-propyl protecting groups. This interaction stabilises the molecules in an arrangement which disfavours polymerisation, hence explaining the compound's observed stability.

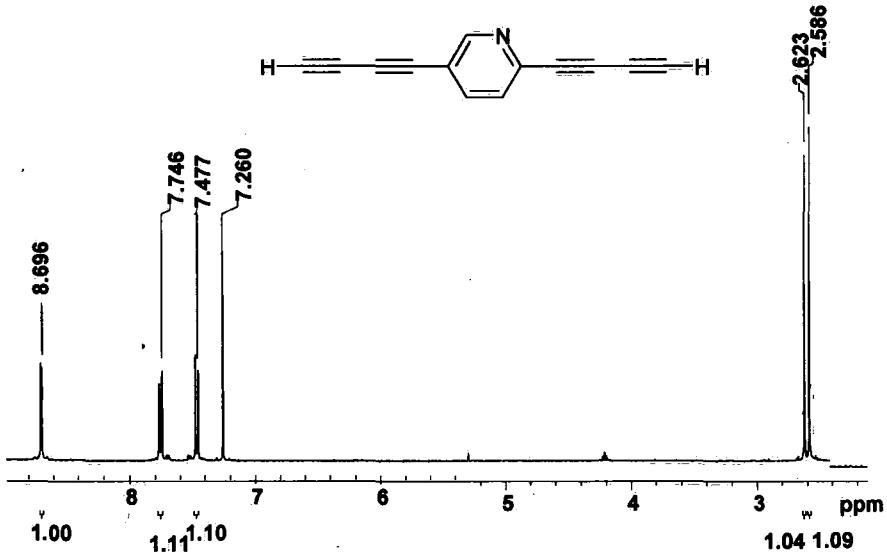
The methodology was then applied to commercially-available 2,5-diiodopyridine **232** to give **233** in 60% yield. Basic deprotection afforded two products which were

identified as the bis-deprotected **234** and mono-deprotected **235** in 27 and 20% yields, respectively, **Scheme III.10**.

An interesting feature of the ^{1}H NMR spectrum of **234** is that different chemical shifts were observed for the two acetylenic protons (δ 2.623 and 2.586 ppm), **Figure III.3**. The integrals for all the proton peaks indicate a high level of purity, with trace amounts of solvent present.



Scheme III.10



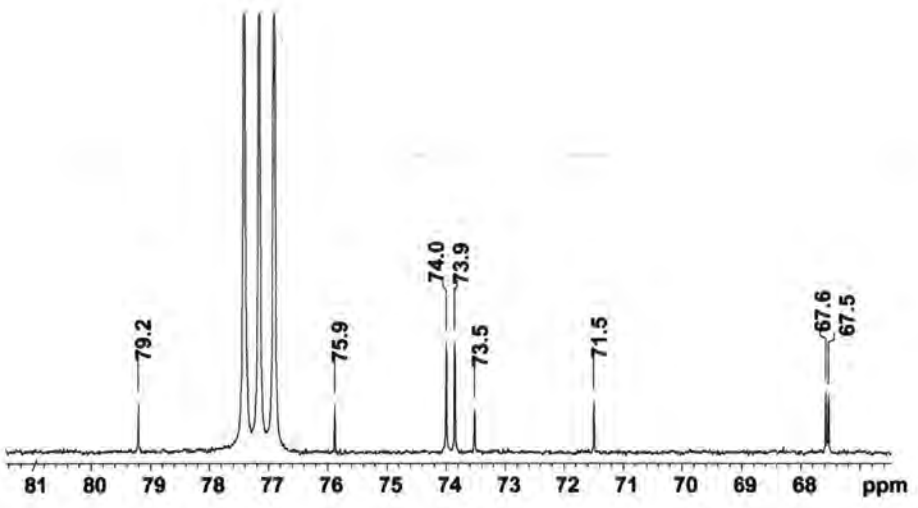
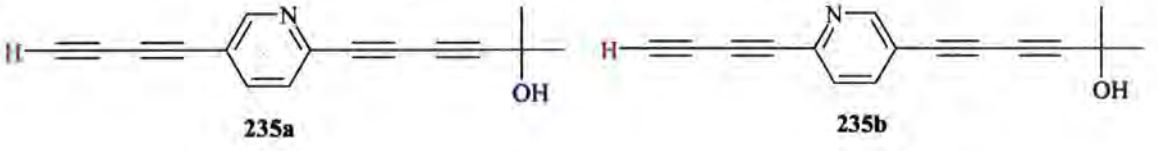


Fig III.3 NMR spectra for compound 234 in $CDCl_3$ at 400 MHz and 100 MHz.

The ^1H NMR of **235** indicates two isomers; **235a** and **235b**, which are in a ratio 2:1, although we could not assign the peaks to their specific isomers. There is no explanation at present to justify why one isomer should be obtained in a higher yield. The acetylenic protons (shown in red) and hydroxy protons (shown in blue) are observed at different ppm values (0.03 ppm and 0.21 ppm difference, respectively).



235a

235b

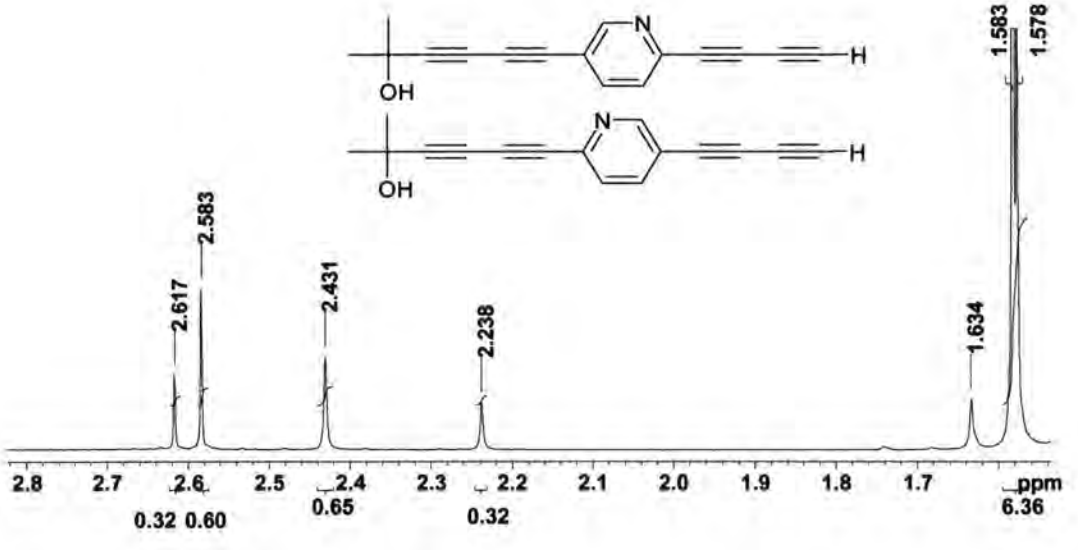


Fig III.4 ^1H NMR spectrum of 235a and 235b at 400 MHz in $CDCl_3$.

A highlight of this phase of the work was obtaining crystals of both **234** and **235b** suitable for X-ray structural analysis. The crystal structure of **234** reveals there is a hydrogen bonding interaction between one terminal acetylenic proton (at C14 position) and the pyridyl nitrogen atom (**Fig III.5**). The herringbone packing indicates the acetylenic proton at the C10 position is forming a weak interaction between the C9-C10 carbon atoms on an adjacent molecule.

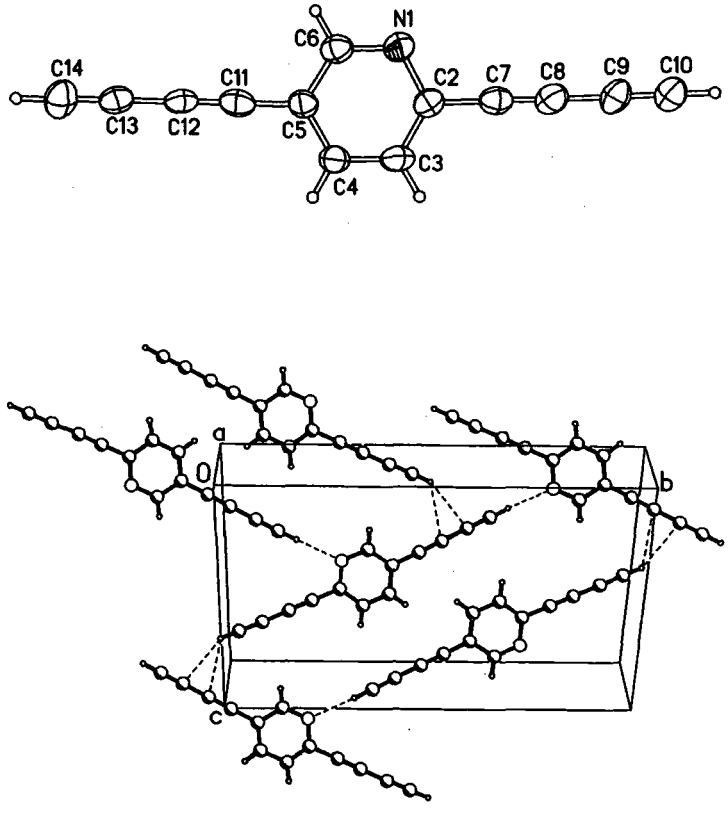
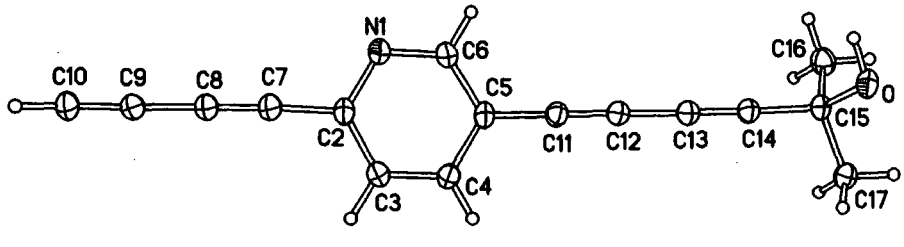


Fig III.5 Crystal structure and packing diagram of 234.

The packing diagram of **235b** indicates an interaction between an hydroxyl proton on the protecting group, with the N-atom in the ring. It is remarkable only crystals of this isomer formed; it was grown from an NMR sample containing both isomers **235a** and **235b**



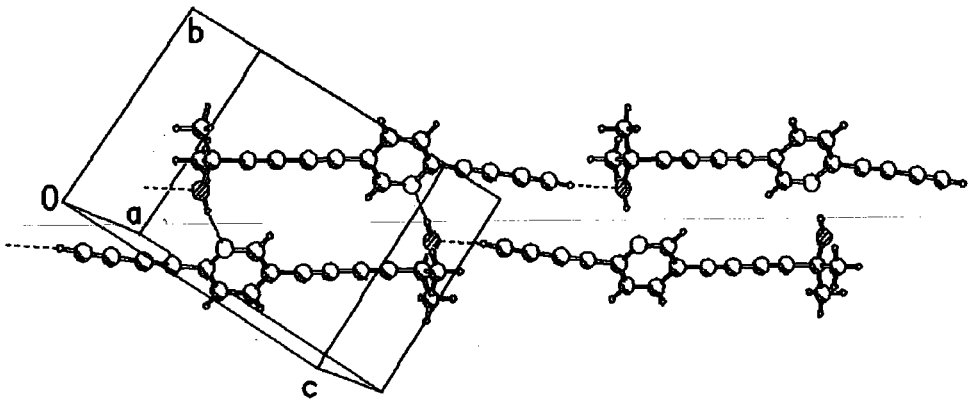
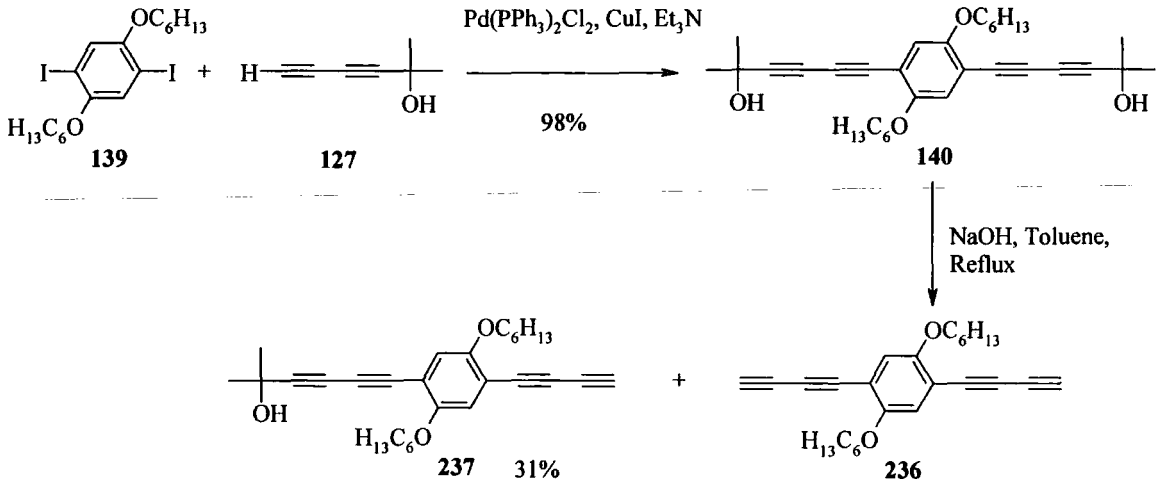


Fig III.6 Crystal structure and packing diagram of 235b.

It has thus been shown that our methodology can be successfully extended to the synthesis and isolation a range of aryl- and heteroaryl bis-butadiynes. Their applicability for molecular wire synthesis is hindered only by the poor yields of the smaller, monocyclic systems.

Even though it is predicted the bis(hexyloxy) derivatised phenyl bis-butadiyne **236** would be an oil, and hence less stable, it was decided to attempt synthesis and isolation, since increased solubility maybe of some benefit later in the synthesis of molecular wires. 1,4-Bis-hexyloxy-2,5-diiodo-benzene, **139**, was coupled with **127** under standard Sonogashira conditions to afford **140** in excellent yield. Deprotection (toluene, NaOH) afforded both **236** and **237** (**Scheme III.11**).

As predicted **237** was isolated as an oil; the alkoxy chains considerably lower the melting points of such compounds. Previous experience suggests butadiynes isolated as oils are considerably less stable than solid analogues (see butadiynes **70** and **182**). The lack of solid state arrangement results in relatively disordered systems, wherein molecules can be in close contact and thus polymerise readily. Compound **237** was dried for characterisation, however, it darkened suddenly when exposed to reduced pressure. The remaining black oil was soluble in $CDCl_3$, however, therefore it was possible to obtain a ^1H NMR spectrum. Despite the appearance of the compound, NMR and MALDI-TOF data suggested the compound was essentially pure, therefore the compound was kept in solution until needed. It was decided further characterization was not needed as subsequent cross-coupled products would be fully characterized. Due to handling difficulties **236** was kept in solution. The mono-deprotected species **237** was of more interest to us.



Scheme III.11

III. 2. 1 Optimisation of Yields

A common feature of the deprotections in **Schemes III.6-III.11** is that reaction times of more than *ca.* 10 minutes resulted in increased decomposition of desired bis-butadiyne product. We sought to fine-tune the reaction conditions to minimise product degradation and thereby increase isolated product yield. By varying the base used it was hoped the reaction would proceed more rapidly to shorten reaction time and hence limit the degradation. Both powdered potassium hydroxide and sodium hydride were used in the deprotection of **229**; however, there was no improvement in yield.

We next varied the reaction solvent. In the literature, refluxing benzene and toluene are the most common solvents reported for this fragmentation. The use of high-boiling polar solvents, such as DMF, *n*-BuOH, DMSO and DMA, has recently been reported.[135] There are many possible reasons, the most likely, however, is that there is a high activation energy barrier for the reaction to proceed, hence high temperatures are required. The high temperature may also be required for the removal of the acetone by-product: if the reaction is in equilibrium, the removal of a side-product will push the reaction towards the desired product (Le Chatelier's principle). The concentration of the reaction mixture has been observed to be an important factor in this deprotection; the less solvent the quicker the reaction proceeds. For the work in Chapter 2 the use of toluene, a non-toxic solvent, afforded the desired arylbutadiynes without any signs of decomposition. However, the presence of black polymerised solid when synthesising

the more delicate bis-butadiynes prompted us to explore benzene as the solvent in this series.

The deprotections of protected bis-butadiynes were repeated in refluxing benzene and the comparative results are collated in **Table III.1.**

The data clearly show that some di-deprotections are favoured in benzene, notably product **230** (64% yield in benzene; 24% yield in toluene).

In the case of **234**, deprotection in benzene did not proceed smoothly; the protected starting material **233** was not soluble in benzene (even at reflux) and neither was desired product **234**. The lack of solubility was causing any product formed to drop out of solution; in effect resulting in solid state bis-butadiyne **234** being heated. Since such compounds are only just stable at room temperature, in the solid state, it is not surprising that any materials precipitating from solution will quickly decompose.

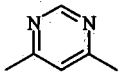
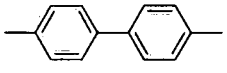
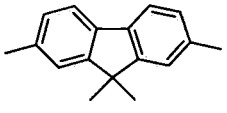
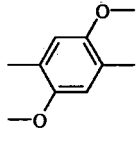
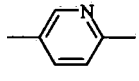
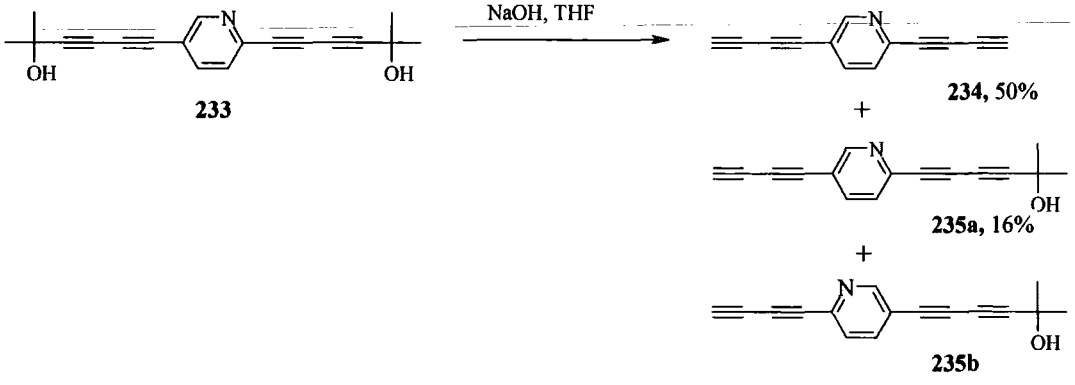
	Structure, HC≡C-C≡C-Ar-C≡C-C≡CH		% yield in toluene	% yield in benzene
Ar =	**214**		22	20
	220		65	47
	225		62	66
	230		24	64
	234		27	N/A[a]

Table III.1 Yields of deprotection reactions in both toluene and benzene. [a] precursor was insoluble in refluxing benzene.

In an attempt to overcome the solubility issues which had arisen for **234**, the deprotection of **233** was performed in a more polar solvent with a lower boiling point, namely THF. As previously mentioned, polar higher boiling point solvents have been used in the literature for such deprotections, [135] but the use of THF was not reported.

The deprotection of **233** to afford **234** proceeded smoothly in 50% yield after 5 min at reflux. The reaction solution was a light yellow colour with no visible signs of black

polymerized product, as observed when both benzene and toluene were utilized. The mono-deprotected species **235a** and **235b** were isolated in 16% yield (**Scheme III.12**).



Scheme III.12

To conclude, the solvent effect studies illustrate it is difficult to predict which solvent system is most suitable for any given compound. As a general rule, if the deprotected species is unstable (*i.e.* if it is a small monocyclic system, which could possibly be an oil), milder deprotection (THF) should be utilized. If the bis-butadiyne is relatively stable (*i.e.* if the aromatic entity is large) then higher temperatures (*i.e.* using benzene and toluene) can be used. It is worth noting that as benzene is extremely toxic its use should be avoided if possible. In the case of the pyridyl bis-butadiyne **234**, solubility is also a consideration, low boiling, polar solvents such as THF were shown to be best.

III. 3 Absorption and Emission Spectra

III. 3. 1 Absorption

As a probe of the extent of conjugation and the HOMO-LUMO levels in our new arylbutadiyne derivatives their solution UV-Vis absorption and emission spectra were recorded. Reliable molar absorption coefficients, ε, could not be obtained due to the instability of some of the compounds in the solid state.

Data for **229** (λ_{max} 294, 313, 380 nm) and **230** (λ_{max} 293, 310, 379 nm) in $CHCl_3$ established that, as expected, the protecting group had no significant effect on the absorption spectra, The blue-shifted absorption at ~310 nm is a feature noted previously

for ethynyldialkoxyphenyl derivatives (alkoxy = OMe and OC_6H_{13}) and is attributed to HOMO-1 to LUMO transition, whereas the peak at *ca.* 380 nm is due to the HOMO-LUMO transition.[77] **Fig III.7**.

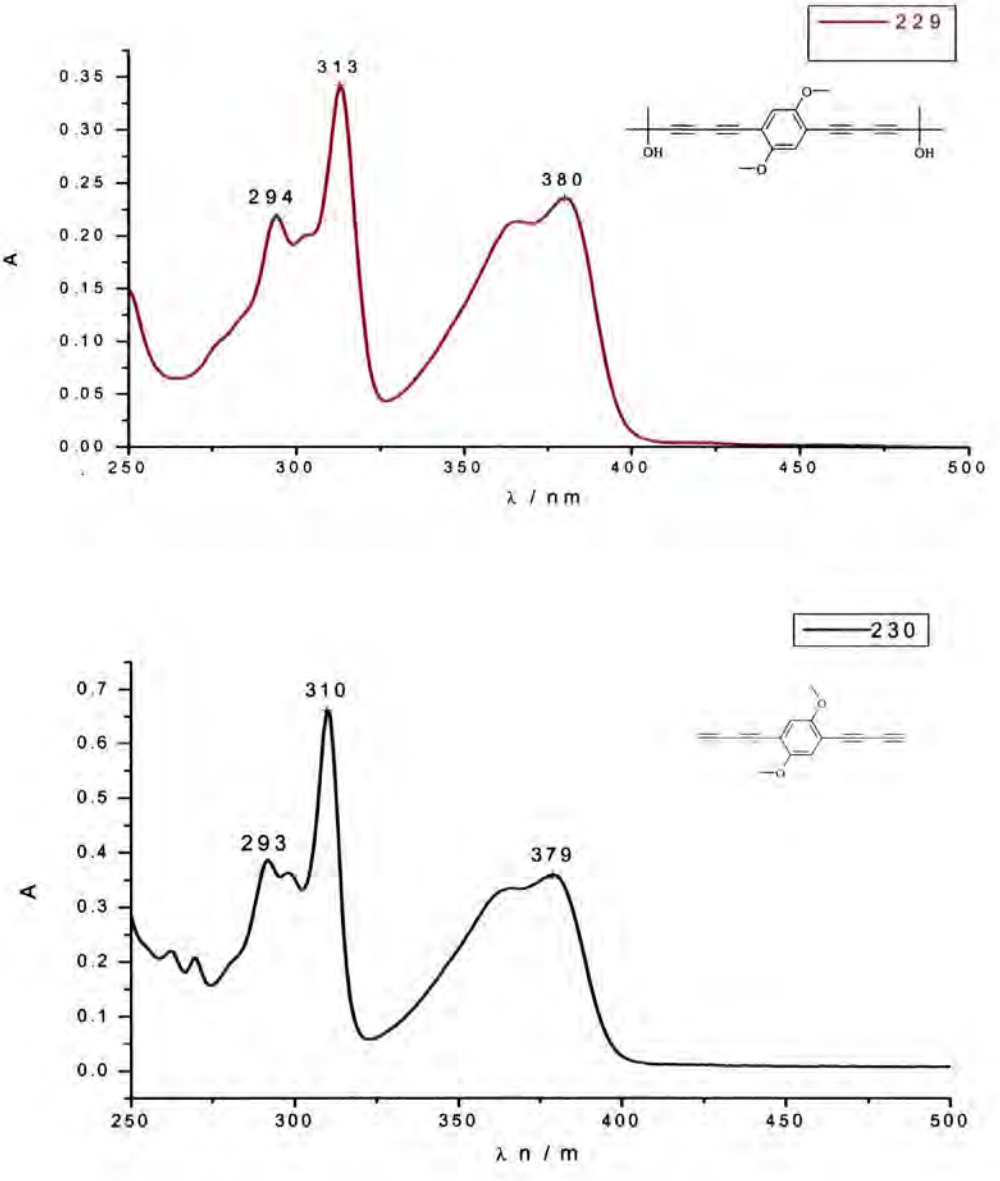


Fig. III.7 UV-Vis spectra of compounds 229 and 230 in chloroform.

The di(hexyloxy) analogue **140** shows a very similar absorption profile (**Fig III.8**).[77]

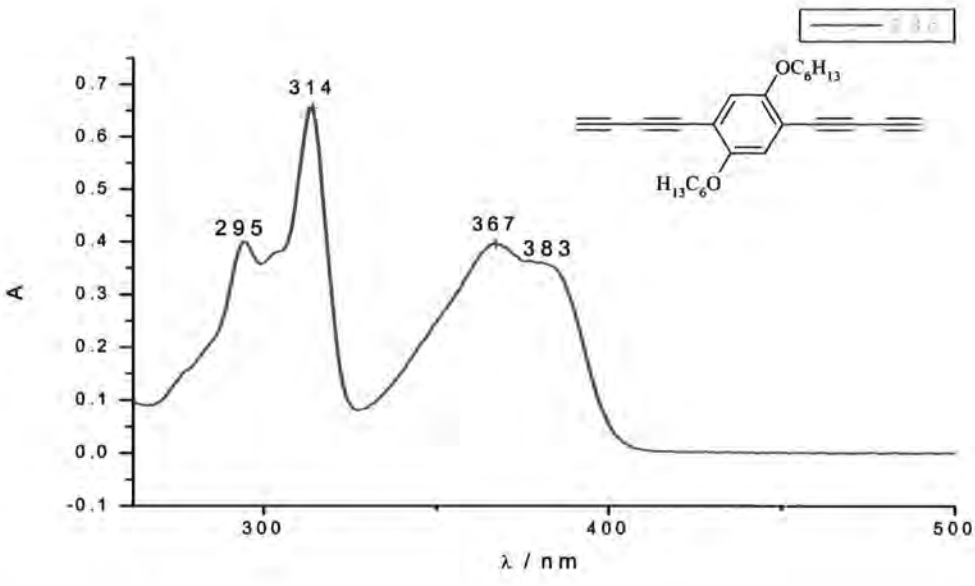


Fig III.8 UV-Vis spectrum of hexyloxybutadiyne 236 in chloroform.

Notably, pyrimidyl bis-butadiyne **214**, where the butadiyne moieties are *meta* to each other, and hence there is only limited conjugation between them, shows λ_{max} at 320 which is slightly blue shifted compared to the *para*- pyridyl species **234** where greater conjugated would be expected (**Fig III.9**).

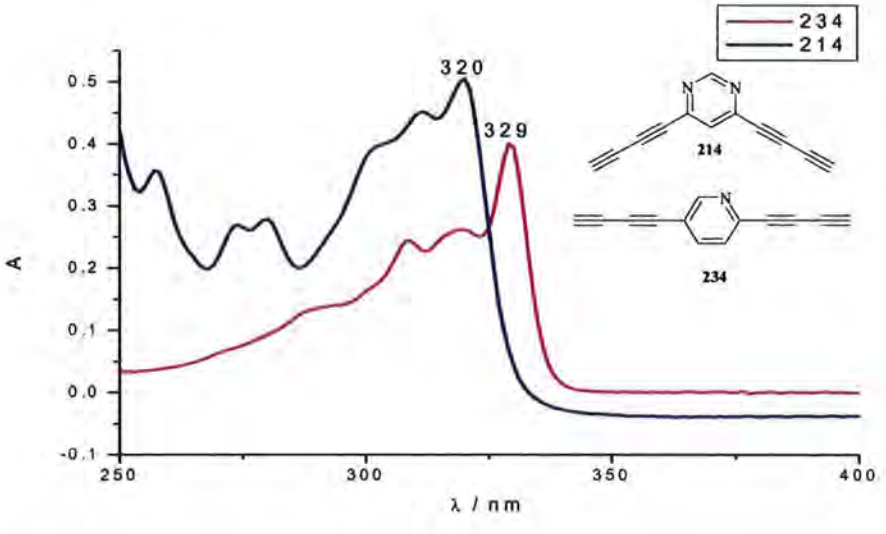


Fig III.9 UV-Vis spectra of compounds 214 and 234 in chloroform.

The comparison of the absorption spectra of **220** and **225** is of interest (**Fig III.10**). The data are consistent with the planar **225** being more conjugated; λ_{max} is red shifted to 356 nm, compared to 321 nm for **220**. Also noteworthy is the broad absorption of the biphenyl **220** compared to more structured spectrum of the fluorene analogue **225**;

twisting along the 4'-4 carbon-carbon bond of **220** could be affording different ground-state twisted conformations, resulting in various transitions to the excited states.[77]

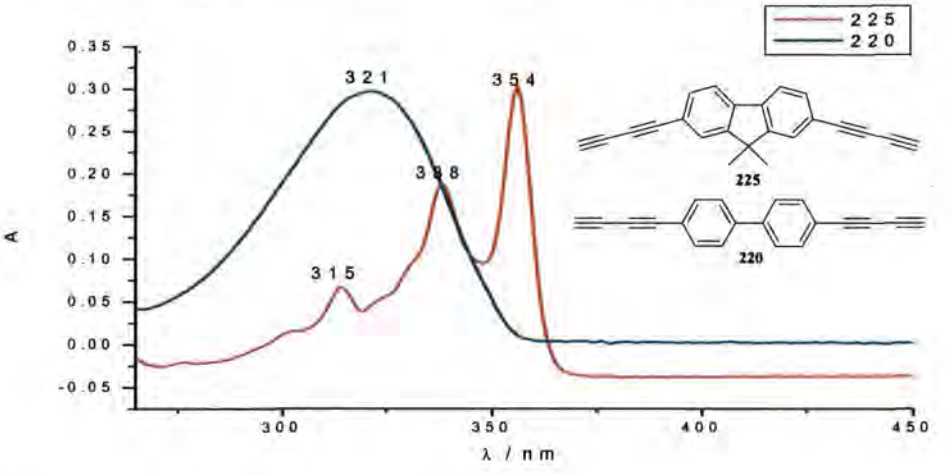
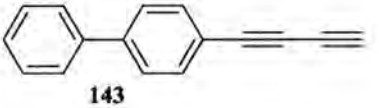


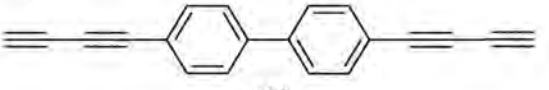
Fig III.10 UV-Vis spectra of compounds 220 and 225 in chloroform.

III. 3. 2 Comparison between mono- and bis- butadiynes.

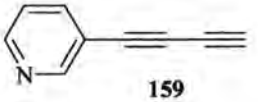
To determine whether there is increased conjugation in bis-butadiyne systems, UV-Vis absorption spectra of the bis-butadiyne was compared to its mono-butadiyne analogue, *e.g.* bis-biphenyl **220** and mono-biphenyl **143**, and to bis-pyridyl **234** compared to mono-pyridyl **159**.



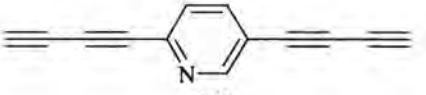
143



220



159



234

Data for **220** (λ_{max} = 321 nm), **143** (λ_{max} = 300 nm) and **234** (λ_{max} = 329 nm) and **159** (λ_{max} = 295 nm) shows, as predicted, there is an increase in conjugation in the bis-butadiyne systems, with a λ_{max} red-shift of *ca.* 20 nm and 30 nm respectively (**Fig III.11**).

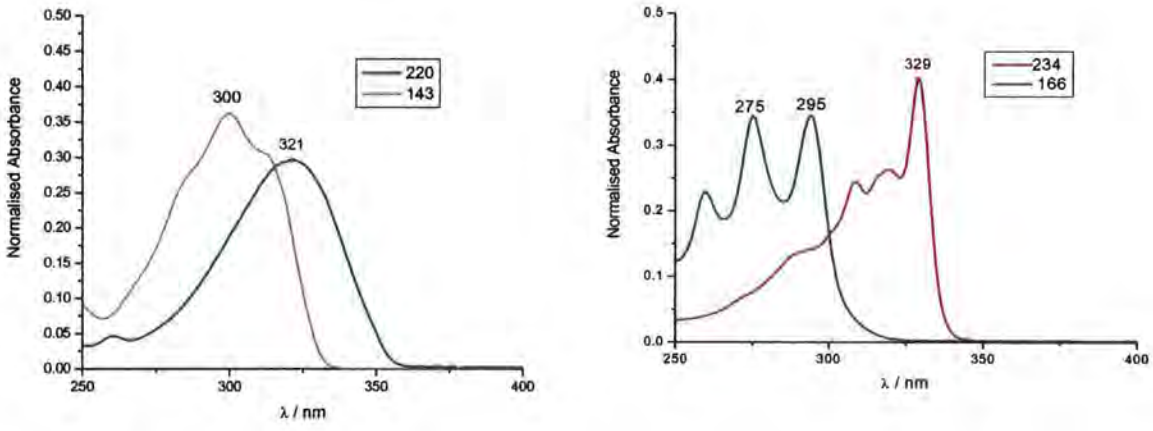


Fig III.11 UV-Vis spectra comparing compounds 220 and 143, and 234 with 159 in chloroform.

III. 3. 3 Emission

Not all bis-butadiyne species were found to give strong emissions; indeed there was no observable emission in species **214** and **234** (**Table III.2**). Among the most notable of the spectra was **225**, with two emission peaks at 359 nm and 378 nm, which is concordant with literature precedent, **Fig III.12**. [131] By comparison with the twisted analogue **220** (λ_{max} is 369 nm), **225** is red shifted to 378 nm, thus confirming increased conjugation due to the planar conformation.

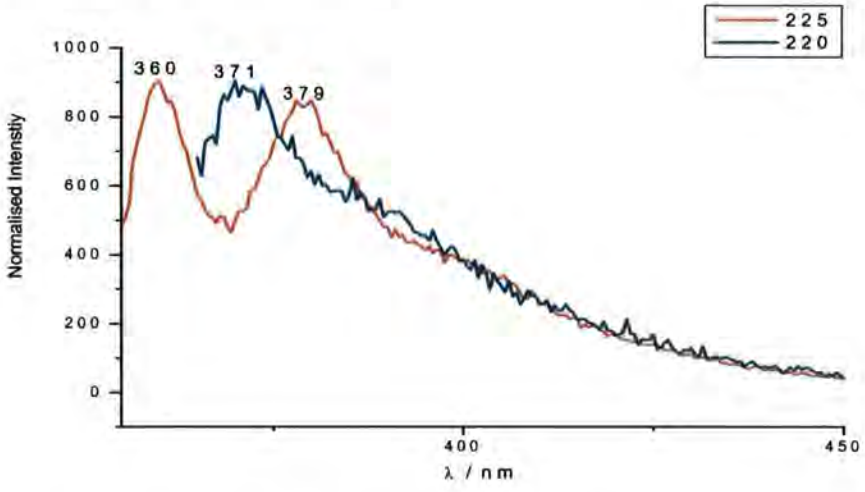


Fig III.12 UV-Vis emission spectra of 220 and 225 in chloroform.

The emission spectrum of **230** is also shown, since it is one of the few compounds which emits in the visible region of the electromagnetic spectrum. It is presumed that

the electron donating methoxy substituent on **230** are interacting with the λ system, hence resulting in greater conjugation and a red-shifted λ_{max}, as compared to other bis-butadiyne systems.

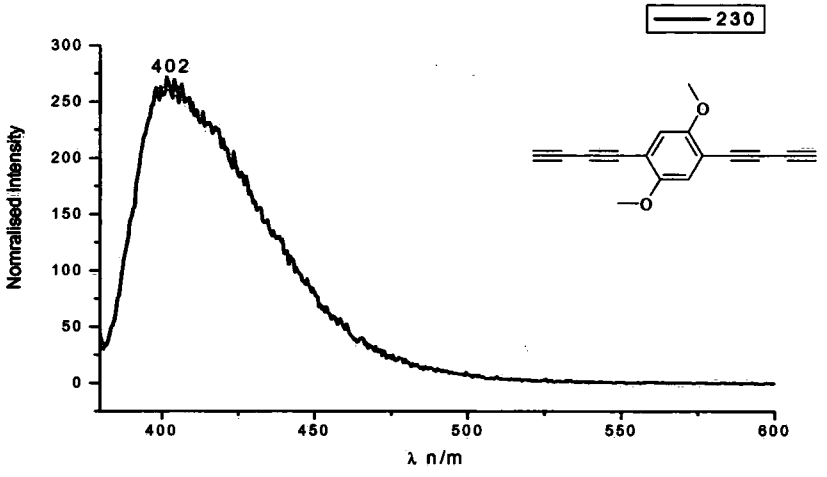


Fig III.13 UV-Vis emission spectrum of 230 in chloroform.

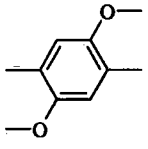
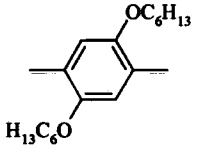
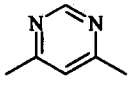
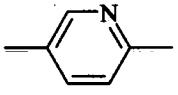
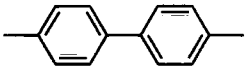
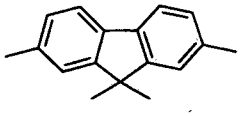
Structure, HC≡C-C≡C-Ar-C≡C-C≡CH		λ_{max}, abs (nm)	λ_{max}, em[a, b] (nm)
Ar = **230**		293, 310, 379	402
236		295, 314, 367, 383	412
214		320	b
234		329	b
220		321	369
225		315, 338, 354	359, 378

Table III.2 [a] excitation at λ max ; [b] no observable emission

The UV-Vis absorption and emission data thus show there is increased conjugation in bis-butadiyne systems. The electron-donating effects of methoxy- and hexyloxy-substituents in compounds **230** and **236**, respectively, result in red-shifted spectra, compared to other compounds. The twisted nature of **220** is well illustrated in the absorption spectra, with a broad absorption band characteristic of transitions from different ground state conformations.

III. 4 Conclusions

The synthesis and isolation of novel bis-butadiyne derivatives has been shown. Such compounds have only been represented once in the literature.[131] Di-deprotected species and mono-deprotected species have both been isolated. The next chapter will focus in detail on their reactivity.

The yields of both di- and mono-deprotected species have been improved, by fine-tuning the reaction conditions, using THF, benzene and toluene as refluxing solvents. It has been show that high-boiling apolar solvents are not necessary for the removal of 2-hydroxy-2-propyl protecting groups; indeed, the relatively low boiling and polar solvent THF has been shown to successfully afford di-deprotected species **234**.

X-ray structural analysis of one di-deprotected species **234** has been obtained, and is believed to be the first crystal structure of such a compound. The packing diagram indicates there is a hydrogen bonding interaction between the terminal acetylenic proton and the nitrogen atom in the ring, which is concordant with findings in the previous chapter. X-ray structural analysis of mono-deprotected species **231** and **235** has also been obtained.

The electronic absorption spectra have been obtained for all deprotected species. Spectra were also obtained for protected species **229** to determine whether the protecting group affects electronic absorptions and emissions. Spectra of butadiynes **143** and **159** were also obtained and compared to their bis-butadiyne analogues **220** and **234** respectively. The red-shifted data of **220** and **234** indicate there is increased conjugation in bis-butadiyne systems.

Chapter IV- Reactions of terminal arylbutadiynes and bis-butadiynes.

IV. 1 Introduction

Having illustrated the synthesis and isolation of both arylbutadiynes and bis-butadiynes in Chapters II and III, their reactions and functionalisation will now be described. In particular, we sought to explore the extent to which such compounds could be functionalized at the terminal carbon.

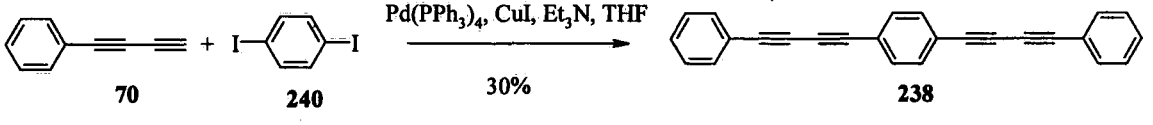
IV. 2 Reactions of terminal butadiynes

IV. 2. 1 Sonogashira Couplings

Further Sonogashira couplings of the arylbutadiynes with appropriate arylhalides seemed the most obvious starting point. The isolation of **149** from the cross-coupling between phenylbutadiyne **70** and *p-t*butyl-iodobenzene **148** in 70 % yield **147** was a promising precedent.

In Chapter I, Section 2.6, the photophysics of 1,4-bis(phenylethynyl)benzene **65** was discussed. It was hypothesized that a bis-butadiyne analogue (*i.e.* **238**) might also display some interesting photophysical properties. The synthesis of **238**[136] and the anthracene analogue **239**[137] was thus attempted using **70** as the key reagent.

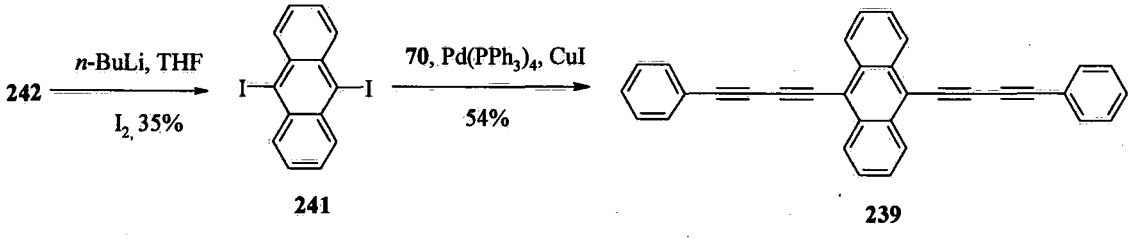
Commercially available 1,4-diiodobenzene **240** underwent a two-fold Sonogashira reaction with 2.5 eq. of isolated phenylbutadiyne **70** to afford the desired species **238** in only 30 % yield, **Scheme IV.1**. This is a low yielding reaction; the reaction was followed by TLC, however it was extremely difficult to differentiate between **238** and any other observed products such as oxidatively homo-coupled product diphenyloctatetrayne. Column chromatography of the crude mixture was not necessary, the product was recrystallised to afford silver crystals of **238**.



70 **240** **238**

Scheme IV.1

9,10-Diiodoanthracene **241** is not commercially available, requiring synthesis from 9,10-dibromoanthracene, **242**. Lithiation of **242** followed by iodination afforded the di-iodinated species **241** in reasonable yield as a bright yellow solid, in accordance with the literature.[138] Analysis did show the presence of remaining di-bromo **242**, however this was thought not to be problematic and might only affect the yield in the next step. Coupling of **241** with **70** under standard Sonogashira conditions gave the di-coupled species **239** in reasonable yield as bright orange crystals, **Scheme IV.2**. Again, purification by column chromatography was not necessary.



Scheme IV.2

Crystals suitable for X-ray analysis were obtained for both **238** and **239**. In the solid state, **238** is planar, with a very small twist angle of 0.3 °. Conversely, the crystal structure for **239** shows a larger twist of the end-capping phenyl rings in relation to the anthracene moiety of 41.4 °, **Fig IV.1**.

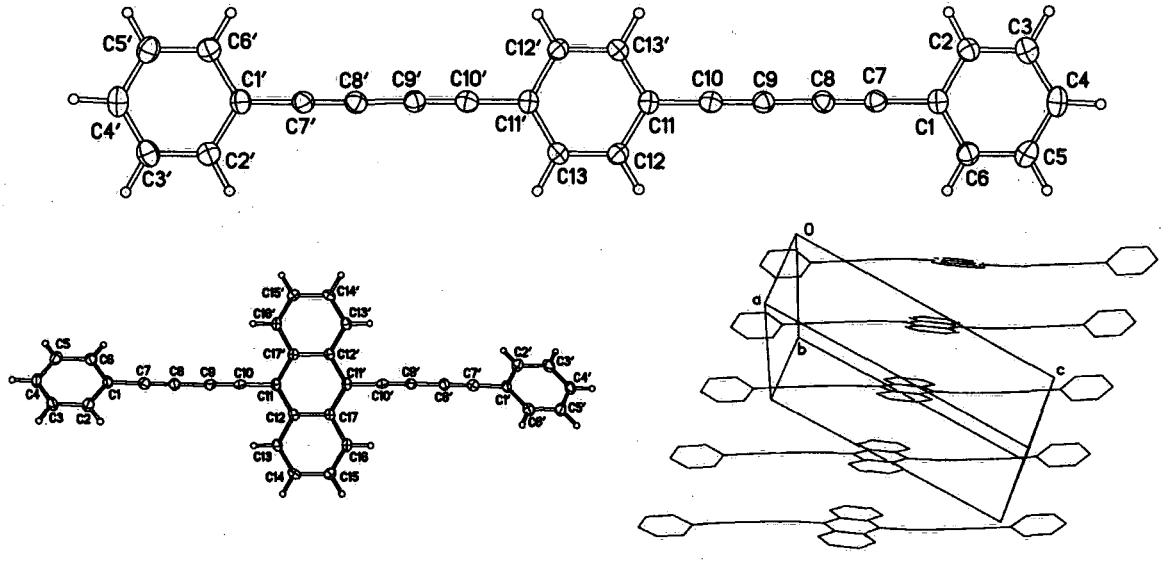


Fig IV.1 Crystal structures of 238 and 239, packing diagram of 239.

The photophysics of **238** and **239** are currently being probed in Dr Beeby's group in Durham.

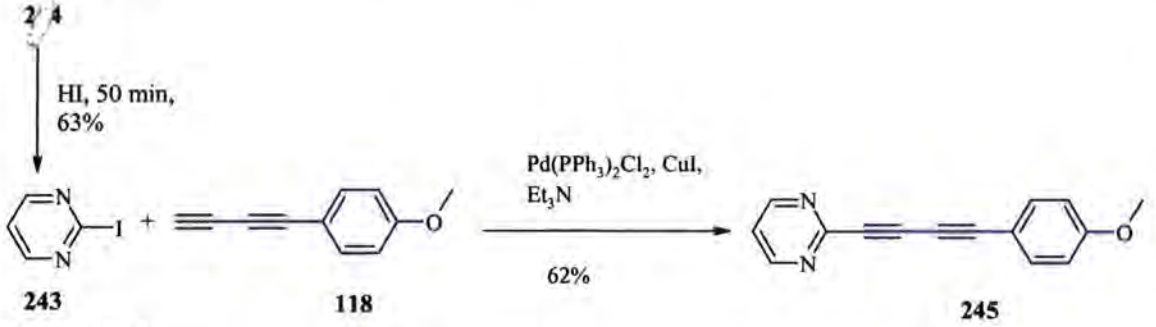
IV. 2. 2 Synthesis of asymmetric butadiynes

An obvious avenue to explore was the synthesis of unsymmetrical butadiynes from the arylbutadiynes synthesised in Chapter II. This work was carried out by Laura Hayward, a 4th year project student, under my supervision.

Fig IV.2; Schematic diagram representing an asymmetric butadiyne derivative.

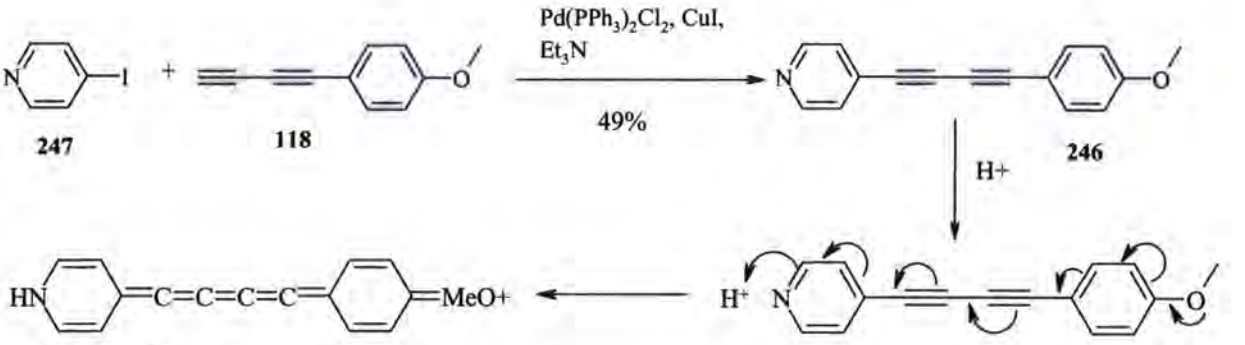
Our abilities to isolate the desired arylbutadiyne Ar-C≡C-C≡CH meant we could explore selective reactions using Sonogashira conditions with a chosen aryl iodide (Ar'-I) to afford the unsymmetrical species as illustrated in **Fig IV.2**.

The reaction between 1-(buta-1,3-diynyl)-4-methoxybenzene **118** and 2-iodopyrimidine **243** was the first reaction attempted. **243** is not commercially available; it was synthesised from 2-chloropyrimidine **244** in 63% yield. It was thought the electron donating methoxy-substituent on **118** and the electron deficient pyrimidine ring would create a push-pull diarylbutadiyne system **245**. The reaction, under standard Sonogashira conditions, afforded **245** as a dark yellow solid in reasonable yield, **Scheme IV. 3**.



Scheme IV. 3

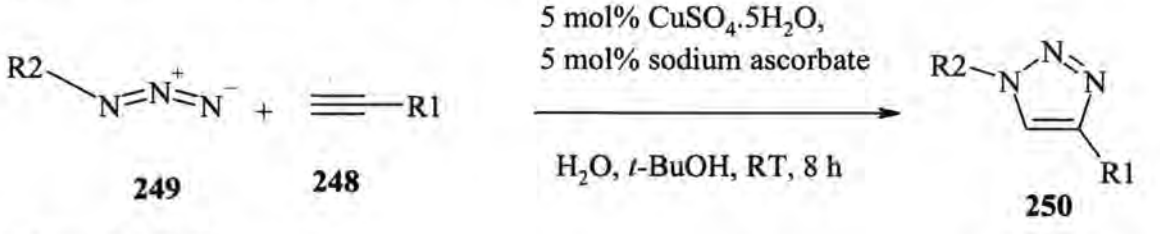
In a similar fashion, the synthesis of **246** from **118** and 4-iodopyridine **247** would afford a compound which could be protonated to yield a cummulenic-type structure (**Scheme IV.4**). The UV-Vis spectra before and after protonation be informative; the cumulene canonical form would be more conjugated, hence there would be a red-shift of the λ_{max}. Unfortunately, time restraints meant this work could not be investigated.



Scheme IV.4

IV. 2. 3 Cycloaddition and formylation reactions of butadiynes

The Huisgen 1,3-dipolar cycloaddition (recently re-named "click-chemistry"[139]) is currently attracting a lot of interest; the quantitative reaction between a terminal alkyne **248** and azide **249** affording a 1,2,3-triazole **250** is of great commercial importance. A typical reaction is outline in **Scheme IV.5**.

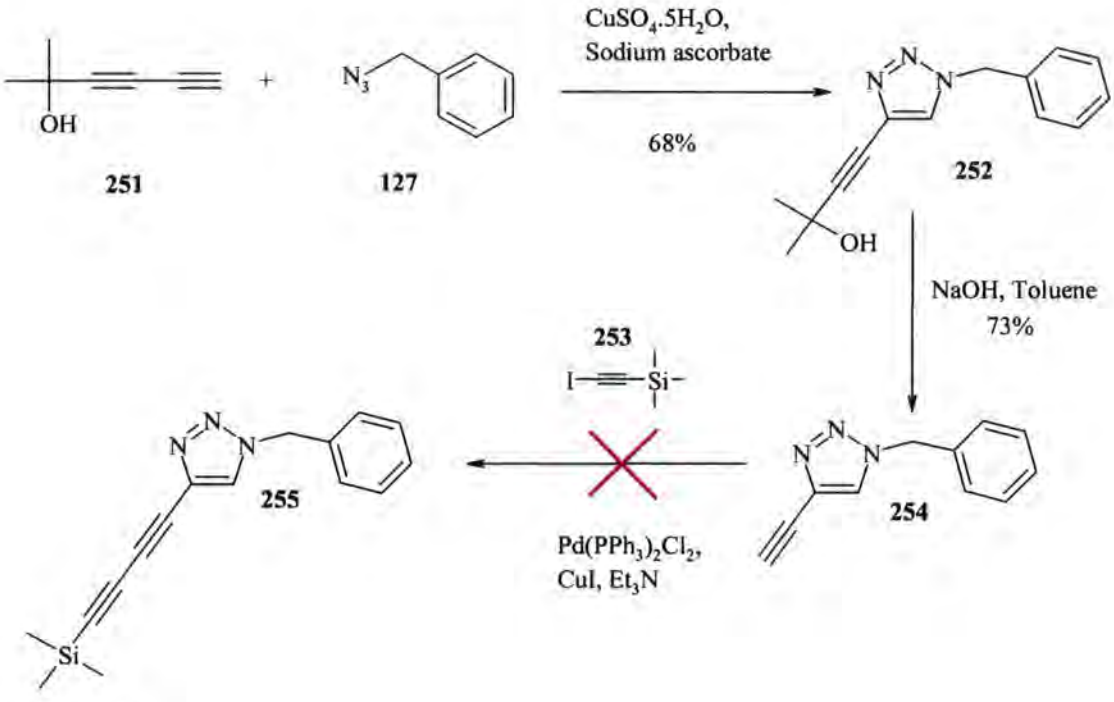


Scheme IV.5 Ref[140]

It was our idea to react arylbutadiynes synthesised in Chapter II, with a suitable organic azide to afford substituted ethynyltriazoles. During this work, Tykwinski *et al.* reported the one-pot *in situ* functionalisation of arylbutadiynes and aryltriynes in a similar fashion.[141] Undeterred we continued this line of investigation with butadiyne derivatives which had not been previously investigated.

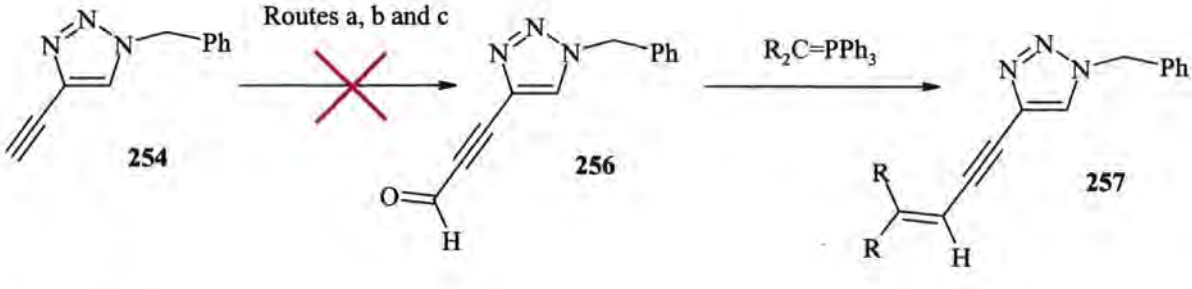
We initially reacted a simple butadiyne with benzyl azide to fine-tune the reaction conditions. Benzyl azide **251** was the chosen reaction partner because it is commercially available, hence reactions involving extremely toxic sodium azide were not necessary. Thus **127** was reacted with benzyl azide **251** at room temperature for 8 h in *t*BuOH and water to afford **252** in good yield,[140] **Scheme IV.6**. To functionalise **252** further, it was decided to deprotect and then react with iodinated TMSA **253** (readily available in our group) using Sonogashira conditions. Basic deprotection in toluene proceeded well to afford **254** in 73% yield as a stable white crystalline solid. Further cross-coupling with

253 to afford **255** was not successful, analysis by TLC indicated a messy reaction mixture with very little desired product.



Scheme IV.6

Nonetheless we considered that **254** could still be a useful intermediate. We envisaged further functionalisation of the terminal alkyne, such as formylation to afford **256**, which could then undergo a Wittig type reaction to introduce an alkenic bond thus affording **257**. Unfortunately, the formylation of **254** was not successful. Despite numerous attempts, with various formylating reagents and different reaction conditions, we could not obtain **256**. **Scheme IV.7** illustrates syntheses attempted and conditions employed. In all cases, analysis by NMR indicated the presence of starting material **254**.

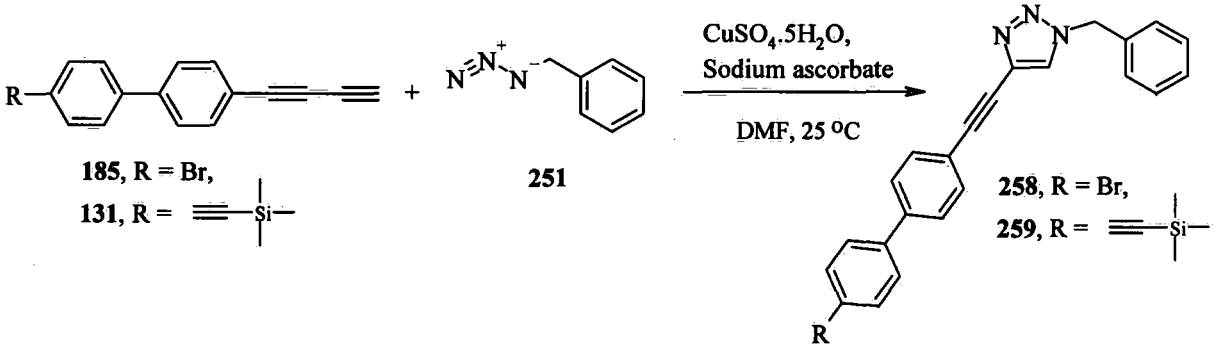


Scheme IV.7

Route	Formylating agent	Conditions
a	DMF (2 eq.)	*n*-BuLi (1 eq.), THF, Argon, -40 °C
b	DMF (2 eq.)	*n*-BuLi (1.1 eq.), THF, Argon, -40 °C
c	1-formylpiperidine (2 eq.)	*n*-BuLi (1.1 eq.), THF, Argon, -70 °C

The 1,3-cycloaddition reaction between arylbutadiynes and organic azides was explored a little further. It is worth noting that the Sonogashira coupling between **254** and an appropriate arylhalide was another possibility, however we did not investigate this avenue of work since the compounds synthesised would not be novel (due to the work published by Tykwinski *et al*).[141]

Arylbutadiynes **185** and **131** have previously been reported in Chapter II. By reacting with benzyl azide **251** in the presence of a copper catalyst in DMF **258** and **259** were both synthesised in 72% yield (**Scheme IV.8**). The presence of the bromo-substituent on **285** and the silyl-protected alkyne in **259** would afford the opportunity for further functionalisation, for example **258** could undergo Suzuki reactions.



Scheme IV.8

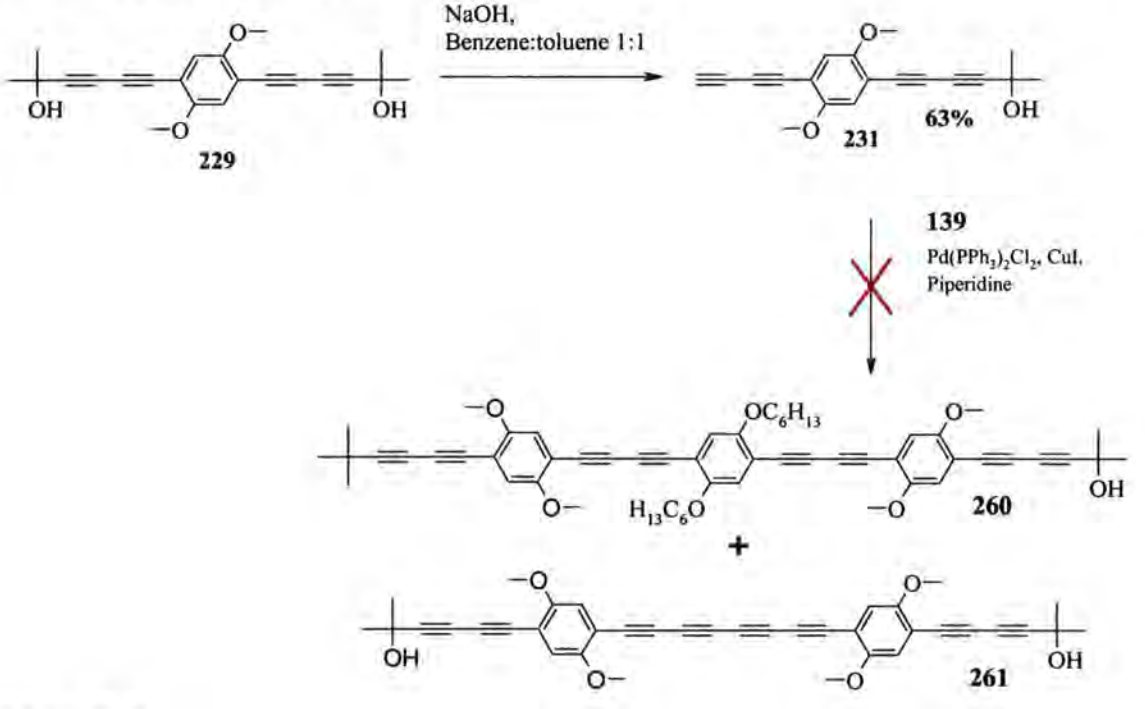
IV. 3 Reactions of bis-butadiynes

The synthesis of mono-deprotected species for use in molecular wire synthesis is an important aspect of this work; it was desirable to maximise their yields to ensure this protocol is a feasible route to controlled rod synthesis.

With the aim of synthesising the mono-deprotected species **231** in greater yields, the deprotections of **229**, were re-examined in refluxing benzene, toluene and benzene:toluene (1:1 v/v) under argon. All other conditions were fixed: 100 mg of starting material and 50 mg of NaOH (powdered) were dissolved in 10 mL of solvent. The reactions were followed by TLC and stopped after 15 minutes (**Scheme IV.9**). Analysis by TLC indicated that the mono-deprotected species **231** was obtained in

greater yield with refluxing benzene:toluene (1:1 v/v). The reaction was repeated on a larger scale, giving species **231** in 63% yield (**Scheme IV.9**).

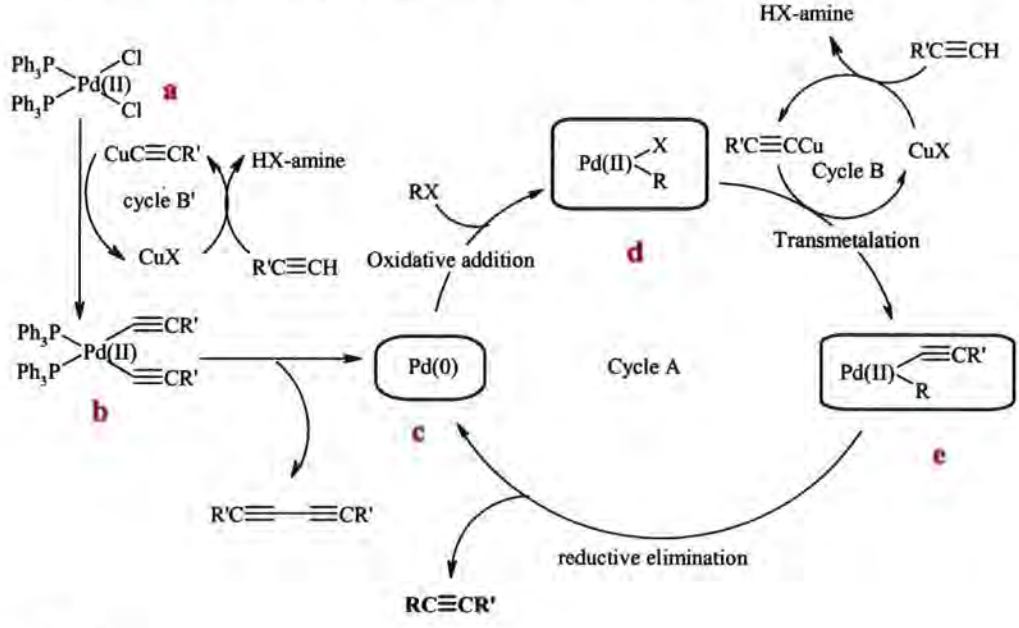
Having successfully shown these compounds can be synthesized in workable yields, by fine-tuning the reaction conditions, their ability to further cross-couple was investigated. It was decided to couple **231** with 1,4-bis-hexyloxy-2,5-diiodobenzene **139**, the hexyloxy chains should aid solubility. The attempted reaction between alkyne **231** (2.5 eq) and **139** in piperidine with $Pd(PPh_3)_2Cl_2$ catalyst was not successful. Analysis by TLC indicated there to be no desired product **260**, only a significant dark spot on the baseline, which was not strongly fluorescent, hence indicating it was not the homocoupled alkyne species **261**. It is assumed piperidine is too basic and could be abstracting the acetylenic proton.



Scheme IV.9

The coupling was repeated using triethylamine and THF as base and solvent respectively. To prevent the formation of species **261**, **231** and **139** were dissolved in THF:Et_3N and the reaction mixture thoroughly degassed with argon for 30 minutes. To further prevent homo-coupling of the alkyne, $Pd(PPh_3)_4$ was chosen instead of $Pd(PPh_3)_2Cl_2$; in $Pd(PPh_3)_4$ the need for the transmetallation stage to afford Pd(0) is not necessary. The proposed catalytic cycle for the Sonogashira reaction is highlighted in **Scheme IV.10**. Like the Suzuki coupling reaction discussed in Chapter I, there are three main steps; oxidative addition of the aryl halide to the Pd(0) species, transmetallation and finally reductive elimination.

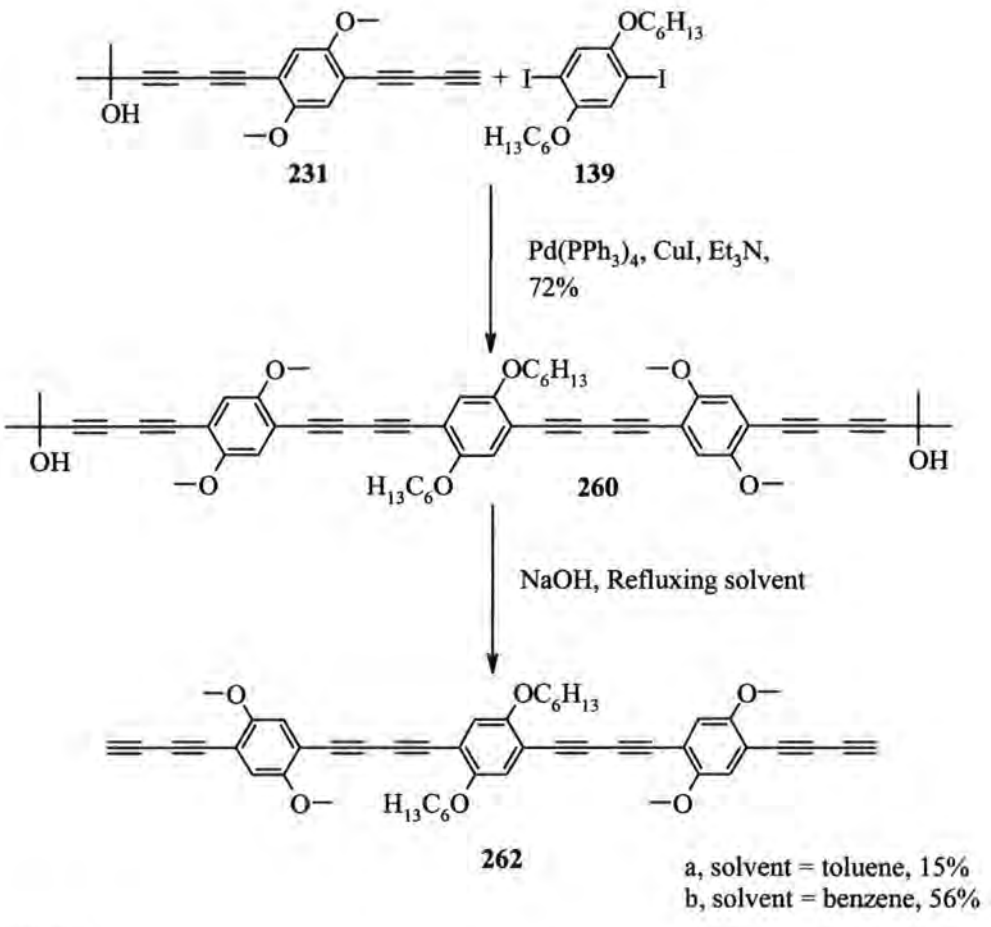
It is during the transmetallation of catalyst species (**a**→ **b**) and the reductive elimination (**b**→ **c**) stage that most homo-coupled species is produced, hence by using $Pd(PPh_3)_4$ it is expected this process will be suppressed. Unfortunately Pd(0) species are less stable, therefore the catalyst requires more careful handling.



Scheme IV.10

Under these modified conditions, **260** was obtained as a bright yellow solid in 72% yield after recrystallisation, **Scheme IV.11**. Having isolated **260**, deprotection was necessary. Having never attempted a bis-deprotection of such a long system previously, it was extremely difficult to predict whether the resulting deprotected species **262** would be stable, in both solution and in solid state. Deprotection was attempted in toluene and benzene, the results shown in **Scheme IV.11**.

Analysis by ^1H NMR (C_6D_6 solvent) indicated the desired product **262** had been isolated. Interestingly, the methoxy protons are two singlets of equal integration (at 3.03 and 3.02 ppm). To ensure one of the singlets is not due to an impurity, the spectrum of starting material **260** was also obtained in C_6D_6; indeed two singlets were also observed.



Scheme IV.11

To estimate the length of such a compound, Hyperchem™ Molecular Modelling Systems version 6.03 for Windows was used, from which it was estimated species **262** is 3.2 nm (terminal C-C distances), **Fig IV.3**.

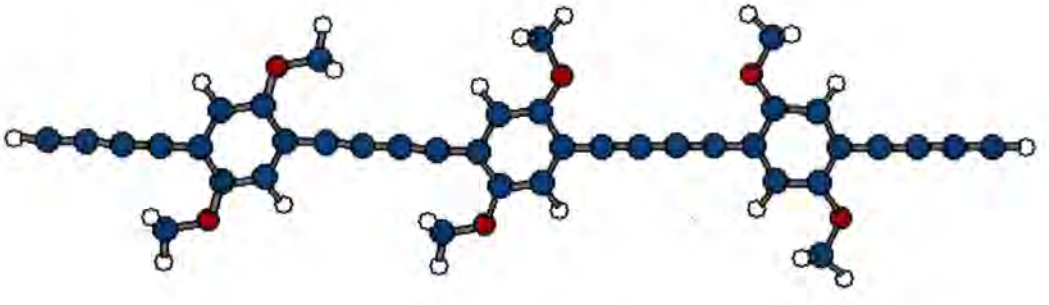
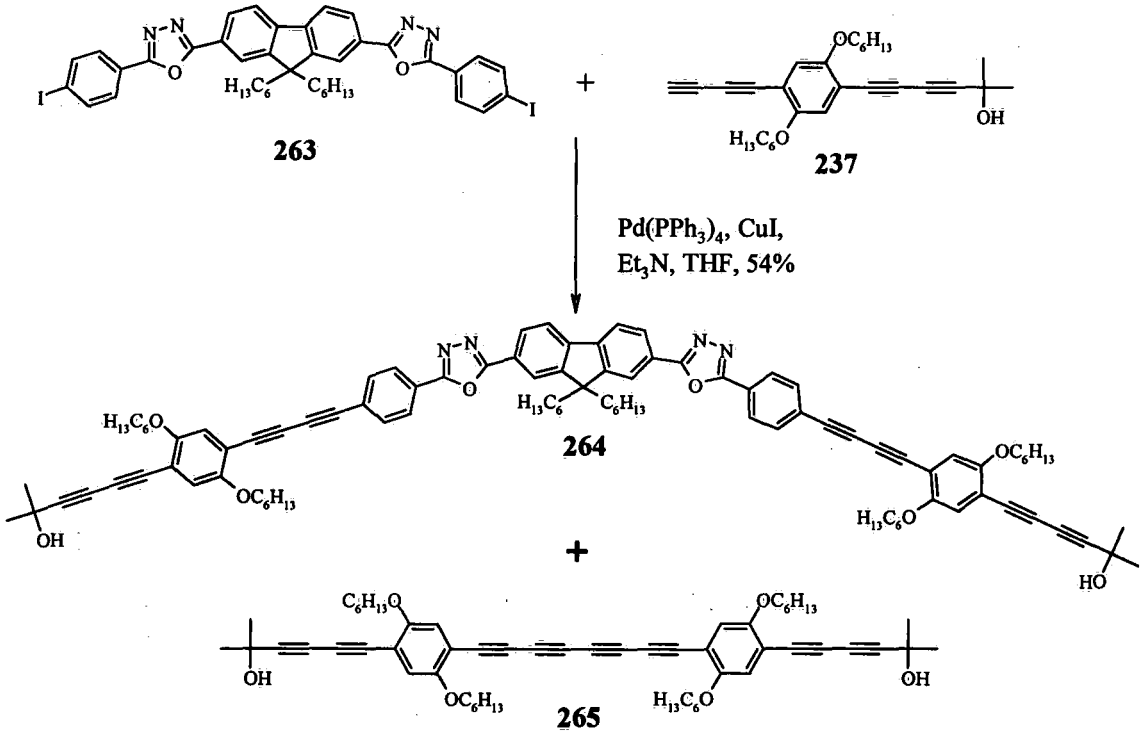


Fig IV.3 Minimised energy conformation of 262, where CH_3 replaces C_6H_{13} on central ring.

The synthesis and isolation of the longer molecular wire-type compounds has, thus, been established. The bis-deprotected species **262** is stable at room temperature for several months (in air as a solid), thus it is a valuable precursor for other molecular rods.

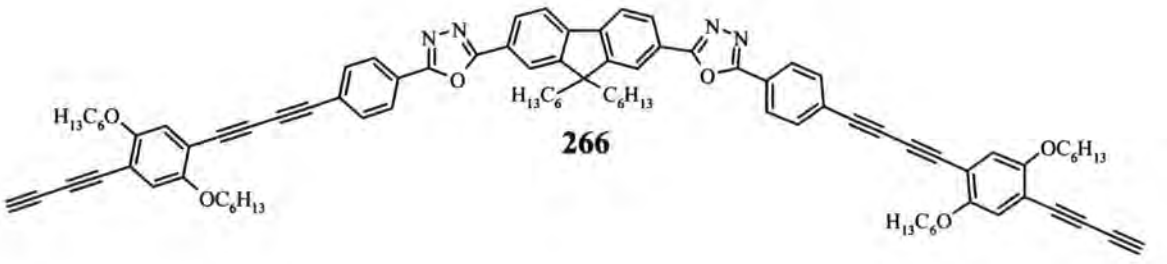
The bright yellow solid of **262** is amorphous, and crystals could not be grown for structural elucidation. Despite the incorporation of hexyloxy chains, **262** is still relatively insoluble in common organic solvents. It was decided, therefore, to synthesise a long conjugated system using bis-hexyloxy mono-deprotected species **237** as the alkynic moiety, which should aid solubility.

Despite handling difficulties associated with **237** (Chapter III, Section 2), 135 mg (2.5 eq.) was isolated and reacted with previously reported and readily available di-iodo compound **263** (1 eq.),[142] to afford species **264** in reasonable yield as a bright yellow solid, **Scheme IV.12**. Purification was very laborious, requiring two columns to remove an extremely-close running impurity, which was possibly the homocoupled octatetrayne **265.**



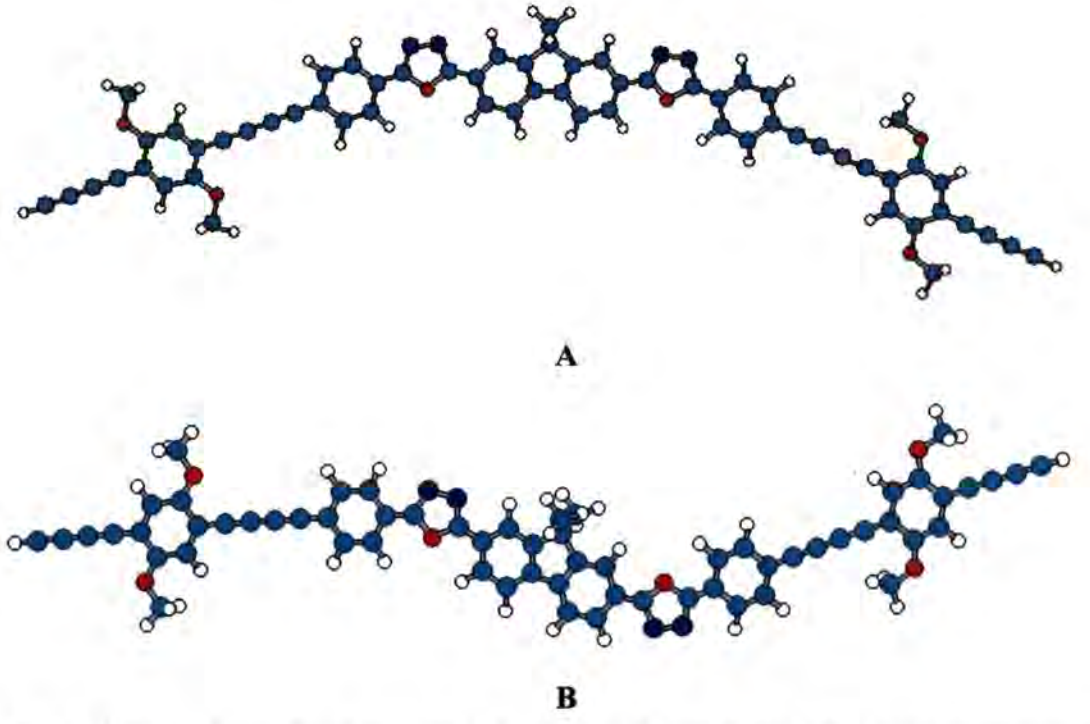
Scheme IV.12

Due to time constraints, deprotection of **264** to afford the bis-deprotected species **266** was not attempted. With the good stability of **262** in mind, it is predicted, species **266** would be stable.



266

To estimate the length of such a compound, Hyperchem™ Molecular Modelling Systems version 6.03 for Windows predicted **Fig IV.4. 264** has two lowest energy conformers **a** and **b**. Both are approximately 5 nm in length.



A

B

Fig IV.4 Minimum energy conformations of 264, where CH_3 replaces C_6H_{13} on fluorene system.

IV. 3. 1 Absorption and Emission spectra for Conjugated wires.

At the time of synthesis, it was observed both **262** and **264** were particularly fluorescent (which aided column chromatography). The UV-Vis absorption and emission spectra were obtained in a chloroform solution. The bright yellow compound **262** shows a lowest energy absorption λ_{max} at 424 nm, in the visible region of the spectrum and bright blue fluorescence (λ_{max} 457 nm). The many absorption bands in the

spectrum are due to the presence of both methoxy and hexyloxy chains.[77] The high energy bands, at 280 and 313 nm, are possibly due to the transition from HOMO-1/HOMO-2 orbital to the LUMO. The red-shifted absorption at 424 nm can be assigned to the HOMO-LUMO transition.[77]

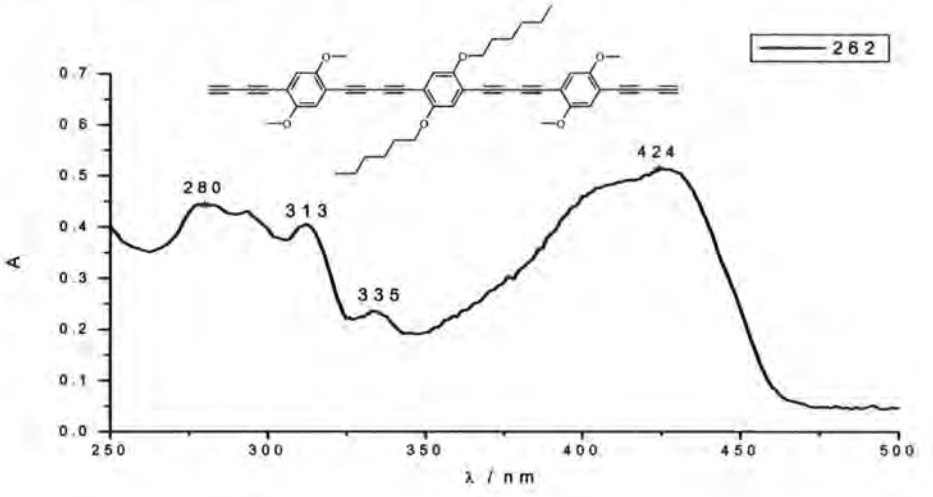


Fig IV.5; UV-Vis absorption spectrum of 262.

Figure IV.6 provides evidence for the increased conjugation length between precursors **230** and **236**, and the wires **260** and **262**. The data shows a clear red-shift of *ca.* 40 nm for species **260** (*c.f.* **230** and **236**). The λ_{max} absorption and emission data are collated in **Table IV.1**, which indicates a Stokes shift of 23 nm for **230** to 34 nm for **262**.

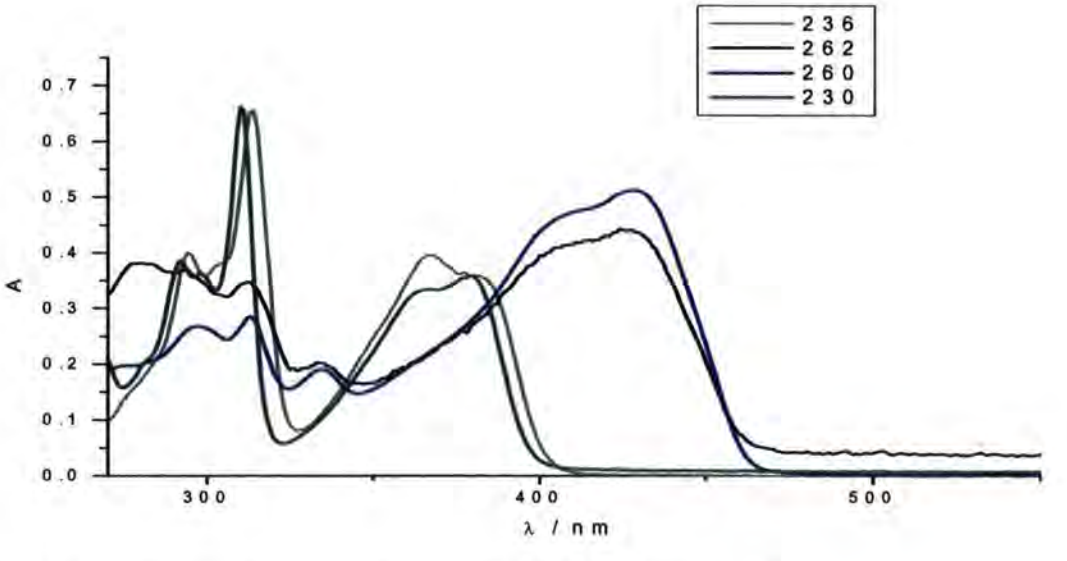


Fig IV.6; UV-Vis absorption spectra for compounds 230, 236, 260 and 236.

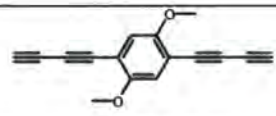
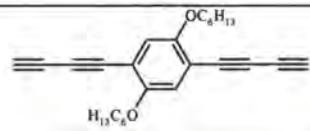
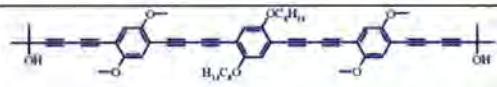
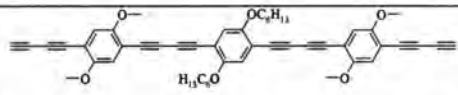
Compound	Number	λ_{max} abs (nm)	λ_{max} ems [a] (nm)
	**230**	292, 310, 379	402
	**236**	295, 314, 367, 383	412
	**260**	297, 314, 335, 427	457
	**262**	280, 313, 335, 424	457

Table IV.1 Absorption and emission data in chloroform solutions for compounds 230, 236, 260 and 262.[a] excitation at λ_{max} abs.

The UV-Vis spectrum for **264** in **Fig IV.7** shows three absorption peaks, which is again concordant with the literature for bis(hexyloxy)aryl species.[77] Plotted alongside is the spectrum for species **236**, thus showing absorption peaks are due to presence of hexyloxy chains

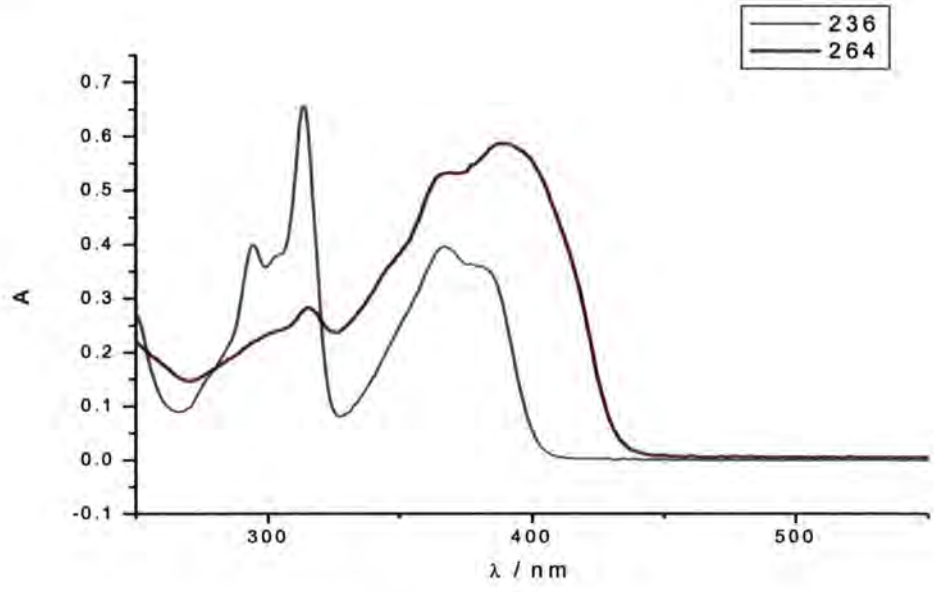
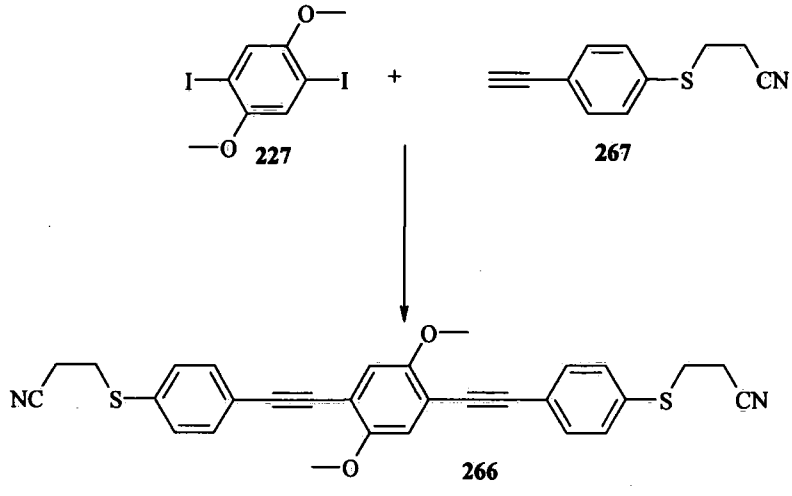


Fig IV.7 UV-Vis absorption spectra for compounds 236 and 264.

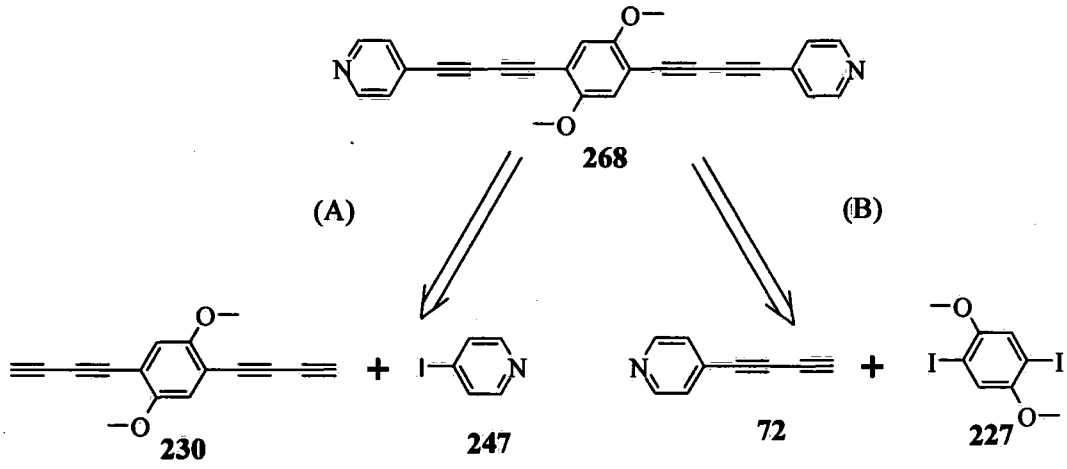
IV. 3. 2 Synthesis of simple wires for attachment to gold surfaces

Our group has reported the synthesis of **266** in moderate overall yield from **227** and **267**. Compound **266** has been assembled on gold substrates and probed by STM-break junction techniques. [143] **Scheme IV.13.**



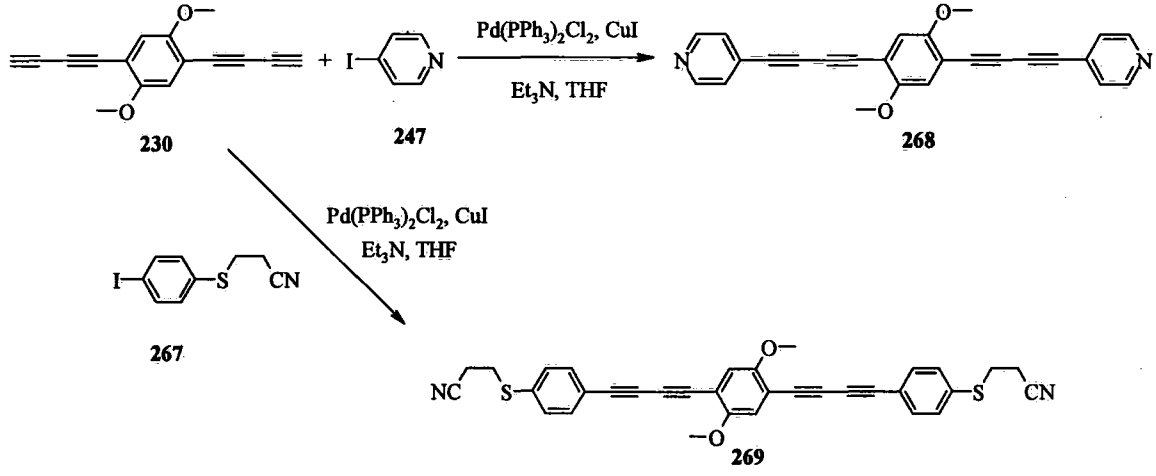
Scheme IV.13

It was of interest, therefore, to synthesise a bis-butadiyne analogue of **266** from the Sonogashira coupling between **230** and either 3-(4-iodo-phenylsulfanyl)-propionitrile **267** or 4-iodopyridine **247**. The use of pyridine-moieties for attachment onto gold surfaces has been highlighted in Chapter I, Section 1. By end-capping **230** with 4-iodopyridine **247**, the molecule might be capable of assembly onto a gold surface. The retrosynthetic analysis of **268**, in **Scheme IV.14**, indicates there are two possible avenues of synthesis; end capping of **230** with 4-iodopyridine **247** (A), or coupling between pyridylbutadiyne **72** and 1,4-diiodo-2,5-dimethoxy-benzene **227** (B), both under standard Sonogashira conditions. We opted for route (A), since pyridylbutadiyne may well homo-couple. It was noted, however, that route (A) might involve handling difficulties of **230**. However, this was found not to be problematic; upon isolation of **230** it was dried, weighed and dissolved in triethylamine promptly with no appearance of dark polymerized matter.



Scheme IV.14

The synthesis for **268** is outlined in **Scheme IV.15**. $Pd(PPh_3)_2Cl_2$ was the preferred catalyst, since homo-coupling of alkyne was perceived not to be problematic. By reacting with **267**, the analogous compound **269** was also synthesized, however in poor yield. ^{1}H and ^{13}C NMR data are consistent with species **269**.



Scheme IV.15

Unfortunately, **269** was not stable; on recrystallisation a dark solid resulted. Such an instability meant the compound would not be useful for assembly onto gold surfaces. The reason for such instability is not fully understood, however it was decided not to proceed down this avenue.

In contrast, **268** was stable as a solid for several months at room temperature stored under ambient conditions.

IV. 4 Conclusions

To conclude, therefore, the reactions and functionalisations of both arylbutadiynes and arylbis-butadiynes have been explored in this chapter. It has been shown that both systems are active in Sonogashira couplings to afford a wide range of novel derivatives, including a variety of candidates for molecular wire systems. Amazingly, deprotection of the long wire **260** afforded species **262**, which was stable at room temperature for several months in air when stored as a solid. UV-Vis absorption and emission spectra in solution show absorption and emission in the visible region of the spectrum for wire **262**, which has an approximate length of 3.2 nm. A longer wire has also been synthesised, **265**, which is approximately 5 nm in length.

Chapter V Experimental

V. 1 General

All glassware for reactions requiring an inert atmosphere was flame-dried and flushed with a blanket of argon. All reagents used were of standard reagent grade and were supplied by Aldrich, Avocado, Fluka or Merck and used as supplied. Anhydrous triethylamine was supplied by Aldrich (Analytical Grade, >99.5%).

Most ^{1}H and ^{13}C NMR spectra were recorded either on a Varian Unity-300 spectrophotometer operating at 299.91 MHz for ^{1}H and 75.41 MHz for ^{13}C or on a Bruker Avance 400 spectrophotometer operating at 400.13 MHz for ^{1}H and 100.61 MHz for ^{13}C, respectively. Spectra were usually obtained in deuterated chloroform, deuterated dimethyl sulphoxide or deuterated benzene. Chemical shifts are quoted in parts per million (ppm) relative to internal solvent peak. The following abbreviations are used for the multiplicities: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet. Coupling constant, (*J*) are reported in Hertz.

Gas Chromatography Mass Spectra were recorded on a Finnigan Trace GC spectrometer, at 70 eV. MALDI-TOF was obtained from a Applied Biosystems Voyager-DE. STR. Elemental analyses were obtained on an Exeter Inc. CE-440 elemental analyser. Melting points were measured in open-end capillaries using a Stuart Scientific SMP3 melting point apparatus. The temperatures at the melting points were ramped at 2.5 /min and were uncorrected.

UV-Vis absorption and emission solution spectra were obtained on a Perkin Elmer UV/Fl - win lab spectrometer.

Column chromatography was performed using Flurochem silica gel (40-60 mesh). Thin layer chromatography (tlc) was performed using Merck DC-Alufolien silica gel plates with UV_{254}, a fluorescent indicator. Visualisation was achieved under a Syngene 230 UV lamp using either longwave (365 nm) or shortwave (254 nm).

General procedure for the Sonogashira Coupling. The iodoarene and 2-methyl-3,5-hexadiyn-2-ol **127** were dissolved in triethylamine. $Pd(PPh_3)_2Cl_2$ and CuI were added and the mixture was stirred at 25 °C for 18 h, with additional heating for 1-2 h if reaction had not gone to completion. Volatile liquids were removed by vacuum evaporation and to the residue, ether was added, boiled, cooled and filtered to remove inorganic impurities. Solvent was removed by reduced pressure and the crude residue chromatographed on a silica column and/or recrystallised to afford products.

General procedure for the basic deprotection. Protected species were dissolved in anhydrous solvent (THF or toluene) or laboratory reagent solvent (benzene). NaOH powder was added and the mixture was stirred and heated with an oil-bath at reflux temperature under Ar. TLC was used to monitor the end-point of the reaction. The reaction mixture was evaporated and the residue purified by column chromatography on silica in the stated eluent.

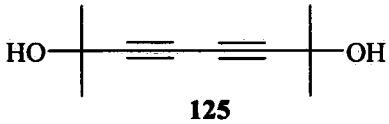
Please note, the extreme toxicities for both benzene and benzyl azide should be a consideration. Extra care should be taken when using these compounds. Benzene should be removed from reaction mixture by rotary evaporator in a fumehood.

CAUTION; arylbutadiynes and their analogues have been, in the past, reported as being explosive. No such problems were encountered during this work. Care should, nonetheless, be taken when handling such sensitive materials. It is for this reason that melting points and elemental analyses of deprotected arylbutadiynes and aryl bis-butadiynes, have not been reported.

V. 2 Experimental Details

V. 2. 1 Experimental Details for Chapter II

2,7-Dimethyl-octa-3,5-diyne-2,7-diol , 125 [144]



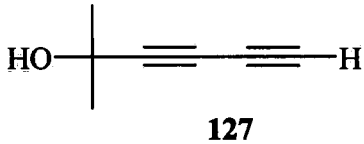
125

2-Methyl-3-butyn-2-ol **126** (84.0 g, 1.00 mole) was dissolved in a solution of methanol (80 mL) and pyridine (20 mL), to which copper(I) chloride (1.20 g, 0.12 mol) was added and the reaction mixture stirred at 35 °C for 24 h whilst oxygen was bubbled through. Excess solvent was removed by reduced pressure and to the remaining green residue, ether (250 mL) was added. The mixture was heated to dissolve solids, cooled and filtered through a 10 cm pad of silica. Excess solvent was removed and the remaining residue recrystallised from toluene to yield **125**, as white crystals (62.7 g, 80% yield): mp 128.7-129.8 °C (Lit value 131-132 °C);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.90 (s, $(OH)_2$, 2H), 1.55 (s, (CH_3), 12H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 84.1, 67.1, 65.4, 31.2.

2-Methyl-hexa-3-5-diyn-2-ol, 127 [119]



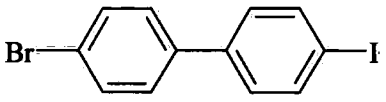
127

2,7-Dimethyl-octa-3,5-diyne-2,7-diol, **125** (20.0 g, 120 mmol) and potassium carbonate (1.33 g, 9.62 mmol) were melted whilst stirring at 190 °C under reduced pressure from water pump until significant darkening of compound in reaction flask. The crude product was collected in a separate flask cooled by a dry ice-acetone bath and the excess solvent (acetone produced during the reaction) removed by reduced pressure *in vacuo* to yield **127** as a light yellow oil (4.54 g, 35% yield);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 2.19 (s, ≡CH, 1H), 1.92 (s, OH, 1H), 1.57 (s, (CH_3), 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 83.3, 69.1, 68.3, 67.9, 65.3, 31.3.

4-Bromo-4'-iodobiphenyl, 134[120]



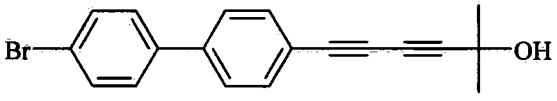
134

4-Bromobiphenyl **133** (11.7 g, 50 mmol) was dissolved in acetic acid (50 mL) and chloroform (20 mL) to which iodine (7.57 g, 29.8 mmol) was added and the reaction stirred at 50 °C. Concentrated nitric acid (4 mL) was added dropwise to the reaction mixture, which was heated at 100 °C for 50 h. The reaction mixture was cooled, filtered and washed with acetic acid (50 mL), and methanol (100 mL) to yield **134** (14.4 g, 80%), mp 176.0-176.4 °C (Lit value 166-168 °C);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.69 (d, J = 8.0 Hz, 2H), 7.55 (d, J = 8.0 Hz, 2H), 7.45 (d, J = 8.0 Hz, 2H), 7.30 (d, J = 8.0 Hz, 2H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 142.8, 138.65, 137.60, 130.1, 128.6, 128.2, 123.1, 92.9.

6-(4'-Bromo-biphenyl-4-yl)-2-methyl-hexa-3,5-diyn-2-ol 135.



135

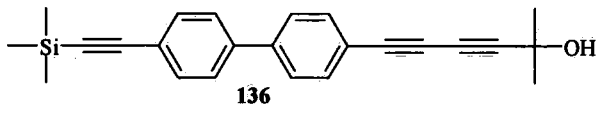
4-Bromo-4'-iodo-biphenyl **134** (8.56 g, 23.8 mmol) was dissolved in THF:triethylamine (100 mL, 4:1, v:v) to which $Pd(PPh_3)_2Cl_2$ (835 mg, 5 mol % of **134**) and copper iodide (417 mg, 5 mol % of **134**) were added. **127** (3.09 g, 28.6 mmol) was dissolved in THF:Et_3N (100 mL, 4:1 v:v) and added slowly to the reaction mixture, which was left to stir at room temperature overnight in a stoppered flask, followed by stirring at 45 °C for 1 h. Excess solvent was removed and to the remaining brown residue, ether was added, heated briefly to dissolve the organics, cooled and filtered. Excess solvent was removed by reduced pressure and the remaining brown residue purified by column chromatography (silica, DCM eluent). Recrystallisation from cyclohexane yielded **135** (5.52 g, 70% yield), mp 198.4-199.7 °C;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.51-7.40 (m, ArH, 6H), 7.35 (d, J = 11.2 Hz, ArH, 2H), 1.55 (s, $(CH_3)_2$, 6H), OH proton was not observed;

^{13}C NMR ($CDCl_3$, 100 MHz): δ 141.8, 139.0, 133.1, 130.8, 129.8, 120.8, 93.8, 87.1, 83.6, 78.5, 74.6, 67.0, 65.8, 31.0;

MS (EI) *m/z*; 340.0 (M^+).

2-Methyl-6-(4'-trimtethylsilanylethynyl-biphenyl-4-yl)-hexa-3,5-diyn-2-ol 136,



136

135 (2.50 g, 7.30 mmol) was dissolved in anhydrous triethylamine (100 mL) to which $Pd(PPh_3)_2Cl_2$ (256 mg, 5 mol %) and copper iodide (70 mg, 5 mol %) were added. To the yellow-green reaction mixture, TMSA (2.82 mL, 18.25 mmol) was added drop-wise and the brown reaction mixture stoppered and stirred at 65 °C for 18 h. Excess solvent was removed and to the remaining brown residue, ether was added, heated, cooled and filtered. Excess solvent was removed by reduced pressure and the remaining brown residue was purified by column chromatography (silica, DCM eluent) to yield **136** as a white solid (1.68 g, 65%): mp 200.8-201.9 °C;

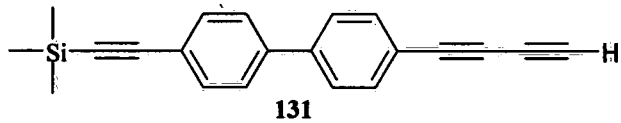
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.57-7.30 (m, ArH, 8H), 1.98 (s, OH, 1H), 1.61 (s, $(CH_3)_2$, 6H), 0.28 (s, Si-$(CH_3)_3$, 9H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 142.1, 139.6, 139.3, 133.4, 133.0, 128.4, 124.6, 122.2, 97.2, 76.5, 74.1, 73.9, 71.2, 69.7, 65.83, 31.2, 1.4;

Anal. Calcd for $C_{24}H_{24}OSi$: C, 80.85; H, 6.78. Found: C, 80.40; H, 6.69.

MS (EI) *m/z* 357.2 (M^+).

(4'-Buta-1,3-diynyl-biphenyl-4-ylethynyl)-trimethylsilane, 131



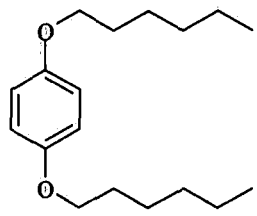
131

136 (409 mg, 1.14 mmol) and powdered sodium hydroxide (205 mg) were stirred in anhydrous toluene (50 mL) and heated at reflux under argon. The reaction was followed by TLC. After 2 h the reaction was complete, solvent removed and the remaining crude residue purified by column chromatography (silica, hexane:DCM, 75:25 v/v eluent), to yield **131** as a white solid (285 mg, 84% yield);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.67 (m, ArH, 6H), 7.55 (d, J = 11.3 Hz, ArH, 2H), 2.39 (s, ≡CH, 1H), 0.01 (s, Si-$(CH_3)_3$, 9H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 142.0, 140.2, 139.1, 134.4, 133.0, 132.6, 127.0, 126.8, 76.7, 76.5, 74.1, 73.9, 70.1, 69.9, 0.1.

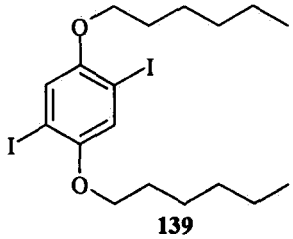
1,4-Bis-hexyloxy-benzene, 138. [121]



138

To a heated solution of potassium hydroxide (11.68 g, 208 mmol) in ethanol (125 mL), hydroquinone **137** (10.00 g, 90 mmol) and 1-bromohexane (28.2 mL, 225 mmol) were added and the reaction mixture was stirred at reflux under argon for 5 h. The mixture was filtered whilst hot to remove any inorganic impurities and the filtrate left to crystallise. The white crystals were filtered and washed with ice-cold water (30 mL) followed by ice-cold methanol (2 x 30 mL) to yield, **138** (17.67 g, 71%): mp 44.8 – 45.6 °C (Lit value 45.2-46.3 °C);
^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.85 (s, ArH, 4H), 3.95 (t, J = 6.5 Hz, $(CH_2)_2$, 4H,), 1.85-1.75 (m, $(CH_2)_2$, 4H), 1.52-1.30 (m, $(CH_2)_6$, 12H), 0.90 (t, J = 6.5 Hz, $(CH_3)_2$, 6H);
^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.2, 115.4, 68.7, 31.6, 29.2, 25.7, 22.6, 14.0.

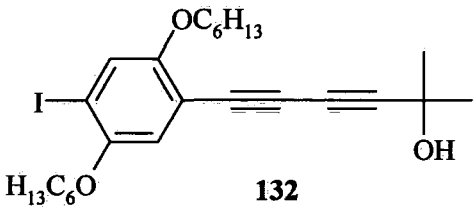
1,4-Bis-hexyloxy-2,5-diiodobenzene, 139[121]



139

To a solution of 1,4-Bis-hexyloxy-benzene **138** (17.00 g, 61.05 mmol), in acetic acid (450 mL), water (45 mL) and concentrated sulphuric acid (4.5 mL), potassium iodate (8.16 g, 38.15 mmol) and iodine (17.37 g, 68.78 mmol) were added and the reaction mixture stirred at 100 °C for 18 h. Excess solvent was removed by reduced pressure and to the remaining brown slurry, methanol (100 mL) was added and the mixture filtered. The solids were washed with methanol (5 x 25 mL), followed by water (3 x 25 mL) and then finally again with methanol (2 x 25 mL) and left to dry. The remaining yellow solid was dissolved in DCM (50 mL) and filtered through a pad of celite (~3 cm thick). Excess solvent was removed from the filtrate and the residue was recrystallised from ethanol to yield **139** as a yellow solid (22.33 g, 69% yield): mp 62.8-64.3 °C (lit value 59.9-60.7 °C);
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.15 (s, ArH, 2H), 3.99 (t, J = 6.6 Hz, $(CH_2)_2$, 4H), 1.80-1.70 (m, $(CH_2)_2$, 4H), 1.60-1.25 (m, $(CH_2)_6$, 12H), 0.85 (t, J = 6.6 Hz, $(CH_3)_2$, 6H);
^{13}C NMR ($CDCl_3$, 100 MHz): δ 152.9, 122.9, 86.3, 70.4, 31.5, 29.1, 25.7, 22.6, 14.0.

6-(2,5-Bis-hexyloxy-4-iodophenyl)-2-methyl-hexa-3,5-diyn-2-ol, 132



132

1,4-Bis-hexyloxy-2,5-diiodo-benzene, **139** (4.89 g, 9.24 mmol) was dissolved in piperidine (45 mL), to which $Pd(PPh_3)_2Cl_2$ (380 mg, 5% by mol of **132**) and copper iodide (194 mg, 5% by mol of **132**) were added to give a green solution, to which **127** (1.00 g, 9.24 mmol) in piperidine (5 mL) was added dropwise. The reaction mixture was stirred at room temperature for 1 h and then at 50 °C for 3 h. Excess solvent was removed and to the remaining residue, ether was added, boiled, cooled to room temperature and filtered to remove any inorganic impurities. Excess solvent was removed from the filtrate and the remaining crude residue containing **132** and **140** purified by column chromatography (silica, DCM eluent) to yield a brown oil of **132** (1.65 g, 35% yield);

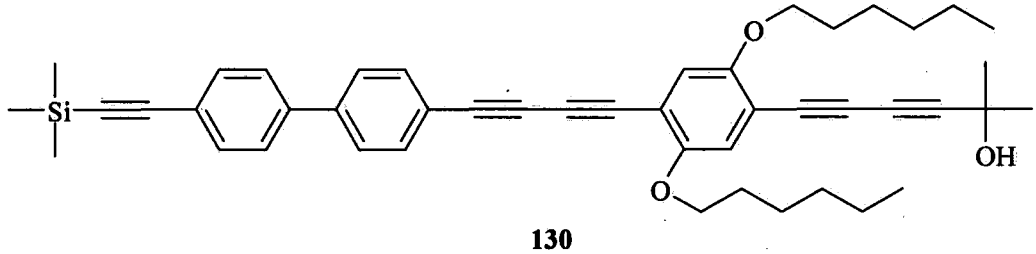
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.15 (s, ArH, 1H), 7.05, (s, ArH, 1H), 3.99 (t, J = 6.6 Hz, $(CH_2)_2$, 4H), 2.10 (s, OH, 1H), 1.80-1.70 (m, $(CH_2)_2$, 4H), 1.65 (s, $(CH_3)_2$, 6H), 1.60-1.25 (m, $(CH_2)_6$, 12H), 0.85 (t, J = 6.6 Hz, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.7, 151.8, 124.0, 116.7, 111.9, 89.2, 87.6, 70.1, 70.1, 67.3, 65.8, 31.5, 31.1, 29.1, 25.7, 25.6, 22.6, 14.0;

Anal. Calcd for $C_{25}H_{35}IO_3$: C, 58.83; H, 6.91. Found: C, 58.58; H, 6.90;

MS (EI) *m/z* 339.2 (M^+).

6-{2,5-Bis-hexyloxy-4-[4-(4'-trimethylsilanylethynyl-biphenyl-4-yl)-buta-1,3-diynyl]-phenyl}-2-methyl-hexa-3,5-diyn-2-ol, 130



130

Halide **132** (1.07 g, 2.10 mmol) was dissolved in anhydrous triethylamine, to which $Pd(PPh_3)_2Cl_2$ (140 mg, 5% by mol of **132**) and copper iodide (50 mg, 5% by mol of **132**) were added. Alkyne **131** (627 mg, 2.10 mmol) was dissolved in a minimum

amount of anhydrous triethylamine and added drop-wise to the reaction mixture which was then stirred at 45 °C for 6 h. Excess solvent was removed by reduced pressure, and to the remaining residue, ether was added, boiled, cooled and filtered. Excess solvent was removed to afford a crude brown product which was purified *via* column chromatography (silica, DCM:hexane, 50:50, v/v) to give a yellow solid. Recrystallisation from cyclohexane yielded **130** as a bright yellow solid (874 mg, 65% yield): mp 174.8-176.5 °C;

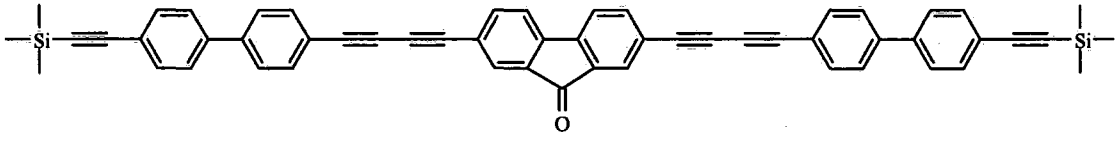
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.58 (m, ArH, 4H), 7.54 (m, ArH, 4H), 6.96 (s, ArH, 1H), 6.93 (s, ArH, 1H), 3.99 (t, J = 6.6 Hz, $(CH_2)_2$, 4H), 2.00 (s, OH, 1H), 1.85-1.75 (m, $(CH_2)_2$, 4H), 1.70-1.55 (m, $(CH_2)_6$, 12H), 1.45 (s, $(CH_3)_2$, 6H), 0.86 (t, J = 6.6 Hz, $(CH_3)_2$, 6H), 0.28 (s, Si-$(CH_3)_3$, 9H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.7, 151.4, 141.9, 141.2, 139.2, 134.4, 133.0, 132.7, 127.0, 125.8, 124.0, 116.7, 112.9, 89.2, 87.6, 77.7, 74.1, 70.1, 70.2, 70.1, 68.9, 67.3, 65.8, 31.5, 31.1, 29.1, 25.7, 25.7, 22.6, 14.1, 0.1;

Anal. Calcd for $C_{46}H_{52}O_3Si$: C, 81.13; H, 7.67. Found: C, 81.13; H, 7.70;

MALDI-TOF *m/z* 680.4 (M^+).

Attempted synthesis of 2,7-bis-[4-(4'-trimethylsilanylethynyl-biphenyl-4-yl)-buta-1,3-diynyl]-fluoren-9-one, 142

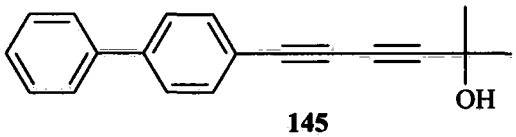


142

Diiodofluorenone **141,** (170 mg, 0.369 mmol) was dissolved THF:Et_3N (50 mL, 40:10 v/v) to which $Pd(PPh_3)_2Cl_2$ (42 mg, 5 mol % of **141**) and copper iodide (11 mg, 5 mol % of **141**) were added to give a yellow precipitate. Alkyne **131** (355 mg, 1.19 mmol) was dissolved in THF:Et_3N (50 mL, 40:10 v/v) and added dropwise to the reaction mixture. The reaction was stirred overnight under argon. Excess solvent was removed and to the remaining brown residue, chloroform was added, boiled, cooled and filtered. Excess solvent was removed by reduced pressure and the remaining brown residue was

purified by column chromatography (DCM:hexane, 50:50, v/v). The reaction was unsuccessful, with starting materials eluting from column.

4-(5-Hydroxy-5-methylhexa-1,3-diynyl)-1,1'-biphenyl, 145



145

4-Iodo-1,1'-biphenyl **144** (500 mg, 1.78 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (390 mg, 3.57 mmol), $Pd(PPh_3)_2Cl_2$ (62 mg), CuI (17 mg), triethylamine (50 mL) and column chromatography (silica, DCM eluent) gave **145** as a white solid (393 mg, 85%, after recrystallisation from hexane): mp 123.5-123.8 °C;

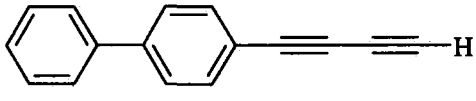
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.65-1.69 (m, Ar-H, 6H), 7.53-7.57 (m, Ar-H, 2H,), 7.47 (tt, J = 7.6 Hz, J = 2.8 Hz, J = 1.2 Hz, Ar-H, 1H,), 2.11 (s, OH, 1H,), 1.69 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 142.2, 140.1, 133.0, 128.9, 127.9, 127.1, 112.0, 120.4, 87.0, 78.7, 73.8, 67.2, 65.8, 31.2;

GC-MS (EI) *m/z* 261.0 (M^+);

Anal. Calcd. for $C_{19}H_{16}O$: C, 87.66; H, 6.19. Found: C, 87.44; H, 6.35.

4-(Buta-1,3-diynyl)-1,1'-biphenyl, 143



143

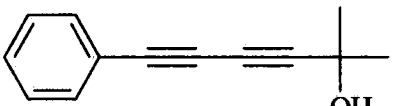
Compound **145** (300 mg, 1.15 mmol), NaOH (150 mg) and toluene (25 mL) afforded **143** as a white solid (213 mg, 91%). The compound was purified by column chromatography (silica, DCM:Et_2O 80:20 v/v). The single crystal (colourless) used for X-ray structural analysis was obtained by slow evaporation of a $CDCl_3$ solution;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.58-7.60 (m, Ar-H, 6H), 7.40-7.46 (m, Ar-H, 3H) 2.52 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 142.6, 140.3, 133.6 129.3, 128.3, 127.5 127.4, 120.1, 75.6, 74.4, 71.9, 68.5;

HRMS (EI^+) calcd. for $C_{16}H_{10}$ 202.0783, found 202.0782.

2-Methyl-6-phenylhexa-3,5-diyn-2-ol, 147



147

Iodobenzene **146** (0.27 mL, 2.45 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (530 mg, 4.90 mmol), $Pd(PPh_3)_2Cl_2$ (86 mg), CuI (23 mg) and triethylamine (50 mL) gave **147** as a white solid after column chromatography (silica, DCM) and recrystallisation from cyclohexane (373 mg, 81%): mp 67.3-68.0 °C;

^{1}H NMR (DMSO-d_6, 400 MHz): δ 7.54-7.56 (m, Ar-H, 2H), 7.39-7.45 (m, Ar-H, 3H), 5.67 (s, OH, 1H), 1.42 (s, $(CH_3)_2$, 6H);

^{13}C NMR (DMSO-d_6, 100 MHz): δ 132.5, 129.2, 128.4, 121.6, 86.9, 78.8, 76.7, 67.1, 65.8, 31.1;

GC-MS (EI) *m/z* 185.1 (M^+).

1-(Buta-1,3-diynyl)benzene, 70. [92]

70

Compound **147** (162 mg, 1.27 mmol), NaOH (80 mg) and toluene (25 mL) afforded **70** as a colourless oil (112 mg, 70%). The compound was purified by column chromatography (silica, hexane);

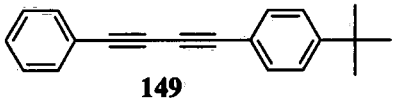
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.53-7.51 (m, Ar-H, 2H), 7.30-7.39 (m, Ar-H, 3H), 2.48 (1H, s, ≡CH);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 133.0, 129.8, 128.7, 121.2, 75.6, 73.7, 71.5, 68.3;

GC-MS (EI) *m/z* 127.1 (M+);

HRMS (EI+) calcd. for $C_{10}H_6$ 126.0470, found 126.0471.

1-*tert*-4-(4-phenyl-buta-1,3-diynyl)-benzene, 149



149

Compound **147** (286 mg, 1.53 mmol) NaOH (143 mg) and toluene (30 mL) afforded **70** as a colourless oil (183 mg, 1.45 mmol) which was purified by column chromatography (silica, hexane). **70**, *p-tert*-butyl-iodobenzene **148** (0.18 mL, 0.96 mmol), $Pd(PPh_3)_2Cl_2$ (34 mg), CuI (10 mg) and

triethylamine (50 mL) afforded a yellow solid of **149** (186 mg, 75% from **147**) after column chromatography (silica, DCM eluent): mp 79.7-80.5 °C;

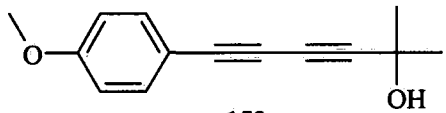
^{1}H NMR ($CDCl_3$, 400 MHz): 7.55-7.53 (m, Ar-H, 2H), 7.47-7.49 (m, Ar-H, 2H), 7.34-7.38 (m, Ar-H, 5H), 1.33 (s, $(CH_3)_3$, 9H);

^{13}C NMR ($CDCl_3$, 75 MHz): δ 152.8, 132.6, 132.4, 129.2, 128.6, 125.6, 122.1, 118.1, 81.3, 74.3, 73.4, 35.1, 31.2;

GC-MS (EI) *m/z* 259.1 (M^+);

Anal. Calcd. for $C_{20}H_{18}$: C, 92.98; H, 7.02. Found: C, 92.75; H, 6.96.

6-(4-Methoxy-phenyl)-2-methyl-hexa-3,5-diyn-2-ol, 153.



153

4-Iodoanisole **152** (500 mg, 2.14 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (461 mg, 4.28 mmol), $Pd(PPh_3)_2Cl_2$ (75 mg) and CuI (20 mg) were stirred in triethylamine (50 mL) overnight at 25 °C. The solvent was removed, and to the residue ether was added, heated to dissolve organics, cooled and filtered. Ether was removed and the crude residue was purified by column chromatography (silica, DCM:hexane, 80:20 v/v) to afford **153** as a white solid (308 mg, 67% after recrystallisation from hexane): mp 67.6-68.3 °C;

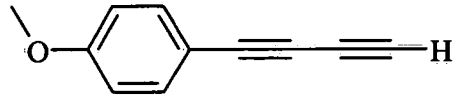
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.45 (d, J = 14 Hz, ArH, 2H), 6.75 (d, J = 14.4 Hz, ArH, 2H), 3.75 (s, O-CH_3, 3H), 2.14 (s, OH, 1H), 1.52 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 160.4, 134.1, 114.2, 113.4, 86.1, 79.1, 71.9, 67.3, 65.8, 55.3, 31.2;

MS (EI) *m/z* 214.3 (M^+);

Anal. calcd. for $C_{14}H_{14}O_2$: C, 78.48; H, 6.59. Found: C, 78.47; H, 6.56.

1-(Buta-1,3-diynyl)-4-methoxybenzene 118.[109]



118

6-(4-Methoxy-phenyl)-2-methyl-hexa-3,5-diyn-2-ol **158** (350 mg, 1.63 mmol) and NaOH (175 mg, 4.38 mmol) were refluxed in anhydrous toluene (20 mL) for 10 min to afford pale yellow

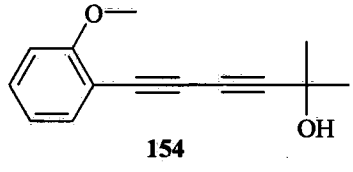
crystals of **118** (213 mg, 84% yield) after purification by column chromatography (silica, DCM:hexane 70:30 v/v). Crystals for X-ray analysis were grown from a chloroform-ether mixture;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.47-7.44 (dt, J = 9.2 Hz, J = 2.4 Hz, ArH, 2H), 6.86-6.83 (dt, J = 9.6 Hz, J = 2.8 Hz, ArH, 2H), 3.82 (s, O-CH_3, 3H), 2.46 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 160.6, 134.1, 114.2, 112.9, 75.6, 72.4, 70.7, 68.4, 55.3;

GC-MS (EI) *m/z* 157.1 (M^+).

6-(2-Methoxy-phenyl)-2-methyl-hexa-3,5-diyn-2-ol 154.



154

2-Iodoanisole (300 mg, 1.28 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (325 mg, 3.21 mmol), $Pd(PPh_3)_2Cl_2$ (28 mg) and CuI (12 mg) in anhydrous triethylamine (30 mL). Column chromatography (silica, DCM:Hexane, 80:20 *v/v*) afforded **154** as an orange oil (200 mg, 75%);

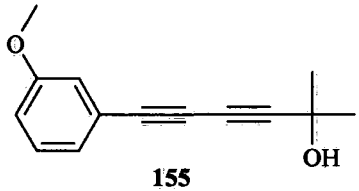
^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.41 (d, J = 7.6 Hz, ArH, 1H), 7.28 (t, J = 8 Hz, ArH, 1H), 6.92-6.82 (m, ArH, 2H), 3.88 (s, O-CH_3, 3H) 2.01 (s, OH, 1H), 1.56 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 161.5, 134.5, 130.7, 120.5, 110.8, 110.7, 87.2, 76.7, 75.4, 67.4, 65.8, 55.8, 31.1;

MS (EI) *m/z* 214.1 (M^+);

Anal. calcd. for $C_{14}H_{14}O_2$: C, 78.48; H, 6.59. Found: C, 77.56; H, 6.47.

6-(3-Methoxyphenyl)-2-methyl-hexa-3,5-diyn-2-ol 155



155

3-Iodoanisole (500 mg, 2.14 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (461 mg, 4.28 mmol), $Pd(PPh_3)_2Cl_2$ (75 mg) and CuI (20 mg) in anhydrous triethylamine (50 mL). Column chromatography (silica, DCM:Hexane, 80:20 *v/v*) afforded **155** as a dark orange oil (222 mg, 50%);

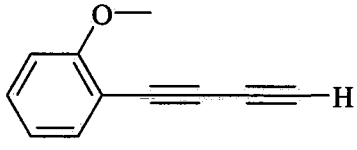
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.20 (t, J = 8.0 Hz, ArH, 1H,), 7.06 (d, J = 7.6 Hz, ArH, 1H), 6.98 (s, ArH, 1H), 6.90 (dd, J = 8.4 Hz, J = 2.0 Hz, ArH, 1H), 3.83 (s, O-CH_3, 3H), 2.63 (s, OH, 1H,), 3.77 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 159.3, 129.5, 125.0, 122.5, 117.2, 116.01, 86.9, 78.7, 73.0, 67.0, 65.7, 55.3, 31.1;

MS (EI) *m/z* 214.1 (M^+);

Anal. calcd. for $C_{14}H_{14}O_2$: C, 78.48; H, 6.59. Found: C, 78.21; H, 6.60.

1-Buta-1,3-diynyl-2-methoxy-benzene 150.



150

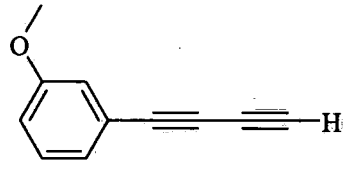
Compound **154** (200 mg, 0.93 mmol), NaOH (100 mg, 2.50 mmol) and anhydrous toluene (20 mL) were refluxed to afford a **150** as pale orange oil (120 mg, 89% yield) after purification by column chromatography (silica, DCM:hexane 70:30 v/v);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.47 (dd, *J* = 7.6 Hz, *J* = 1.6 Hz, ArH, 1H), 7.33 (t, *J* = 8.4 Hz, ArH, 1H), 6.93-6.87 (m, ArH, 2H,) 3.89 (s, O-CH_3, 3H), 2.53 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 161.8, 134.7, 131.0, 120.5, 110.7, 110.1, 77.2, 71.9, 71.8, 68.3, 55.8;

GC-MS (EI) *m/z* 157.2 (M^+).

1-Buta-1,3-diynyl-3-methoxybenzene 151.



151

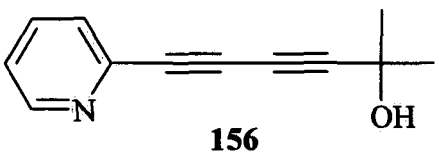
Compound **155** (212 mg, 0.99 mmol), NaOH (106 mg, 2.65 mmol) and anhydrous toluene (20 mL) were refluxed to afford **151** as a pale orange oil (100 mg, 65% yield). The compound was purified by column chromatography (silica, DCM:hexane 70:30 v/v);

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.37 (t, *J* = 7.6 Hz, ArH, 1H), 7.25 (d, *J* = 7.6 Hz, ArH, 1H), 7.16 (s, ArH, 1H), 7.09 (dd, *J* = 8 Hz, *J* = 0.4 Hz, ArH, 1H), 3.93 (s, O-CH_3, 3H,), 2.61 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz) δ 159.5, 129.8, 125.6, 122.2, 117.6, 116.6, 75.5, 73.5, 71.6, 68.3, 55.6;

GC-MS (EI) *m/z* 157.2 (M^+).

2-Methyl-6-(pyridine-2-yl)hexa-3,5-diyn-2-ol, 156



156

2-Iodopyridine (280 mg, 1.38 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (302 mg, 2.77 mmol), $Pd(PPh_3)_2Cl_2$ (48 mg), CuI (10 mg) and triethylamine (40 mL) gave **156** as a white solid after column chromatography (silica, DCM:Et_2O, 50:50 v/v) and recrystallisation from cyclohexane (204 mg, 80%): mp 114.3-115.2 °C;

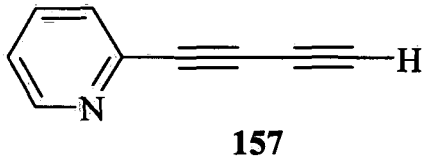
^{1}H NMR (DMSO-d_6, 400 MHz): δ 8.58 (dt, J = 4.8 Hz, J = 1.6 Hz, J = 0.8 Hz, Ar-H, 1H), 7.83-7.86 (m, Ar-H, 1H), 7.66 (d, J = 7.2 Hz, Ar-H, 1H), 7.43-7.45 (m, Ar-H, 1H), 5.73 (s, OH, 1H), 1.44 (s, $(CH_3)_2$, 6H);

^{13}C NMR (DMSO-d_6, 100 MHz): δ 150.4, 140.9, 136.9, 128.3, 124.3, 90.4, 77.2, 72.2, 64.7, 63.8, 30.9;

MS (ES+) *m/z* 186.1 (M^+);

Anal. Calcd. for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 77.48; H, 5.93; N, 7.38.

2-(Buta-1,3-diynyl)pyridine, 157



157

Compound **156** (250 mg, 1.63 mmol), NaOH (125 mg) and toluene (25 mL) afforded **157** as a white solid (141 mg, 66%). The compound was purified by column chromatography (silica, DCM:Et_2O, 60:40 v/v). The single crystal (colourless) used for X-ray structural analysis was obtained by slow evaporation of a DCM-ether mixture;

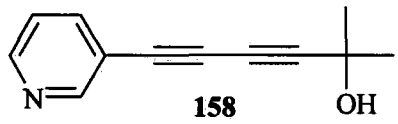
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.66 (dq, J = 4.8 Hz, J = 1.4 Hz, J = 1.2 Hz, Ar-H, 1H), 7.67 (td, J = 7.6, J = 1.6 Hz, Ar-H, 1H), 7.51 (dt, J = 7.6 Hz, J = 2.0 Hz, J = 1.2 Hz, Ar-H, 1H), 7.27-7.31 (m, Ar-H, 1H), 2.51 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 150.4, 141.6, 136.2, 128.3, 123.8, 74.0, 73.1, 72.2, 67.7;

GC-MS (EI) *m/z* 128.1 (M^+);

HRMS (EI+) calcd. for C_9H_5N 127.0422, found 127.0422.

2-Methyl-6-(pyridine-3-yl)hexa-3,5-diyn-2-ol, 158



158

3-Iodopyridine (300 mg, 1.46 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (320 mg, 2.92 mmol), $Pd(PPh_3)_2Cl_2$ (51 mg) and CuI (14 mg) in anhydrous triethylamine (40 mL) gave **158** as a white solid after column chromatography (silica, DCM:Et_2O 50:50 v/v), recrystallised from cyclohexane (221 mg, 82%): mp 103.1 - 104.0 °C;

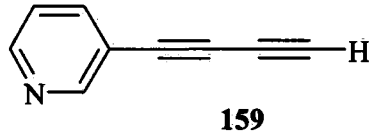
^{1}H NMR (DMSO-d_6, 400 MHz): δ 8.77 (s, Ar-H, 1H), 8.64 (s, Ar-H, 1H), 7.99 (d, J = 8.0 Hz, Ar-H, 1H), 7.45-7.48 (m, Ar-H, 1H), 5.71 (s, OH, 1H), 1.43 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 152.9, 148.6, 139.7, 123.0, 119.4, 89.3, 76.8, 74.7, 66.1, 64.9, 31.0;

MS (ES+) *m/z* 186.1 (M^+);

Anal. Calcd. for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 77.51; H, 6.00; N, 7.25.

3-(Buta-1,3-diynyl)pyridine, 159



159

Compound **158** (250 mg, 1.63 mmol), NaOH (125 mg) and toluene (25 mL) afforded **159** as a white solid (113 mg, 65%). The compound was purified by column chromatography (silica, DCM:Et_2O, 60:40 v/v);

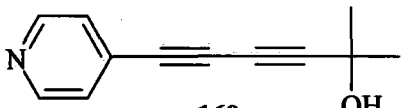
^{1}H NMR ($CDCl_3$, 200 MHz): δ 8.74 (s, Ar-H, 1H), 8.58 (dd, J= 4.8 Hz, J =1.6 Hz, Ar-H, 1H), 7.79 (dt J = 7.8 Hz, J = 2.0 Hz, J = 1.8 Hz, Ar-H, 1H), 7.24-7.30, (m, Ar-H, 1H), 2.55 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.4, 149.9, 139.6, 123.0, 118.5, 77.4, 72.5, 71.9, 67.6;

GC-MS (EI) *m/z* 128.1 (M^+);

HRMS (EI+) calcd. for C_9H_5N 127.0422, found 127.0422.

2-Methyl-6-(pyridine-4-yl)hexa-3,5-diyn-2-ol, 160



160

4-Iodopyridine **247** (280 mg, 1.38 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (300 mg, 2.77 mmol), $Pd(PPh_3)_2Cl_2$ (48 mg), CuI (10 mg) and triethylamine (40 mL) gave **160** as a white solid after column chromatography (silica, DCM:Et_2O 50:50 v/v), recrystallised from cyclohexane, (200 mg, 80%): mp 129.6-130.6 °C;

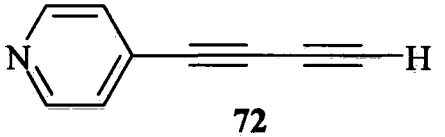
^{1}H NMR ((DMSO-d_6, 400 MHz): δ 8.89 (s, Ar-H, 2H), 7.59 (s, Ar-H, 2H), 5.73 (s, OH, 1H), 1.41 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 149.4, 130.3, 126.6, 90.1, 78.1, 75.3, 66.0, 65.3, 31.1;

MS (ES+) *m/z* 186.1 (M^+);

Anal. Calcd. for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 77.47; H, 5.94; N, 7.48.

4-(Buta-1,3-diynyl)pyridine, 72[90]



72

Compound **160** (100 mg, 0.54 mmol), NaOH (50 mg) and toluene (20 mL) afforded **72** as a white solid (43 mg, 64%). The compound was purified by column chromatography (silica, DCM:Et_2O, 60:40 v/v). The single crystal (colourless) used for X-ray structural analysis was obtained by slow evaporation of a ethanol-chloroform mixture;

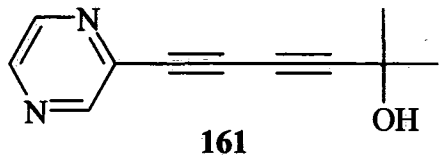
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.54 (dd, J = 4.4 Hz, J = 1.6 Hz, Ar-H, 2H), 7.29 (dd, J = 4.4 Hz, J = 1.6 Hz, Ar-H, 2H), 2.51 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 150.1, 129.6, 126.5, 77.8, 73.7, 72.4, 67.5;

GC-MS (EI) *m/z* 128.2 (M^+);

HRMS (EI+) calcd. for C_9H_5N 127.0422, found 127.0422.

2-Methyl-6-(pyrazin-2-yl)hexa-3,5-diyn-2-ol, 161



161

2-Iodopyrazine (250 mg, 1.21 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (200 mg, 1.82 mmol), $Pd(PPh_3)_2Cl_2$ (42 mg), CuI (11 mg) and triethylamine (40 mL) gave **161** as a white solid after column chromatography (silica, ether eluent), recystallised from a minimum amount of toluene (180 mg, 78%): mp 85.2-85.5 °C;

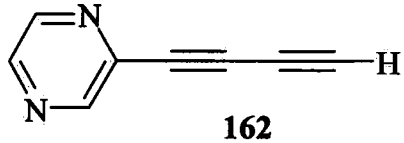
^{1}H NMR ($CDCl_3$, 400 MHz): 8.70 (d, J = 1.2 Hz, Ar-H, 1H), 8.57-8.54 (m, Ar-H, 1H), 8.51 (d, J = 2.8 Hz, Ar-H, 1H), 2.39 (s, OH, 1H), 1.59 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): 148.5, 144.7, 143.4, 139.3, 89.5, 77.7, 74.5, 66.2, 65.9, 30.9;

MS (ES+) *m/z* 187.1 (M^+);

Anal. Calcd. for $C_{10}H_{10}N_2O$: C, 70.95; H, 5.41; N, 15.04. Found: C, 70.98; H, 5.49; N, 15.04.

2-(Buta-1,3-diynyl)pyrazine, 162



162

Compound **161** (100 mg, 0.54 mmol), NaOH (50 mg) and toluene (20 mL) afforded **162** as a white solid (41 mg, 64%). The compound was purified by column chromatography (silica, DCM:Et_2O, 50:50 v/v). The single crystal (colourless) used for X-ray structural analysis was obtained by slow evaporation of a chloroform-hexane mixture;

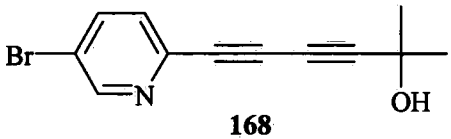
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.73 (s, Ar-H, 1H), 8.56 (d, J = 6.4 Hz, Ar-H, 2H), 2.61 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 149.3, 145.3, 144.4, 139.4, 74.4, 71.7, 67.8, 66.5;

GC-MS (EI) *m/z* 129.1 (M^+);

HRMS (EI+) calcd. for $C_8H_4N_2$ 128.0374, found 128.0374.

6-(5-Bromo-pyridin-2-yl)-2-methyl-hexa-3,5-diyn-2-ol, 168



168

5-Bromo-2-iodopyridine **167** (700 mg, 2.46 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (534 mg, 4.94 mmol), $Pd(PPh_3)_2Cl_2$ (87 mg, 3% mol of **167**), CuI (24 mg, 3% mol of **167**) and triethylamine (100 mL). Column chromatography (silica, DCM:Et_2O 90:10 v/v) afforded **168** as a white solid (552 mg, 85%): mp. 128.3-128.8 °C;

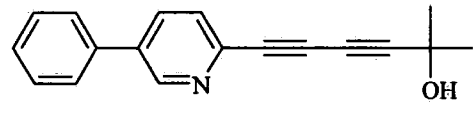
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.62 (s, ArH, 1H), 7.77 (dd, J = 8.4 Hz, J = 2.4 Hz, ArH, 1H), 7.33 (d, J = 8 Hz, ArH, 1H), 2.65 (s, OH, 1H), 1.52 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 151.5, 140.4, 138.9, 128.9, 121.0, 88.6, 76.9, 74.5, 66.5, 65.6, 40.0;

MS (EI) *m/z* 264.1 (M^+);

Anal. Calcd. for $C_{12}H_{10}BrNO$: C, 54.57; H, 3.82; N, 5.30. Found: C, 54.57; H, 3.93; N, 4.98.

2-Methyl-6-(5-phenyl-pyridin-2-yl)-hexa-3,5-diyn-2-ol, 171



171

Compound **168** (382 mg, 1.45 mmol), phenylboronic acid **170** (264 mg, 2.17 mmol, 1.5 eq) and $Pd(PPh_3)_2Cl_2$ (76 mg, 5% of boronic acid **170**) were dissolved in degassed THF (40 mL), to which degassed Na_2CO_3 (aq) (1 M, 4.24 mL, 2 eq of boronic acid **170**) was added and the reaction refluxed under argon whilst being carefully monitored by TLC analysis. THF was removed and the remaining residue dissolved in ether. The organic layer was washed with brine (3 x 50 mL), dried over $MgSO_4$, filtered and the solvent removed. A white solid of **171** (215 mg, 57% yield) was obtained after column chromatography (DCM, changing to DCM:Et_2O, 90:10 v/v eluent) and recrystallisation from cyclohexane: mp 122.1-122.6 °C;

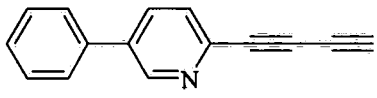
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.82 (s, Ar-H, 1H), 7.86-7.83 (dd, J = 8.4 Hz, J = 2.4 Hz, Ar-H, 1H), 7.59-7.41 (m, Ar-H, 6H), 2.48 (s, OH, 1H), 1.60 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 148.9, 140.8, 137.1, 136.6, 134.5, 129.4, 128.8, 128.2, 127.2, 88.2, 73.9, 67.7, 65.8, 65.2, 31.2;

MS (ES+) *m/z* 262.3(M^+);

Anal. Calcd. for $C_{18}H_{15}NO$: C, 82.73; H, 5.79; N, 5.36. Found: C, 82.44; H, 5.72; N, 5.41.

2-Buta-1,3-diynyl-5-phenylpyridine, 172



172

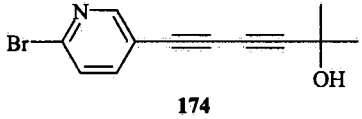
Compound **171** (136 mg, 0.524 mmol), NaOH (65 mg) and toluene (20 mL) afforded **172** as a white solid (82 mg, 85%). The compound was purified by column chromatography (DCM eluent);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.83 (s, Ar-H, 1H), 7.87-7.84 (dd, J = 7.6 Hz, J = 2.0 Hz, Ar-H, 1H), 7.59-7.42 (m, Ar-H, 6H), 2.53 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 148.9, 140.1, 136.8, 136.7, 134.3, 129.2, 128.8, 128.7, 128.3, 127.1, 74.1, 73.7, 72.4, 67.8;

MS MALDI-TOF *m/z* 204.1 (M^+).

6-(6-Bromo-pyridin-3-yl)-2-methyl-hexa-3,5-diyn-2-ol, 174



174

2-Bromo-5-iodopyridine **173** (500 mg, 1.76 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (238 mg, 2.20 mmol), $Pd(PPh_3)_2Cl_2$ (37 mg, 5% by mol of **173**), CuI (10 mg, 5% by mol of **173**) and triethylamine (50 mL). Column chromatography (silica, DCM:Et_2O 90:10 v/v) afforded **174** as a white solid (367 mg, 1.39 mmol, 79%): mp 125.5-126.4 °C;

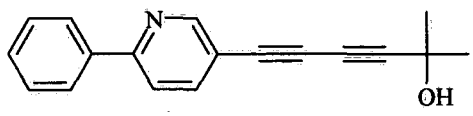
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.48 (d, J = 8.0 Hz, Ar-H, 1H), 7.59 (dd, J = 8.4 Hz, J = 2.0 Hz, Ar-H, 1H), 7.45 (d, J = 8.0 Hz, Ar-H, 1H), 2.97 (s, OH, 1H), 1.57 (s, (CH_3), 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.4, 142.0, 141.5, 127.9, 118.5, 89.2, 77.9, 73.9, 66.4, 65.7, 31.1;

MALDI-TOF *m/z* 265.0 (M^+);

Anal. Calcd. for $C_{12}H_{10}BrNO$: C, 54.57; H, 3.82; N, 5.30, Found: C, 54.56; H, 3.91; N, 5.01.

2-Methyl-6-(6-phenyl-pyridin-3-yl)-hexa-3,5-diyn-2-ol, 175



175

Compound **174** (330 mg, 1.25 mmol) and phenyl boronic acid **170** 229 mg, 1,87 mmol) were dissolved in degassed THF (40 mL), to which degassed Na_2CO_3 (aq) (1M, 3.74 mL, 3.74 mmol) and $Pd(PPh_3)_2Cl_2$ (66 mg, 5% by mol of boronic acid **170**) were added and the reaction carefully monitored by TLC analysis. THF was removed and the remaining residue dissolved in ether. The organic layer was washed with brine (3 x 50 mL), dried over $MgSO_4$, filtered and the solvent removed. A white solid (245 mg, 75% yield) of **175** was obtained after column chromatography (DCM, DCM:Et_2O, 90:10 eluent) and recrystallisation from cyclohexane: mp 123.2-123.6 °C;

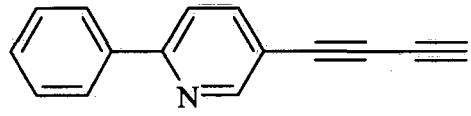
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.80 (dd, J = 2.0 Hz, J = 0.8 Hz, Ar-H, 1H), 7.99-7.97 (m, Ar-H, 2H), 7.81 (dd, J = 8.4 Hz, J = 2.4 Hz, Ar-H, 1H), 7.70 (dd, J = 8.4 Hz, J = 0.8 Hz, Ar-H, 1H), 7.48-7.45 (m, Ar-H, 3H), 2.55 (s, OH, 1H), 1.58 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 157.0, 153.2, 140.3, 138.4, 129.8, 129.0, 127.2, 119.9, 117.2, 88.4, 77.0, 75.8, 66.9, 65.8, 31.2;

MS (ES+) *m/z* 262.4 (M^+);

Anal. Calcd. for $C_{18}H_{15}NO$: C, 82.73; H, 5.79; N, 5.36, Found: C, 82.89; H, 5.51; N, 5.27.

5-Buta-1,3-diynyl-2-phenyl-pyridine, 176



176

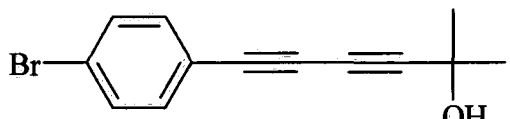
Compound **175** (115 mg, 0.414 mmol), NaOH (60 mg) and toluene (20 mL) afforded **176** as a white solid (73 mg, 82%). The compound was purified by column chromatography (DCM eluent);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.81-8.80 (m, Ar-H, 1H), 8.01-7.99 (m, Ar-H, 2H), 7.84 (dd, J = 8 Hz, J = 2 Hz, Ar-H, 1H), 7.71 (dd, J = 8 Hz, J = 1.2 Hz, Ar-H, 1H), 7.50-7.42 (m, Ar-H, 3H), 2.58 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 157.2, 153.5, 140.5, 138.4, 129.8, 129.0, 127.2, 119.8, 116.7, 77.2, 72.8, 72.5, 67.9;

MALDI-TOF *m/z* 204.1 (M^+).

6-(4-Bromophenyl)-2-methyl-hexa-3,5-diyn-2-ol, 177



177

4'-Iodo-4-Bromobenzene **178** (1.00 g, 3.7 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (500 mg, 4.63 mmol), $Pd(PPh_3)_2Cl_2$ (77.9 mg), CuI (21 mg) and triethylamine (50 mL). Column chromatography (silica, DCM) afforded **177** as a white solid (779 mg, 80%): mp 105.4-106.3 °C;

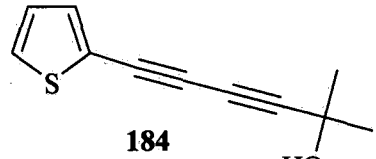
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.38 (d, J = 8.4 Hz, ArH, 2H), 7.23 (d, J = 8 Hz, ArH, 2H), 2.71 (s, OH, 1H), 1.54 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 133.6, 131.8, 123.7, 120.5, 87.5, 77.6, 74.5, 66.9, 65.7, 31.1;

MS (EI) *m/z* 263.9 (M^+);

Anal. Calcd. for $C_{13}H_{11}BrO$: C, 59.34; H, 4.21. Found: C, 59.20; H, 4.13.

2-Methyl-6-(thiophen-2-yl)hexa-3,5-diyn-2-ol, 184



184

2-Iodothiophene **183** (0.38 mL, 1.81 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (293 mg, 2.17 mmol), $Pd(PPh_3)_2Cl_2$ (64 mg), CuI (17 mg) and triethylamine (50 mL) gave **184** as a yellow solid after column chromatography (silica, DCM, followed by DCM:Et_2O 80:20 v/v), recrystallisation from cyclohexane (132 mg, 75%): mp 73.8-74.2 °C;

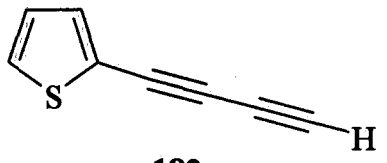
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.31-7.30 (m, Ar-H, 2H), 6.96-6.98 (m, Ar-H, 1H), 1.90 (s, OH, 1H), 1.58 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.4, 128.6, 127.1, 121.8, 88.8, 77.4, 71.9, 67.0, 65.8, 31.1;

GC-MS (EI) *m/z* 191.0 (M^+);

HRMS (EI+) calcd. for $C_{11}H_{10}OS$ 190.0452, found 190.0452.

2-(Buta-1,3-diynyl)thiophenes, 182

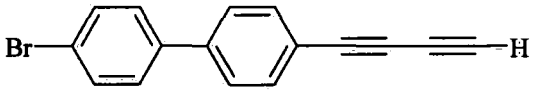


182

Compound **184** (190 mg, 0.99 mmol), NaOH (95 mg) and toluene (25 mL) afforded **182** as a yellow oil (81 mg, 60%). The compound was purified by column chromatography (silica, hexane);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.28 (dd, J = 6.6 Hz, J = 1.2 Hz, Ar-H, 1H), 7.26 (dd, J = 8.2 Hz, J = 1.2 Hz, Ar-H, 1H), 6.92 (dd, J = 5.2 Hz, J = 3.8 Hz, Ar-H, 1H), 2.56 (s, ≡CH, 1H);
GC-MS (EI) *m/z* 133.1 (M^+);
HRMS (EI+) calcd. for C_8H_4S 132.0034, found 132.0034.

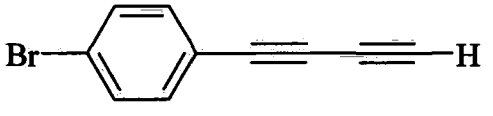
4-Bromo-4'-buta-1,3-diynyl-biphenyl, 185



185

Compound **135** (218 mg, 0.64 mmol), NaOH (100 mg) and toluene (25 mL) afforded **185** as a dark brown solid, which darkened considerably before purification by column chromatography (silica). After isolation from column, and upon further drying, compound turned black, hence it was not characterised further.

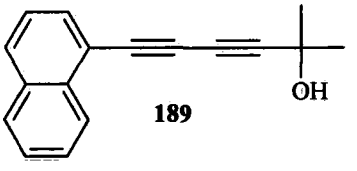
1-Bromo-4-buta-1,3-diynyl-benzene, 186



186

Compound **177** (260 mg, 0.98 mmol), NaOH (130 mg) and toluene (25 mL) afforded **186** as a dark brown solid, which darkened considerably before purification by column chromatography (silica, DCM:hexane, 50:50 v/v). After purification the product turned black, hence further characterisation was not attempted.

2-Methyl-6-naphthalen-1-yl-hexa-3,5-diyn-2-ol, 189



189

Iodonaphthalene **188** (500 mg, 1.97 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (320 mg, 2.96 mmol), $Pd(PPh_3)_2Cl_2$ (70 mg, 5% by mol of **188**), CuI (20 mg,

5% by mol of **188**) and triethylamine (50 mL). Column chromatography (silica, DCM) and recystallisation from hexane afforded **189** as a white solid (165mg, 36%): mp 65.0-66.1 °C;

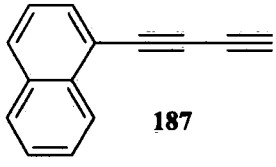
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.30 (d, J = 8.4 Hz, Ar-H, 1H), 7.86 (dd, J = 8 Hz, J = 2.8 Hz, Ar-H, 2H), 7.73 (dd, J = 6.7 Hz, J = 0.8 Hz, 1H), 7.61-7.51 (m, Ar-H, 2H), 7.44-7.40 (m, Ar-H, 1H), 1.98 (s, OH, 1H), 1.63 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.1, 133.2, 132.2, 129.9, 128.6, 127.4, 126.8, 126.2, 125.3, 119.4, 87.7, 77.0, 77.3, 67.4, 66.0, 31.3;

MALDI-TOF *m/z* 235.1 (M^+);

Anal. Calcd. for $C_{17}H_{14}O$: C, 87.15; H, 6.02. Found: C, 86.90; H, 5.94.

1-Buta-1,3-diynyl-naphthalene, 187



187

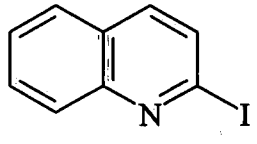
Compound **189** (100 mg, 0.427 mmol), NaOH (50 mg) and toluene (15 mL) afforded **187** as a brown oil (46 mg, 0.26 mmol, 61%). The compound was purified by column chromatography (silica, DCM eluent):

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.23 (d, J = 8 Hz, Ar-H, 1H), 7.78 (t, J = 8 Hz, Ar-H, 2H), 7.70-7.68 (m, Ar-H, 1H), 7.53-7.43 (m, Ar-H, 2H), 7.45-7.43 (m, Ar-H, 1H), 2.63 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.2, 133.2, 132.6, 130.2, 128.6, 127.5, 126.9, 126.1, 125.3, 118.8, 78.2, 73.9, 72.5, 68.3;

GC-MS (EI) *m/z* 176.1 (M^+).

2-Iodoquinoline, 191. [129]

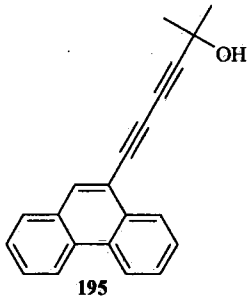


191

2-chloroquinoline **192** (1.00 g, 6.10 mmol), chlorotrimethylsilane (0.77 mL 6.10 mmol), sodium iodide (1.83 g, 12.0 mmol) and propionitrile (10 mL) were heated to reflux and stirred for 20 h. The reaction mixture was poured into solution of NaOH (2.0 M, 10 mL) and ice (10 g) and the aqueous phase extracted with ether (3 x 20 mL). The combined organic phases were washed with water (2 x 20 mL) and brine (1 x 20 mL) and dried over $MgSO_4$. Filtration and solvent evaporation afforded a brown solid, recrystallisation from hexanes gave **191**

as a yellow solid (442 mg, ca. 30%). This compound was impure as judged by ^{1}H and ^{13}C NMR spectra.

2-Methyl-6-phenanthren-9-yl-hexa-3,5-diyn-2-ol, 195



195

Iodophenanthrene **194** (500 mg, 1.64 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (266 mg, 2.46 mmol), $Pd(PPh_3)_2Cl_2$ (58 mg 5% by mol), CuI (16 mg, 5% by mol) in anhydrous triethylamine (50 mL). Column chromatography (silica, DCM) afforded **195** as a cream solid (289 mg, 62% yield): mp 106.1-107.3 °C;

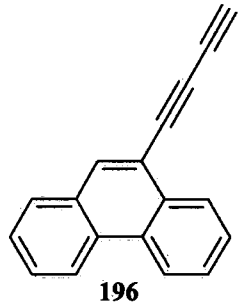
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.66-8.60 (m, Ar-H, 2H), 8.41-8.37 (m, Ar-H, 1H), 8.05 (s, Ar-H, 1H), 7.83-7.80 (m, Ar-H, 1H), 7.70-7.64 (m, Ar-H, 3H), 7.60-7.56 (m, Ar-H, 1H), 2.27 (s, OH, 1H), 1.66 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.1, 131.3, 131.0, 130.7, 130.1, 128.8, 128.2, 127.41, 127.38, 127.2, 126.9, 122.9, 122.7, 118.2, 87.7, 77.6, 67.5, 66.0, 31.1;

MS-MALDI-TOF *m/z* 285.4 (M^+);

Anal. Calcd. for $C_{21}H_{16}O$: C, 88.70; H, 5.67. Found: C, 88.25; H, 6.05.

9-Buta-1,3-diynyl-phenanthrene, 196


196

Compound **195** (212 mg, 0.75 mmol), NaOH (106 mg) and toluene (25 mL) afforded **196** as a yellow solid, which quickly turned green (96 mg, 57%). The compound was purified by column chromatography (silica, DCM:hexane, 80:20);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.67 (m, Ar-H, 2H), 8.42-8.39 (m, Ar-H, 1H), 8.10 (s, Ar-H, 1H), 7.85-7.82 (m, Ar-H, 1H), 7.71-7.67 (m, Ar-H, 3H), 7.62-7.58 (m, Ar-H, 1H), 2.64 (s, ≡CH, 1H);

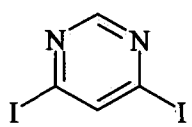
^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.7, 131.3, 130.9, 130.8, 130.1, 128.8, 128.4, 127.51, 127.49, 127.1, 126.8, 123.0, 122.8, 117.7, 77.8, 74.1, 72.3, 68.5;

MS (EI) *m/z* 227.1 (M^+).

V. 2. 2 Experimental Details for Chapter III

The deprotections, to afford bis-deprotected and mono-deprotected species, are reported in toluene (*Route A*), benzene (*Route B*) and THF where appropriate.

4,6-Diiodopyrimidine, 212. [133]



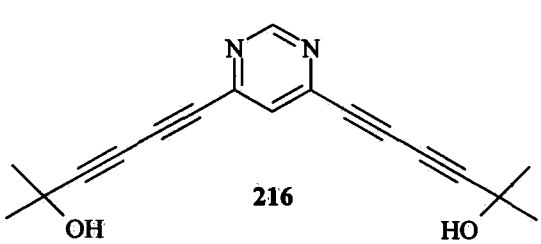
212

A mixture of 4,6-dichloropyrimidine **215** (2.50 g, 16.7 mmol) in 48% aqueous HI (33 mL) was stirred at 25 °C for 72 h in the dark to afford a yellow precipitate. The mixture was filtered and the solid added to a mixture of 10% aq. potassium carbonate (30 mL) and 10% aq. sodium thiosulfate (2 mL). The mixture was extracted with chloroform and the solvent was removed by reduced pressure. Recrystallisation from hexane afforded a light yellow solid of **212** (4.15 g, 75 %): mp 107.3-108.4 °C (lit. mp 107.5-108.5 °C);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.55 (s, Ar-H, 1H), 8.27 (s, Ar-H, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 161.2, 138.4, 132.1.

6-[6-(5-Hydroxy-5-methyl-hexa-1,3-diynyl)-pyrimidin-4-yl]-2-methyl-hexa-3,5-diyn-2-ol, 216



216

4,6-Diiodopyrimidine **212** (650 mg, 1.97 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (640 mg, 5.92 mmol), $Pd(PPh_3)_2Cl_2$ (138 mg), CuI (40 mg), triethylamine (50 mL) at room temperature for 18 h gave **216** as a yellow solid (422 mg, 76%) after column chromatography (silica, DCM:Et_2O, 90:10 v/v) and recrystallisation from toluene: mp 158.1-158.7 °C;

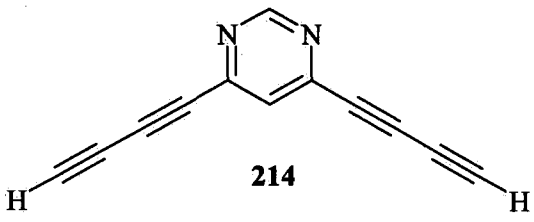
^{1}H NMR ($CDCl_3$, 400 MHz): δ 9.15 (d, J = 1.2 Hz, Ar-H, 1H), 7.52 (d, J = 1.2 Hz, Ar-H, 1H), 2.22 (s, OH, 2H), 1.59 (s, $(CH_3)_2$, 12H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 159.5, 150.2, 127.1, 91.2, 78.9, 74.7, 69.9, 66.0, 31.1;

MS (ES+) *m/z* 293.3 (M^+);

Anal. Calcd. for $C_{18}H_{16}N_2O_2$: C, 73.96; H, 5.52. Found: C, 73.93; H, 5.49.

4,6-Di-(buta-1,3-diynyl)-pyrimidine, 214



214

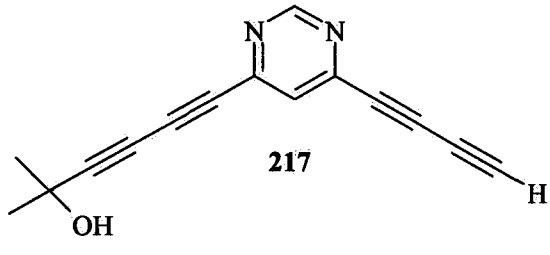
Route A; Compound **216** (100 mg, 0.34 mmol), NaOH (50 mg) and toluene (10 mL) afforded **214** as a white solid (13 mg, 22%). *Route B*; Compound **216** (100 mg, 0.34 mmol), NaOH (50 mg) and benzene (10 mL) afforded **214** as a white solid (12 mg, 20%). The compound was purified by column chromatography (silica, DCM:Et_2O, 90:10 v/v) which separated **214** from **217** and **216**;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 9.15 (d, J = 1.2 Hz, Ar-H, 1H), 7.53 (d, J = 1.2 Hz, Ar-H, 1H), 2.67 (s, ≡CH, 2H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 159.5, 149.8, 127.5, 78.8, 75.5, 71.1, 67.0;

MS (DSQ) *m/z* 176.0 (M^+).

6-(6-Buta-1,3-diynyl-pyridin-4-yl)-2-methyl-hexa-3,5-diyn-2-ol, 217



217

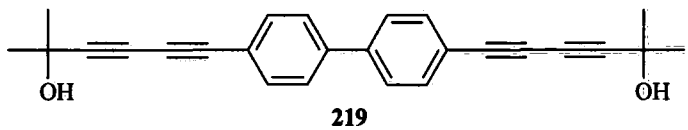
Compound **216** (100 mg, 0.342 mmol), NaOH (50 mg) and toluene (15 mL) afforded **217** as a white solid (12 mg, 15%). The compound was purified by column chromatography (silica, DCM:Et_2O, 90:20 v/v) which separated **217** from **214** and **216**;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 9.13 (d, J = 1.2 Hz, Ar-H, 1H), 7.49 (d, J = 1.2 Hz, Ar-H, 1H), 2.67 (s, ≡CH, 1H), 2.19 (s, OH, 1H), 1.59 (s, C-$(CH_3)_2$), 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 159.4, 150.2, 149.6, 127.3, 91.2, 79.0, 78.6, 75.4, 74.5, 71.1, 70.0, 66.1, 65.9, 31.0;

MS-MALDI-TOF *m/z* 235.2 (M^+).

6-[4'-(5-Hydroxy-5-methyl-hexa-1,3-diynyl)-2,5-dimethoxy-biphenyl]-2-methyl-hexa-3,5-diyn-2-ol, 219



219

4',4-Diiodobiphenyl **218** (300 mg, 0.74 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (245 mg, 2.22 mmol), $Pd(PPh_3)_2Cl_2$ (52 mg), CuI (14 mg), triethylamine (50 mL) at room temperature for 18 h and heating at 50 °C for 2 h afforded **219** as a yellow solid (185 mg, 64%) after column chromatography (silica, DCM:Et_2O, 80:20 v/v): mp *ca.* 150 °C (decomp.).

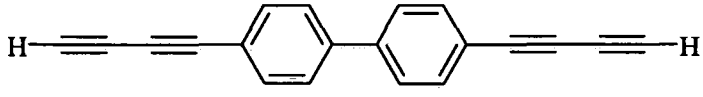
^1H NMR ($CDCl_3$, 400 MHz): δ 7.57-7.52 (m, Ar-H, 8H), 1.98 (s, OH, 2H), 1.59 (s, $(CH_3)_2$, 12H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 141.3, 133.1, 127.0, 121.1, 82.6, 67.4, 65.7, 64.1, 61.1, 31.1;

MS-EI *m/z* 367.2 (M^+);

Anal. Calcd for $C_{26}H_{22}O_2$: C, 85.22; H, 6.05. Found: C, 84.70; H, 6.05.

4-4'-Di-(buta-1,3-diynyl)-biphenyl, 220



220

Route A; Compound **219** (90 mg, 0.25 mmol), NaOH (45 mg) and toluene (12 mL) afforded **220** as a yellow solid (40 mg, 65%).

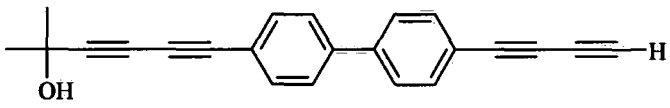
Route B; Compound **219** (100 mg, 0.27 mmol), NaOH (50 mg) and benzene (10 mL) afforded **220** as a yellow solid (32 mg, 47%). The compound was purified by column chromatography (silica, DCM eluent) which separated **220** from **221** and **219**;

^1H NMR ($CDCl_3$, 400 MHz): δ 7.61-7.58 (m, Ar-H, 4H), 7.56-7.54 (m, Ar-H, 4H), 2.52 (s, ≡CH, 2H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 141.2, 133.6, 127.3, 120.8, 75.2, 74.8, 72.1, 68.3;

MS-MALDI-TOF *m/z* 251.1 (M^+).

6-(4'-Buta-1,3-diynyl-biphenyl-4-yl)-2-methyl-hexa-3,5-diyn-2-ol, 221



221

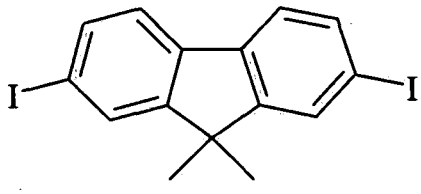
Compound **219** (90 mg, 0.25 mmol), NaOH (45 mg) and toluene (12 mL) afforded **221** as a yellow solid (23 mg, 0.07 mmol, 30%). The compound was purified by column chromatography (silica, DCM eluent) which separated **221** from **220** and **219**;

^{1}H NMR ($CDCl_3$, 500 MHz): δ 7.61-7.55 (m, Ar-H, 8H), 2.54 (s, ≡CH, 0.8H), 2.00 (s, OH, 0.8H), 1.61 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 125 MHz): δ 141.16, 140.8, 133.5, 133.2, 127.2, 121.2, 120.6, 87.4, 78.6, 75.2, 74.6, 74.3, 72.0, 68.2, 67.2, 65.9, 31.3;

MALDI-TOF *m/z* 309.1 (M^+).

2,7-Diiodo-9,9-dimethyl-9*H*-fluorene, 222



222

In a three-necked flask purged with argon and fitted with thermometer, 2,7-diiodofluorene **223** (1.00 g, 2.39 mmol) was dissolved in anhydrous THF (40 mL) under argon. The reaction mixture was cooled to 0 °C and *t*-BuOK (1M in 2-methyl-2-propanol, 3 mL, 3 mmol) slowly added to afford a deep red solution. MeI (0.19 mL, 3 mmol) was added dropwise and the reaction was stirred at 25 °C for 1 h then cooled to 0 °C and *t*-BuOK (1 M in 2-methyl-2-propanol, 3 mL, 3 mmol) and MeI (0.19 mL, 3 mmol) were added and the reaction stirred overnight at 25 °C to afford a yellow precipitate. Filtration through celite, followed by solvent removal by reduced pressure afforded **222** as a yellow solid after recrystallisation from methanol (502 mg, 47%);

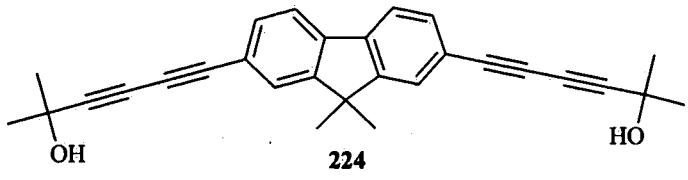
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.75 (d, J = 1.5 Hz, 2H), 7.67 (dd, J = 8.0 Hz, J = 1.5 Hz, 2H), 7.44 (d, J = 8.0 Hz, 2H), 1.46 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.2, 137.8, 136.2, 132.1, 121.8, 93.1, 47.2, 26.8.

MS (EI) *m/z* 447.2 (M^+);

Anal. Calcd for $C_{15}H_{12}I_2$: C, 40.39; H, 2.71. Found: C, 39.90; H, 2.64.

6-[7-(5-Hydroxy-5-methyl-hexa-1,3-diynyl)-9,9-dimethyl-9*H*-fluoren-2-yl]-2-methyl-hexa-3,5-diyn-2-ol, 224



224

2,7-Diiodo-9,9-dimethyl-9*H*-fluorene **222** (705 mg, 1.57 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (514 mg, 4.70 mmol), $Pd(PPh_3)_2Cl_2$ (110 mg), CuI (30 mg), triethylamine (70 mL) at room temperature for 18 h and heating at 50 °C for 1 h afforded **224** as a yellow crystalline solid (602 mg, 93%) after column chromatography (silica, DCM:Et_2O, 80:20 v/v) and recrystallisation from chloroform-hexane: mp 166.1-166.7 °C;

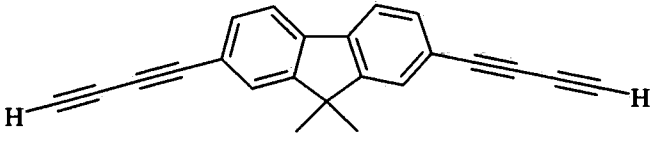
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.64 (d, J = 8 Hz, Ar-H, 2H), 7.56, (d, J = 4 Hz, Ar-H, 2H), 7.47 (dd, J = 8 Hz, J = 4Hz, Ar-H, 2H), 2.13 (s, OH, 2H), 1.60 (s, C-$(CH_3)_2$, 12H), 1.45 (s, Fl-$(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.9, 139.3, 131.8, 126.9, 120.6, 120.5, 87.1, 79.4, 73.7, 67.1, 65.8, 46.9, 31.1, 26.8;

MALDI-TOF *m/z* 407.2 (M^+);

Anal. Calcd for $C_{29}H_{26}O_2$: C, 85.68; H, 6.45; N, 7.87. Found: C, 85.33; H, 6.09; N, 7.51.

2,7-Di(buta-1,3-diynyl)-9,9-dimethyl-9*H*-fluorene, 225



225

Route *A*; Compound **224** (200 mg, 0.50 mmol), NaOH (100 mg) and toluene (15 mL) afforded **225** as a yellow solid (88 mg, 62%).

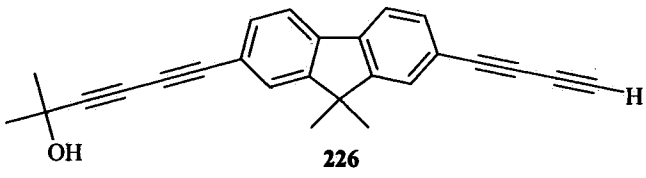
Route B; Compound **224** (100 mg, 0.25 mmol), NaOH (50 mg) and benzene (10 mL) afforded **225** as a yellow solid (47 mg 0.16 mmol, 66%). The compound was purified by column chromatography (silica, DCM eluent) which separated **225** from **226** and **224**;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.58 (d, J = 8 Hz, Ar-H, 2H), 7.51, (d, J = 4 Hz, Ar-H, 2H), 7.44 (dd, J = 8 Hz, J = 4Hz, Ar-H, 2H), 2.45 (s, ≡CH, 2H), 1.39 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 154.0, 1 154.0, 139.5, 132.1, 127.2, 120.6, 120.1, 75.9, 74.0, 71.7, 68.2, 47.0, 26.8;

MALDI-TOF *m/z* 291.1 (M^+).

6-(7-Buta-1,3-diynyl-9,9-dimethyl-9*H*-fluoren-2-yl)-2-methyl-hexa-3,5-diyn-2-ol, 226



226

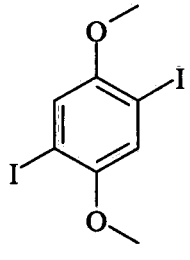
Compound **224** (200 mg, 0.50 mmol), NaOH (100 mg) and toluene (15 mL) afforded **226** as a dark brown oil (64 mg, 37%). The compound was purified by column chromatography (silica, DCM eluent) which separated **226** from **225** and **224**;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.67-7.64 (m, Ar-H, 2H), 7.58-7.55 (m, Ar-H, 2H), 7.52-7.46 (m, Ar-H, 2H), 2.52 (s, ≡CH, 1H), 2.04 (s, OH, 1H), 1.60 (s, $(CH_3)_2$, 6H), 1.45 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 144.0, 139.6, 139.3, 132.1, 131.8, 127.1, 126.9, 120.7, 120.53, 120.49, 120.0, 87.1, 79.4, 76.0, 74.0, 73.8, 71.7, 68.2, 67.1, 65.8, 46.9, 31.1, 26.8;

MS-MALDI-TOF *m/z* 349.2 (M^+).

1,4-Diiodo-2,5-dimethoxybenzene 227 [134]



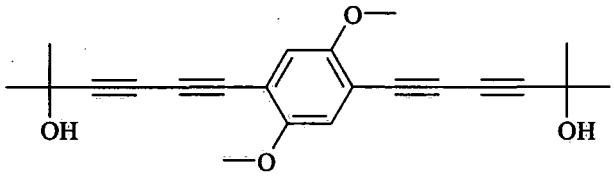
227

To a solution of 1,4-dimethoxybenzene **228** (5.00 g, 36 mmol) in acetic acid:H_2O:H_2SO_4 (90:9:1 v/v, 125 mL), potassium iodate (4.83 g, 22.6 mmol) and iodine (10.29 g, 40 mmol) were added and the reaction mixture stirred at reflux overnight. The reaction mixture was cooled, filtered and the product washed with acetic acid (3 x 50 mL) and water (3 x 50 mL). **227** was obtained as pale yellow crystals (10.78 g, 77 %): mp 172.3 – 173.2 °C (lit. = 171 °C);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.19 (s, Ar-H, 2H), 3.83 (s, $(O\text{-}CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.5, 121.8, 85.6, 57.4.

6-[4-(5-Hydroxy-5-methyl-hexa-1,3-diynyl)-2,5-dimethoxyphenyl]-2-methyl-hexa-3,5-diyn-2-ol, 229



229

1,4-Diiodo-2,5-dimethoxy-benzene **227** (500 mg, 1.28 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (350 mg, 3.21 mmol), $Pd(PPh_3)_2Cl_2$ (90 mg), CuI (25 mg), Et_3N:THF (50 mL, 95:5 v/v) at room temperature for 18 h and heating at 50 °C for 1 h afforded **229** as a yellow solid (292 mg, 64%) after column chromatography (silica, DCM:Et_2O, 50:50 v/v) and recrystallisation from cyclohexane: mp 163.0-163.8 °C;

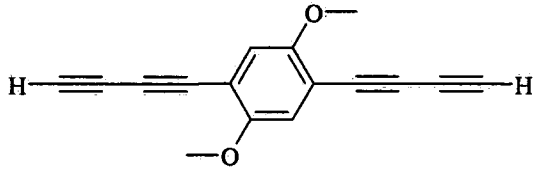
^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.92 (s, Ar-H, 2H), 2.00 (s, OH, 2H), 1.57 (s, $(CH_3)_2$, 12H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.3, 116.2, 112.8, 88.7, 79.0, 74.8, 67.1, 65.8, 56.4, 31.1;

MALDI-TOF *m/z* 351.3 (M^+);

Anal. Calcd. for $C_{22}H_{22}O_4$: C, 75.41; H, 6.33. Found: C, 75.27; H, 6.79.

1,4-Di(buta-1,3-diynyl)-2,5-dimethoxbenzene, 230



230

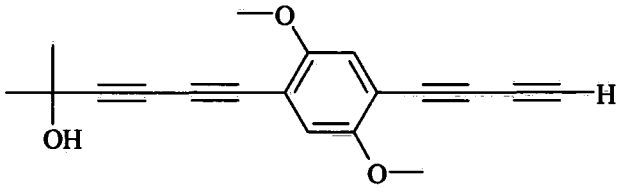
Route A; Compound **229** (175 mg, 0.48 mmol), NaOH (90 mg) and toluene (20 mL) afforded **230** as a yellow solid (27 mg, 24%). *Route B*; Compound **229** (100 mg, 0.29 mmol), NaOH (50 mg) and benzene (10 mL) afforded **230** as a yellow solid (43 mg, 64%). The compound was purified by column chromatography (silica, DCM eluent) which separated **230** from **231** and **229**;

^{1}H NMR ($CDCl_3$, 500 MHz): δ 6.95 (s, Ar-H, 2H), 3.83 (s, $(O\text{-}CH_3)_2$, 6H), 2.61 (s, ≡CH, 2H);

^{13}C NMR ($CDCl_3$, 125 MHz): δ 155.8, 116.6, 112.7, 79.6, 73.5, 71.5, 68.3, 56.6;

MS-MALDI-TOF *m/z* 235.1 (M^+).

6-(4-Buta-1,3-diynyl-2,5-dimethoxyphenyl)-2-methyl-hexa-3,5-diyn-2-ol, 231



231

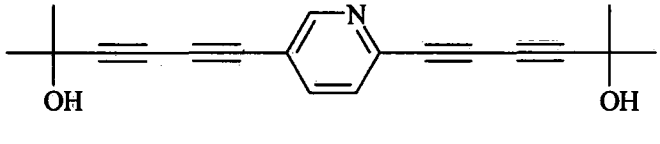
Route A; Compound **229** (170 mg, 0.48 mmol), NaOH (90 mg) and toluene (20 mL) afforded **231** as yellow solid (72 mg, 52%). *Route B*; Compound **229** (300 mg, 0.86 mmol), NaOH (150 mg) and toluene:benzene (20 mL, 50:50 v/v) afforded **231** as a yellow solid (154 mg, 62%). The compound was purified by column chromatography (silica, DCM), which separated **231** from **230** and **229**. The single crystal (colourless) used for X-ray structural analysis was obtained by slow evaporation from deuterated chloroform;

^{1}H NMR ($CDCl_3$, 500 MHz): δ 6.95 (s, Ar-H, 1H), 6.93 (s, Ar-H, 1H), 3.83 (s, (O-CH_3)$_2$, 6H), 2.61 (s, ≡CH, 1H), 1.99 (s, OH, 1H), 1.58 (s, C-(CH_3)$_2$, 6H);

^{13}C NMR ($CDCl_3$, 125 MHz): δ 155.8, 155.4, 116.5, 116.4, 113.3, 112.3, 88.9, 79.5, 79.4, 74.9, 73.5, 68.3, 67.3, 66.0, 56.6, 31.3;

MS-MALDI-TOF *m/z* 293.1 (M^+).

6-[6-(5-Hydroxy-5-methyl-hexa-1,3-diynyl)-pyridin-3-yl]-2-methyl-hexa-3,5-diyn-2-ol, 233



233

2,5-Diiodopyridine **232** (500 mg, 1.51 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (410 mg, 3.77 mmol), $Pd(PPh_3)_2Cl_2$ (106 mg), CuI (30 mg), triethylamine-THF (50 mL, 95:5 v/v) at room temperature for 18 h and heating at 50 °C for 1 h afforded **233** as a yellow solid (263 mg, 60%) after column chromatography (silica, dichloromethane-diethyl ether, 50:50 v/v) and recrystallisation from cyclohexane: mp 191.0-191.4 °C;

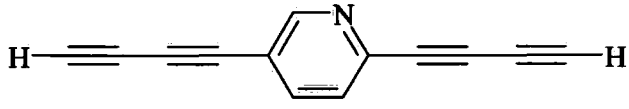
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.67-8.66 (m, Ar-H, 1H), 7.71 (dd, J = 8.0 Hz, J = 4.0 Hz, Ar-H, 1H), 7.43 (dd, J = 8.0 Hz, J = 4.0 Hz, Ar-H, 1H), 2.07 (s, OH, 1H), 2.02 (s, OH, 1H), 1.60 (s, C-(CH_3)$_2$, 6H), 1.59 (s, C-(CH_3)$_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.7, 141.6, 139.4, 127.4, 119.0, 89.5, 89.4, 79.0, 77.3, 75.8, 75.1, 66.8, 66.7, 65.9, 31.22, 31.19;

MS-(ES+) *m/z* 292.2 (M^+);

Anal. Calcd for $C_{19}H_{17}NO_2$: C, 78.33; H, 5.88. Found: C, 78.35; H, 5.88.

2,5-Di(buta-1,3-diynyl)-pyridine, 234



234

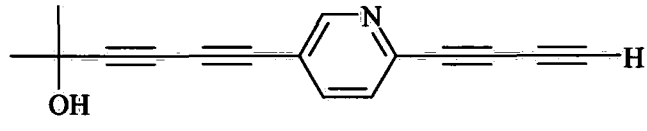
Route A; Compound **233** (150 mg, 0.515 mmol), NaOH (100 mg) and toluene (15 mL) afforded **234** as a white solid (24 mg, 27%). *Route B*; Compound **233** (80 mg, 0.27 mmol), NaOH (40 mg) and THF (8 mL) afforded **234** as a white solid (24 mg, 50%). The compound was purified by column chromatography (silica, DCM), which separated **234** from **235** and **233**. The single crystal (colourless) used for X-ray structural analysis was obtained by slow evaporation of a dichloromethane-ether mixture;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.71-8.70 (m, Ar-H, 1H), 7.77 (dd, *J* = 8.0 Hz, *J* = 2.0 Hz, Ar-H, 1H), 7.48 dd, *J* = 8.0 Hz, *J* = 2.0 Hz, Ar-H, 1H), 2.62 (s, CH, 1H), 2.60 (s, ≡CH, 1H);

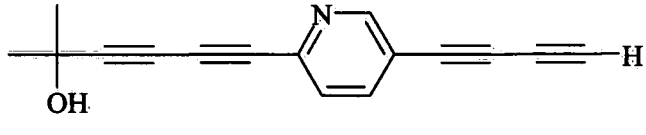
^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.7, 141.0, 139.7, 127.5, 118.6, 79.1, 75.7, 73.8, 73.7, 73.4, 71.3, 67.42, 67.37;

MS-MALDI-TOF *m/z* 176.1 (M^+).

6-(6-Buta-1,3-diynyl-pyridin-3-yl)-2-methyl-hexa-3,5-diyn-2-ol, 235a and 6-(5-Buta-1,3-diynyl-pyridin-2-yl)-2-methyl-hexa-3,5-diyn-2-ol 235b



235a



235b

Compound **233** (150 mg, 0.515 mmol), NaOH (100 mg) and toluene (15 mL) afforded a mixture of isomers **235a** and **235b** as a white solid (26 mg, 20%). The mixture was purified by column chromatography (silica, DCM), which separated **235a** and

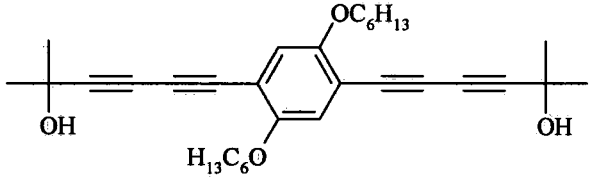
235b from **234** and **233**. The single crystal (colourless) of **235a** used for X-ray structural analysis grew on storage of a $CDCl_3$ solution. NMR data showed the presence of isomers in a *ca* 2:1 ratio. We could not assign the peaks to the specific isomers.

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.61 (m, Ar-H, 1.40H), 7.61 (m, Ar-H, 1.49H), 7.37 (m, Ar-H, 1.44H), 2.55 (s, ≡CH, 0.50H), 2.52 (s, ≡CH, 0.88H), 2.37 (s, OH, 0.88H), 2.18 (s, OH, 0.46H), 1.52 (s, C-$(CH_3)_2$, 8.8H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 153.6, 153.5, 141.5, 140.6, 139.6, 139.4, 127.5, 127.2, 119.2, 118.2, 89.5, 89.3, 78.9, 78.8, 77.2, 75.8, 75.6, 74.6, 73.7, 73.6, 73.4, 71.4, 67.44, 67.41, 66.5, 66.4, 65.68, 65,66;

MS-MALDI-TOF *m/z* 234.1 (M^+).

6-[2,5-Bis-hexyloxy-4-(5-hydroxy-5-methyl-hexa-1,3-diynyl)-phenyl]-2-methyl-hexa-3,5-diyn-2-ol, 140



140

1,4-Bis-hexyloxy-2,5-diiodo-benzene, **139** (800 mg, 1.51 mmol), 2-methyl-3,5-hexadiyn-2-ol **127** (489 mg, 4.52 mmol), $Pd(PPh_3)_2Cl_2$ (106 mg), CuI (30 mg), triethylamine (60 mL,) at room temperature for 18 h and heating at 45 °C for 1 h afforded **140** as a yellow solid (731 mg, 98%) after column chromatography (silica, DCM:Et_2O, 95:5 v/v) and recrystallisation from hexane: mp 123.5-124.6 °C;

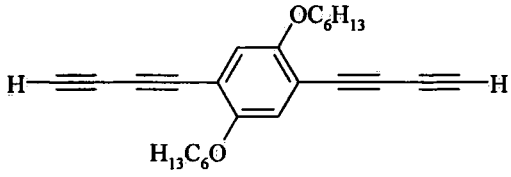
^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.89 (s, Ar-H, 2H), 3.93 (t, J = 6.8 Hz, O-$(CH_2)_2$, 4H), 2.00 (s, OH, 2H), 1.82-1.75 (m, $(CH_2)_2$, 4H), 1.58 (s, $(CH_3)_4$, 12H), 1.48-1.42 (m, $(CH_2)_2$, 4H), 1.38-1.32 (m, $(CH_2)_4$, 8H), 0.93-0.90 (m, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.3, 117.9, 113.8, 88.4, 79.0, 75.1, 71.8, 68.4, 31.6, 31.2, 29.1, 25.7, 22.7, 14.17, 14.15;

Anal. Calcd for $C_{32}H_{42}O_4$: C, 78.33; H, 8.63. Found: C, 78.30; H, 8.63;

MS (EI) *m/z* 491.3 (M^+).

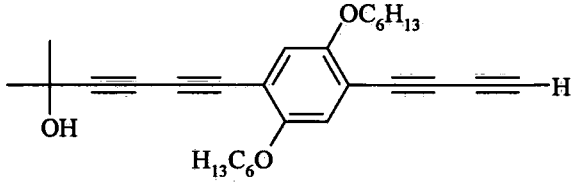
1,4-Di-buta-1,3-diynyl-2,5-bis-hexyloxy-benzene, 236



236

Compound **140** (500 mg, 1.57 mmol), NaOH (250 mg) and toluene (30 mL) afforded **236** as a brown oil. The compound was purified by column chromatography (silica, DCM), which separated **236** from **140** and **237**. Considerable instability was observed for compound **237**, therefore it was decided to keep **236** in the column eluent and analyse by mass spectrometry only. Therefore, a yield and other spectroscopic data are not reported.
MS-MALDI-TOF *m/z* 374.2 (M^+).

6-(4-Buta-1,3-diynyl-2,5-bis-hexyloxy-phenyl)-2-methyl-hexa-3,5-diyn-2-ol, 237

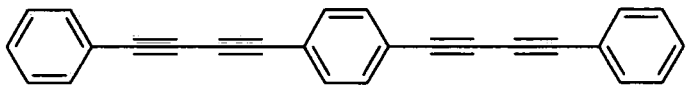


237

Compound **140** (500 mg, 1.57 mmol), NaOH (250 mg) and toluene (30 mL) afforded **237** as a brown oil (68 mg 31%). The compound was purified by column chromatography (silica, DCM), which separated **237** from **236** and **140**;
^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.92 (s, Ar-H, 1H), 6.90 (s, Ar-H, 1H), 3.96-3.91 (m, $(OCH_2)_2$, 4H), 2.58 (s, ≡CH, 1H), 2.02 (s, OH, 1H), 1.82-1.75 (m, $(CH_2)_2$, 4H), 1.57 (s, $(CH_3)_2$, 6H), 1.50-1.42 (m, Ar-H, 4H), 1.37-1.32 (m, $(CH_2)_4$, 8H) 0.93-0.89 (m, $(CH_3)_2$, 6H);
^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.3, 154.9, 117.9, 117.8, 113.8, 112.8, 88.4, 79.1, 79.0, 75.1, 72.9, 71.8, 69.9, 68.4, 67.3, 65.9, 31.6, 31.2, 29.1, 25.7, 22.7, 14.17, 14.15;
MS (MALDI-TOF) *m/z* 261.2 (M^+).

V. 2. 3 Experimental Details for Chapter IV

1,4-Bis-(4-phenyl-buta-1,3-diynyl)-benzene, 238[136]



238

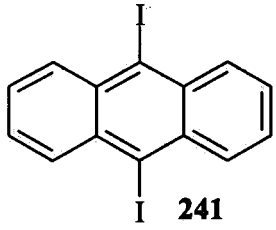
1-(Buta-1,3-diynyl)benzene, **70** (105 mg, 0.83 mmol) and 1,4-diiodobenzene **240** (109 mg, 0.33 mmol) were dissolved in triethylamine (40 mL) and thoroughly degassed with argon. $Pd(PPh_3)_4$ (39 mg, 10% by mol of **240**) and CuI (7 mg, 10% by mol of **240**) were added in one portion and the reaction stirred at room temperature for 4 h, followed by heating at 45 °C for 18 h. Solvent was removed by reduced pressure and to the remaining residue ethanol was added, heated to boiling point, cooled and filtered. The solid was recrystallised from chloroform to afford silver-white crystals of **238** (32 mg, 30%): mp 262.9-263.3 °C

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.54-7.52 (m, Ar-H, 4H), 7.49 (s, Ar-H, 4H), 7.37-7.35 (m, Ar-H, 5H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 132.7, 132.6, 129.5, 128.7, 122.9, 121.9, 83.2, 81.1, 76.8, 74.0.

MALDI-TOF *m/z* 327.1 (M^+).

9,10-Diiodoanthracene, 241[138]



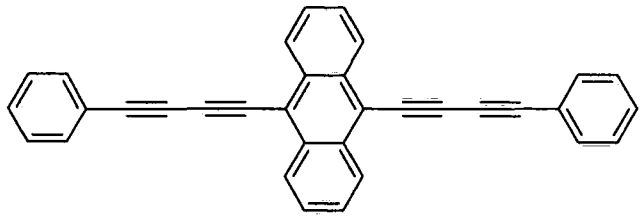
241

9,10-Dibromoanthracene **242** (2.00 g, 5.95 mmol) and anhydrous diethyl ether (20 mL) were stirred under argon to afford a yellow slurry. The reaction mixture was cooled to -78 °C, to which *n*-BuLi (6.0 mL, 2.6 M in hexanes) was added dropwise over 30 min. The reaction was warmed to room temperature and stirred for a further 1 h. Iodine (5.00 g, 39.4 mmol) was added gradually and the mixture was left to stir for 18 h at 25 °C under argon then filtered and the solids washed with $Na_2S_2O_3$ (aq. saturated solution, 3 x 50 mL) and water (3 x 50 mL). Recrystallisation from $CHCl_3$ afforded **241** as a bright yellow solid (895 mg, 35 %): mp 240.7-241.9 °C (lit. = 254 °C);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.58-8.52 (m, Ar-H, 4H), 7.63-7.58 (m, Ar-H, 4H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.6, 134.2, 128.1, 127.6, 108.9.

9,10-Bis-(4-phenyl-buta-1,3-diynyl)-anthracene, 239[137]



239

1-(Buta-1,3-diynyl)benzene, **70** (136 mg, 1.08 mmol) and 9,10-diiodoanthracene, **241** (154 mg, 0.40 mmol) were dissolved in triethylamine (50 mL) and thoroughly degassed with argon. $Pd(PPh_3)_4$ (46 mg, 10% by mol of **241**) and CuI (7 mg, 10% by mol of **241**) were added in one portion and the reaction stirred at room temperature overnight. Triethylamine was removed by reduced pressure and to the remaining residue ethanol was added, boiled, cooled and filtered. The solid was further recrystallised from $CHCl_3$ to afford orange crystals of **239** (90 mg, 54 %). The single crystal grown for X-ray analysis was grown from a hot solution in $CHCl_3$, which was cooled slowly: mp decomp. at *ca.* 260 °C;

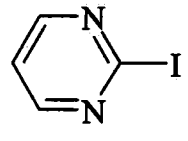
^1H NMR ($CDCl_3$, 400 MHz): δ 8.63–8.61 (m, Ar-H, 4H), 7.67-7.62 (m, Ar-H, 8H), 7.42-7.40 (m, Ar-H, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz, 50 °C): δ 133.6, 132.8, 129.6, 128.7, 127.7, 127.4, 122.1, 118.2, 87.3, 86.0, 78.9, 74.5;

MALDI-TOF $m/z = 427$ (M^+);

Anal. calcd. for $C_{34}H_{18}$: C, 95.75; H, 4.25. Found: C, 94.89; H, 4.25.

2-iodopyrimidine, 243[145]



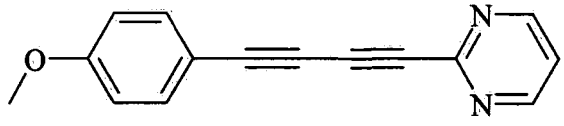
243

Aqueous hydroiodic acid (47%, 20 mL) was cooled to 0 °C, to which 2-chloropyrimidine **244** (5.00 g, 44 mmol) was added and the reaction stirred at 0 °C for 50 min. A saturated solution of K_2CO_3 (25 mL) was added in one portion to neutralise the mixture, followed by a saturated solution of sodium sulphite (25 mL). The aqueous layer was extracted with ether (5 x 50 mL), the combined organics dried over $MgSO_4$, filtered and ether removed. Recrystallisation from petroleum ether (bp. 40-60 °C) afforded **243** as a white solid (5.71 g, 27 mmol, 63 %): mp 31.2-31.7 °C (lit. = 32 °C);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.55 (d, J = 0.8 Hz, Ar-H, 2H), 8.27 (d, J = 0.8 Hz, Ar-H, 2H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 157.9, 143.1, 128.7.

2-[4-(4-Methoxyphenyl)-buta-1,3-diynyl]-pyrimidine 245.



245

2-Iodopyrimidine **243** (229 mg, 1.12 mmol), 1-buta-1,3-diynyl-4-methoxy-benzene **118** (116 mg, 0.74 mmol), $Pd(PPh_3)_2Cl_2$ (20 mg) and CuI (3 mg) were reacted in anhydrous triethylamine (30 mL). Column chromatography (silica, DCM:Et_2O 90:10 v/v) afforded **245** as a pale yellow solid (107 mg, 62%): mp 164.6-165.9 °C;

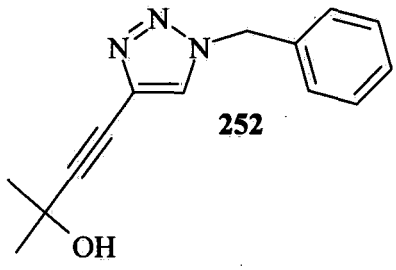
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.72 (d, J = 4.8 Hz, ArH, 2H), 7.50 (d, J = 8 Hz, ArH, 2H), 7.25-7.24 (m, ArH, 1H,), 6.88-6.85 (m, ArH, 2H), 3.84 (s, O-CH_3, 3H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 168.2, 158.5, 152.7, 134.6, 120.1, 114.3, 112.8, 83.5, 78.9, 73.0, 72.3, 55.4;

MS (EI) *m/z* 235.0 (M^+);

Anal. calcd. for $C_{15}H_{10}N_2O$: C, 76.91; H, 4.30; N, 11.96. Found: C, 76.49; H, 4.25; N, 11.71.

4-(1-Benzyl-1*H*-[1,2,3]triazol-4-yl)-2-methyl-but-3-yn-2-ol 252,



252

Benzyl azide **251** (0.94 mL, 7.40 mmol) and 2-methyl-3,5-hexadiyn-2-ol **127** (800 mg, 7.40 mmol) were dissolved in *t*-BuOH (20 mL), to which water (30 mL) was added and the reaction mixture was stirred. $CuSO_4.5H_2O$ (92 mg, 5%) and sodium ascorbate (146 mg, 10%) were added and the reaction stirred at 25 °C for 8 h (followed by TLC) to afford a green solution. The organic layer was separated and washed with a saturated EDTA solution (3 x 30 mL) and the combined organic phase dried over $MgSO_4$, filtered and solvent removed. Purification by column chromatography (silica, DCM, followed by gradual addition of Et_2O) afforded **252** as a white solid (1.21 g, 68%): mp 91.4 – 92.3 °C;

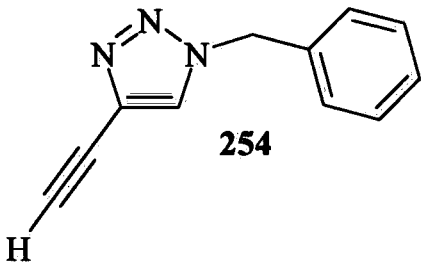
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.50 (s, Ar-H, 1H), 7.36-7.32 (m, Ar-H, 3H), 7.24-7.21 (m, Ar-H, 2H), 5.48 (s, CH_2, 2H), 2.91 (s, OH, 1H), 1.57 (s, $(CH_3)_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.2, 131.0, 129.3, 129.0, 128.2, 126.0, 97.6, 71.6, 66.4, 65.5, 54.4, 31.2;

Anal. calcd. for $C_{14}H_{15}N_3O$: C, 69.69; H, 6.27; N, 17.41. Found: C, 69.56; H, 6.21; N, 17.23;

MS (EI) *m/z* 241.0 (M^+).

1-Benzyl-4-ethynyl-1*H*-[1,2,3]triazole, 254



254

Compound **252** (100 mg, 0.41 mmol) and NaOH (50 mg) were dissolved in anhydrous toluene (25 mL) under argon. The reaction was refluxed and carefully monitored by TLC. After 2 h toluene was removed and the remaining crude residue was purified by column chromatography (silica, DCM, DCM:Et_2O, 95:5, v/v) to afford **254** as a white crystalline solid (53 mg, 75%): mp 78.0-79.1 °C;

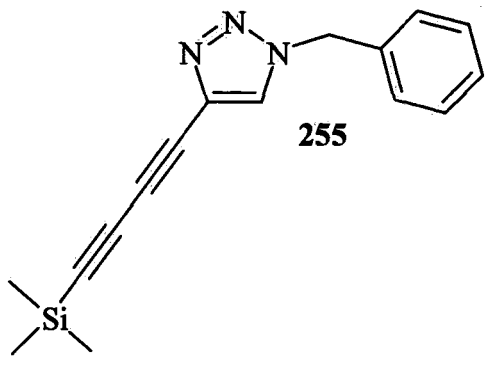
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.60 (s, Ar-H, 1H), 7.40-7.36 (m, Ar-H, 3H), 7.29-7.26 (m, Ar-H, 2H), 5.53 (s, CH_2, 2H), 3.22 (s, ≡CH, 1H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 134.1, 130.5, 129.3, 129.1, 128.3, 126.7, 81.2, 73.2, 54.4;

MS (EI) *m/z* 183.0 (M^+).

Anal. calcd. for $C_{11}H_9N_3$: C, 72.11; H, 4.95; N, 22.93. Found: C, 71.98; H, 4.75; N, 23.27;

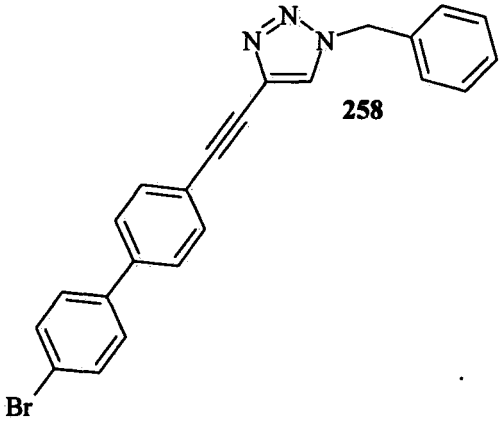
Attempted preparation of 1-benzyl-4-(4-trimethylsilanyl-buta-1,3-diynyl)-1*H*-[1,2,3]triazole, 255



255

254 (363 mg, 1.98 mmol) and CuI (20 mg, 5% by mol) were dissolved in THF:Et_3N (50 mL, 1:1 v/v) under argon. I-TMSA **253** (670 mg, 2.97 mmol) and $Pd(PPh_3)_2Cl_2$ (70 mg, 5% by mol) was added and the reaction tightly stoppered and stirred at room temperature for 18 h. The solvent was removed from the reaction mixture and the crude residue purified by column chromatography (silica, DCM, DCM:Et_2O, 95:5, v/v), however no **255** eluted. Starting materials **254** and **253** were recovered.

1-Benzyl-4-(4'-bromobiphenyl-4-ylethynyl)-1*H*-[1,2,3]triazole, 258



258

Compound **192** (350 mg, 1.2 mmol), benzyl azide **251** (0.15 mL, 1.2 mmol), $CuSO_4.5H_2O$ (100 mg) and sodium ascorbate (100 mg) were dissolved in DMF (10 mL) and water (2 mL) and the reaction left to stir for 18 h in a tightly stoppered flask at 25 °C. Water (25 mL) was added and the aqueous layer extracted with ethyl acetate (3 x 30 mL). The combined organic layers were dried over $MgSO_4$, filtered and solvent removed. The crude residue was purified by column chromatography (silica, DCM followed by DCM:Et_2O, 95:5, v/v) to afford **258** as a white solid (348 mg, 72%): mp 202.9 – 203.5 °C;

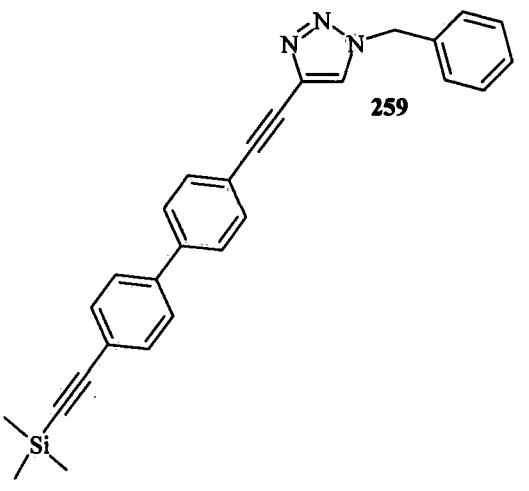
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.63 (s, Ar-H, 1H), 7.60-7.53 (m, Ar-H, 6H), 7.47-7.38 (m, Ar-H, 5H), 7.32-7.30 (m, Ar-H, 2H), 5.57 (s, $(CH_2)_2$, 2H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 140.2, 139.1, 134.1, 132.1, 132.0, 129.2, 129.0, 128.6, 128.23, 126.8, 125.8, 122.0, 121.6, 92.3, 79.4, 54.4;

Anal. calcd. for $C_{23}H_{16}BrN_3$: C, 66.68; H, 3.89; N, 10.14. Found: C, 66.62; H, 3.88; N, 10.25;

MS (ES+) *m/z* 415.2 (M^+).

1-Benzyl-4-(4'-trimethylsilanylethynyl-biphenyl-4-ylethynyl)-1*H*-[1,2,3]triazole, 259



259

Compound **131** (380 mg, 1.26 mmol), benzyl azide **251** (0.16 mL, 1.26 mmol), $CuSO_4.5H_2O$ (100 mg) and sodium ascorbate (100 mg) were dissolved in DMF (12 mL) and water (2 mL) and the reaction left to stir for 18 h in a tightly stoppered flask at 25 °C. Analysis by TLC indicated the reaction had gone to completion. Work-up as for **258**, afforded **259** as a white solid (375 mg, 69%): mp 197.5- 197.9 °C;

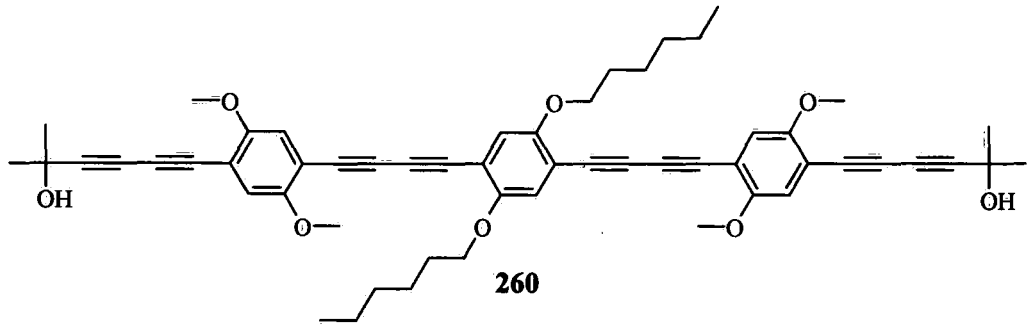
^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.63 (s, Ar-H, 1H), 7.57-7.45 (m, Ar-H, 8H), 7.41-7.39 (m, Ar-H, 3H), 7.32-7.30 (m, Ar-H, 2H), 5.57 (s, CH_2, 2H), 0.26 (s, Si-$(CH_3)_3$, 9H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 140.5, 140.1, 134.1, 132.5, 132.1, 131.4, 129.2, 129.0, 128.2, 126.9, 126.7, 125.8, 122.5, 121.6, 104.8, 95.3, 92.4, 79.4, 54.4, 0.0;

Anal. calcd. for $C_{28}H_{25}SiN_3$: C, 77.92; H, 5.84; N, 9.74. Found: C, 77.75; H, 5.80; N, 9.75.

MS (ES+) *m/z* 432.3 (M^+).

6-{4-[4-(2,5-Bis-hexyloxy-4-{4-[4-(5-hydroxy-5-methyl-hexa-1,3-diynyl)-2,5-dimethoxy-phenyl]-buta-1,3-diynyl}-phenyl)-buta-1,3-diynyl]-2,5-dimethoxy-phenyl}-2-methyl-hexa-3,5-diyn-2-ol, 260

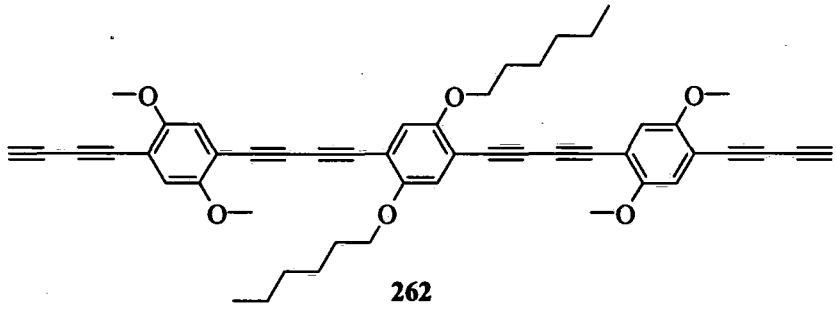


260

Alkyne **231** (308 mg, 1.05 mmol) and halide **139** (223 mg, 0.42 mmol), were dissolved in THF:Et_3N (50 mL, 20:80 v/v) and the solution was degassed thoroughly. $Pd(PPh_3)_4$ (47 mg, 10% by mol of **139**), CuI (8 mg, 10% by mol of **139**) were added in one portion and stirred at room temperature for 18 h followed by heating at 50 °C for 1 h affording **260** as a yellow solid (263 mg, 72%) after column chromatography (silica, DCM, followed by gradual addition of Et_2O) and recrystallisation from cyclohexane: mp 171.2-172.3 °C;

^{1}H NMR (C_6D_6, 200 MHz): δ 6.94 (s, Ar-H, 4H), 6.91 (s, Ar-H, 2H), 3.95 (t, J = 6.6 Hz, (O-CH_2)$_2$, 4H), 3.83 (s, (O-CH_3)$_4$, 12H), 2.24 (s, (OH)$_2$, 2H), 1.80-1.76 (m, (CH_2)$_2$, 4H), 1.56 (s, (CH_3)$_4$, 12H), 1.50-1.33 (m, (CH_2)$_6$, 12H), 0.89 (t, J = 6.8 Hz, (CH_3)$_2$, 6H);
^{13}C NMR ($CDCl_3$, 125 MHz): δ 155.2, 155.1, 154.7, 117.5, 116.0, 115.9, 113.4, 122.9, 112.6, 88.7, 80.1, 79.6, 79.3, 79.0, 74.8, 69.7, 67.0, 67.5, 56.3, 31.5, 31.0, 28.9, 25.5, 22.6, 15.2, 14.0;
MALDI-TOF *m/z* 860 (M^+).

1-(Buta-1,3-diynl)-4-(4-(4-(4-(4-(buta-1,3-diynyl)-2,5-dimethoxyphenyl)buta-1,3-diynyl-2,5-bis(hexyloxy)phenyl)buta-1,3-diynyl0-2,5-dimethoxybenzene 262,



262

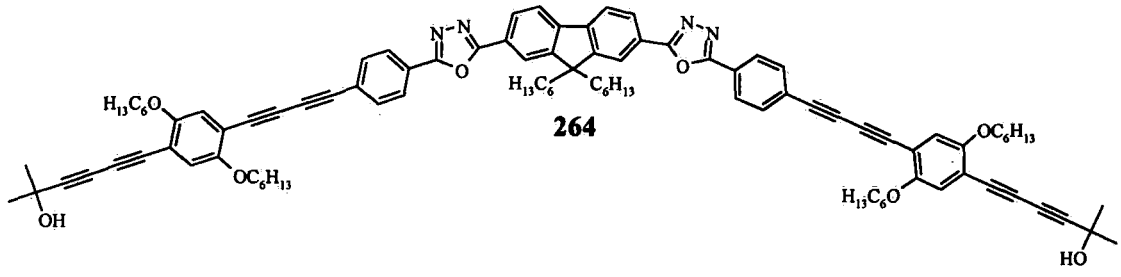
Compound **260** (100 mg, 0.12 mmol), NaOH (50 mg) in refluxing benzene (10 mL) afforded **262** as a yellow solid (48 mg, 56 %). The compound was purified by column chromatography (silica, dichloromethane eluent);

^{1}H NMR (C_6D_6, 500 MHz): δ 6.78 (s, Ar-H, 2H), 6.57 (s, Ar-H, 2H), 6.55 (s, Ar-H, 2H), 3.41 (t, J = 6.0 Hz, $(O\text{-}CH_2)_2$, 4H), 3.03 (s, $(O\text{-}CH_3)_2$, 6H), 3.02 (s, $(O\text{-}CH_3)_2$, 6H), 1.90 (s, ≡CH, 2H), 1.52-1.13 (m, $(CH_2)_8$, 16H), 0.86 (t, J = 7.5 Hz, $(CH_3)_2$, 6H);

^{13}C NMR (C_6D_6, 125 MHz): δ 156.2, 155.8, 155.4, 117.6, 116.5, 116.1, 113.93, 113.88, 112.5, 81.8, 80.9, 80.7, 73.7, 72.3, 69.3, 68.6, 55.5, 31.7, 29.2, 25.9, 22.9, 14.2;

MALDI-TOF *m/z* 743.3 (M^+).

Synthesis of 264



264

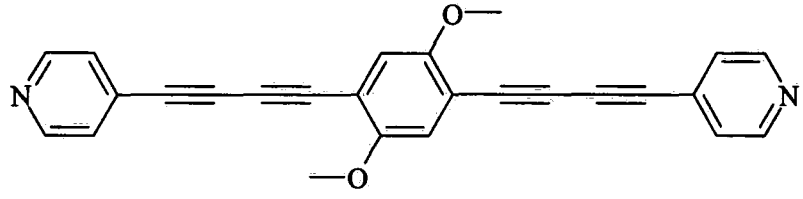
Alkyne **237** (135 mg, 0.312 mmol) and halide **263** (109 mg, 0.125 mmol) were dissolved in THF:Et_3N (30 mL, 50:50, v/v) and the reaction mixture thoroughly degassed. $Pd(PPh_3)_4$ (20 mg, 10 % by mol of **263**) and CuI (3 mg, (10 % by mol of **263**) were added and the reaction stirred at 25 °C for 2 h, followed by heating to 45 °C for 2 h. The reaction was followed by TLC. The solvent removed, ether added, boiled, cooled and filtered. The solvent was removed and the remaining residue purified twice by column chromatography (silica, DCM eluent) to afford **264** as a light brown oil (101 mg, 54% yield);

^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.19-8.15 (m, Ar-H, 8H), 7.93-7.91 (m, Ar-H, 2H), 7.71-7.68 (m, Ar-H, 4H), 6.97 (s, Ar-H, 2H), 6.93 (s, Ar-H, 2H), 3.97-3.96 (m, O-$(CH_2)_4$, 8H), 2.21 (s, OH, 2H), 2.17-2.13 (m, $(CH_2)_2$, 4H), 1.86-1.77 (m, $(CH_2)_4$, 8H), 1,59 (s, $(CH_3)_4$, 12H), 1.54-1.45 (m, $(CH_2)_4$, 8H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 165.4, 164.2, 155.2, 155.0, 152.5, 143.7, 133.2, 127.0, 126.5, 125.6, 124.2, 123.4, 121.6, 121.3, 117.9, 117.8, 113.9, 113.3, 88.6, 79.2, 79.1, 77.4, 77.2, 75.2, 69.9, 67.3, 65.9, 56.2, 31.6, 31.3, 29.7, 29.18, 29.16, 25.74, 25.73, 24.0, 22.74, 22.72, 22.6, 14.2, 14.1;

MS-MALDI-TOF *m/z* 1483.9 (M^+)

4-(4-(2,5-dimethoxy-4-(4-pyridin-4-yl)buta-1,3-diynyl)phenyl)buta-1,3-diynyl)pyridine, 268



268

Compound **230** (86 mg, 0.367 mmol) and 4-iodopyridine **247** (225 mg, 1.10 mmol) were dissolved in anhydrous Et_3N:THF (50:50, 50 mL), to which CuI (6 mg, 5% by mol of **247**) and $Pd(PPh_3)_2Cl_2$ (26 mg, 5 % by mol of **247**) were added and the reaction stirred overnight at 25 °C followed by heating to 50 °C for 1 h. The solvent was removed and the crude residue purified by column chromatography (DCM:Et_2O, 50:50, v/v) to elute **268** (76 mg, 53 %) as a light brown oil.

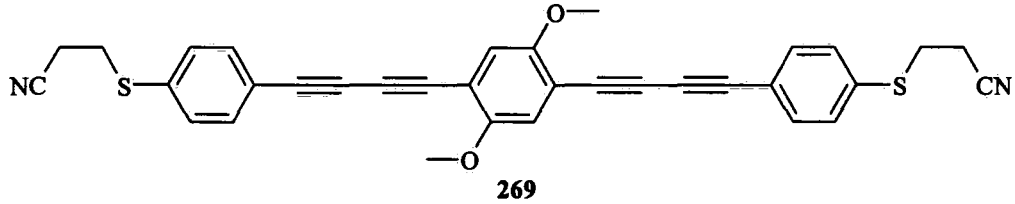
^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.56 (dd, J = 4.4 Hz, 1.6 Hz, Ar-H, 4H), 7.39 (dd, J = 4.4 Hz, 1.6 Hz, Ar-H, 4H), 6.96 (s, Ar-H, 2H), 3.81 (s, O-(CH_3)$_2$, 6H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.6, 150.0, 129.1, 126.5, 116.4, 112.3, 77.3, 74.7, 68.3, 64.3, 55.3;

MS-MALDI-TOF *m/z* 389.1 (M^+).

Anal. calcd. for $C_{21}H_{16}N_2O_2$: C, 80.40; H, 4.15; N, 7.21. Found: C, 79.95; H, 4.40; N, 6.99.

3-{4-[4-(4-{4-[4-(2-Cyanoethylsulfanyl)-phenyl]-buta-1,3-diynyl}-2,5-dimethoxy-phenyl)-buta-1,3-diynyl]-phenylsulfanyl}-propionitrile 269



269

1,4-Di(buta-1,3-diynyl)-2,5-dimethoxy-benzene **230** (168 mg, 0.72 mmol) and3-(4-iodo-phenylsulfanyl)-propionitrile **267** (518 mg, 1.80 mmol), were dissolved in Et_3N:THF (50 mL, 40:10 v/v) and the solution was degassed thoroughly. $Pd(PPh_3)_2Cl_2$ (125 mg, 5% by mol **267**), CuI (30 mg, 5% by mol **267**) added in one portion and stirred at room temperature for 18 h followed by heating at 50 °C for 1 h affording **269** as a

yellow solid (287 mg, 0.52 mmol, 72%) after column chromatography (silica, dichloromethane-diethyl ether, 50:50 v/v) and recrystallisation from cyclohexane: mp 171.2-172.3 °C;

^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.49 (d, J = 8 Hz, Ar-H, 4H), 7.32 (d, J = 8 Hz, 4H), 6.99 (s, Ar-H, 2H), 3.88 (s, $(O\text{-}CH_3)_2$, 6H, 3.20 (t, J = 8 Hz, $(CH_2)_2$, 4H), 2.65 (t, J = 8 Hz, $(CH_2)_2$, 4H);

^{13}C NMR ($CDCl_3$, 100 MHz): δ 155.3, 135.5, 133.2, 129.8, 120.5, 17.6, 116.0, 112.9, 82.8, 79.7, 78.3, 77.4, 75.1, 56.4, 29.3, 18.2.

Chapter VI References

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