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CRITICAL REVIEW

Synthesis of azobenzenes: the coloured pieces of molecular materials†

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Azobenzenes are ubiquitous motifs very important in many areas of science. Azo compounds display crucial properties for important applications, mainly for the chemical industry. Because of their discovery, the main application of aromatic azo compounds has been their use as dyes. These compounds are excellent candidates to function as molecular switches because of their efficient *cis–trans* isomerization in the presence of appropriate radiation. The classical methods for the synthesis of azo compounds are the azo coupling reaction (coupling of diazonium salts with activated aromatic compounds), the Mills reaction (reaction between aromatic nitroso derivatives and anilines) and the Wallach reaction (transformation of azoxybenzenes into 4-hydroxy substituted azoderivatives in acid media). More recently, other preparative methods have been reported. This *critical review* covers the various synthetic methods reported on azo compounds with special emphasis on the more recent ones and their mechanistic aspects (170 references).

1. Introduction

Aromatic azo compounds are widely used in the chemical industry as dyes and pigments,[1] food additives, indicators,[2] radical reaction initiators[3] and therapeutic agents.[4] In addition, azo compounds have shown promise in electronics[5] and drug delivery.[6] Moreover, azobenzenes recently have been targeted for potential applications in areas of nonlinear optics, optical storage media, chemosensors, liquid crystals,[7] photochemical molecular switches,[8] molecular shuttles,[9] nanotubes[10] and in the manufacture of protective eye glasses and filters.[11] The development of chromophores with characteristics like high chemical stability (*i.e.*, number of cycles without decomposition), thermal stability over a wide temperature range and having two forms easily detectable by a method that does not cause irreversible molecular alterations is a major challenge for researchers who focus their interest in this area. Moreover, the light driven reversible isomerisation of azobenzenes between *cis* and *trans* forms makes them excellent candidates to modulate the relative movement of different moieties. For instance, the motion of one molecule containing an azobenzene group is able to control the movement of a complementary substrate non-covalently bound to the azobenzene fragment.[12] In biological systems, the photoresponse of azo compounds modifies the activity of enzymes and polypeptides.[13] Azo compounds are also of interest for a more accurate diagnosis of Alzheimer's disease because their physiological activity can be used as a diagnostic probe for the visualization of amyloid plaques in the brains of mentally deteriorating patients.[14]

The classical methods to prepare azobenzenes are the azo coupling reaction, the Mills and the Wallach reactions. Recently, several more efficient methods have been reported and a recent review by Len *et al.* has stressed the applications of the azobenzenes in carbohydrate chemistry.[15] Now, this publication reviews the recent advances in the synthesis of azo compounds with special emphasis on the more recent developments. This review covers the following reactions:

(1) Azo coupling reaction
(2) Mills reaction

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† This paper is dedicated to Professor Mª Carmen Carreño García on the occasion of her 60th birthday.

Estíbaliz Merino

Estíbaliz Merino obtained her PhD degree at the Universidad Autónoma de Madrid in 2007 under the supervision of Prof. Carmen Carreño working in the synthesis of azobenzenes and natural products. Then she moved to Germany as a postdoctoral researcher to work with Prof. Magnus Rueping at Goethe-University of Frankfurt am Main and RWTH-Aachen University in the field of organocatalysis (2007–2009). In January 2010, she started to work with Prof. Avelino Corma in Instituto de Tecnología Química in Valencia as Juan de la Cierva researcher. Her current research interests focus on the synthesis of natural products and catalysis, including organocatalysis and heterogeneous catalysis.

(3) Wallach reaction
(4) Reduction of azoxybenzenes
(5) Reductive coupling of aromatic nitro derivatives
(6) Oxidation of anilines
(7) Dehydrogenation of arylhydrazines
(8) Dimerization reaction of diazonium salts
(9) Triazene rearrangement
(10) Thermolysis of azides
(11) Decomposition of *N*,*N*′-*p*-benzoquinonediimines dioxides
(12) Reaction of arylcalcium derivatives with nitrous oxide
(13) Metal catalyzed coupling of arylhydrazines
(14) Opening of benzotriazoles
(15) Reaction of quinones with arylhydrazines
(16) Reaction of quinone acetals with arylhydrazines

2. Methods of synthesis of azobenzenes

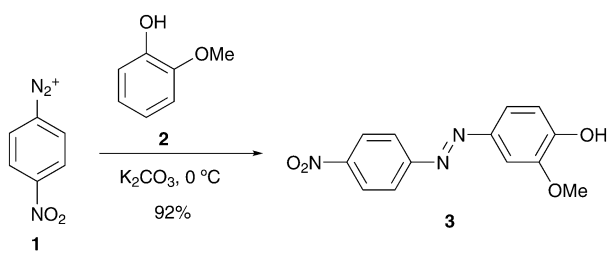
2.1 Azo coupling reaction

The majority of azobenzenes are obtained by this type of reaction. The methodology is based on the initial diazotization of an aromatic primary amine at low temperature, which then reacts with an electron rich aromatic nucleophile. Reaction times are usually short and the yields high. For instance, this method allows the synthesis of azo compound **3** in 92% yield by reaction between the diazonium salt **1** and phenol **2** at 0 °C using K_2CO_3 as base (Scheme 1).[16]

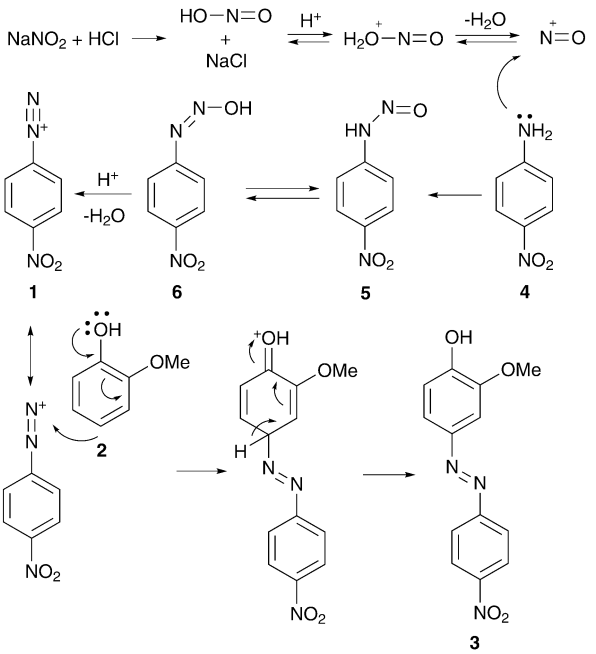
Diazonium salts are weak electrophiles that react with electron rich species, such as substituted arenes having electron donor groups like amine or hydroxyl, to give azobenzenes.[17] Normally, such a substitution reaction takes place at the *para* position to the electron donor group on the activated aromatic ring, acting as a nucleophile. When this position is already occupied, the substitution occurs in the *ortho* position.

This reaction is very pH dependent. In accordance with the mechanism shown in Scheme 2, the formation of diazonium salt from a primary amine, acid is necessary to liberate *in situ* nitrous acid from $NaNO_2$. Further protonation and H_2O elimination provides the nitrosating agent (+N=O), whose reaction with the amine leads to the *N*-nitroso derivative **5**, a tautomer of the diazohydroxide **6**. A second protonation and H_2O elimination affords the diazonium salt **1** stabilized by resonance.[18]

Regarding the reactivity of the starting materials, phenols have to react in the ionized form to undergo coupling because the neutral species are not sufficiently nucleophilic. In this case, moderately alkaline solutions are essential since the diazonium salt evolves into a diazohydroxide in the presence of a base, thus inhibiting the coupling. Therefore, the coupling



Scheme 1



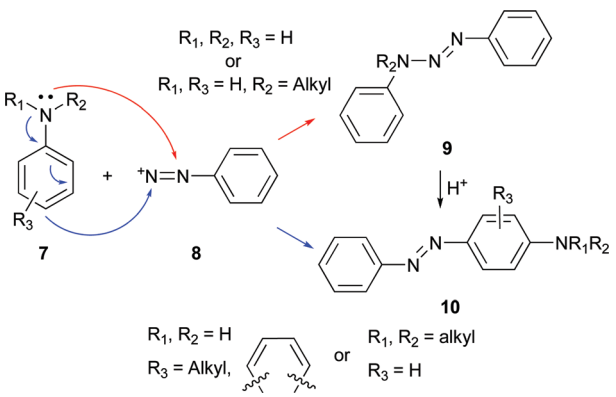
Scheme 2

of phenols has to be done in mild basic media at controlled pH, while the aromatic amines should react in weak acid medium to prevent *N*-coupling without reducing the nucleophilicity of the nitrogen that will be protonated in strong acid media.

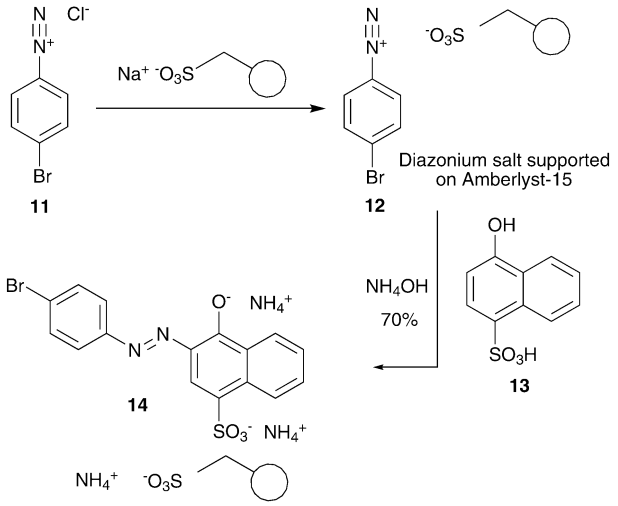
After the diazonium salt is formed, several mechanisms for the coupling have been proposed.[18] Currently, the most accepted is an electrophilic aromatic substitution of the phenol, or aniline, with the electrophilic nitrogen of the diazonium salt (Scheme 2).

For coupling of phenols the maximum rate is observed at pH ≈ 10. When aromatic amines are the nucleophilic reagents, two pathways are possible: the N–N bond formation giving rise to the amino diazo compound **9**, further transformed into an azo compound by rearrangement. When the reactivity of the aryl group is increased by the presence of electron donor substituents or fused rings, the direct C–N bond formation leads to the azo compounds **10** (Scheme 3).[17b]

The azo coupling can also occur in solid phase. For this process, the diazonium salt **11** undergoes anion exchange with



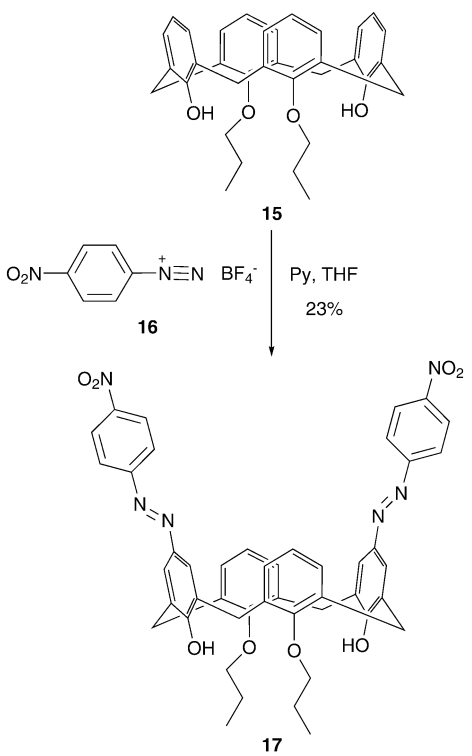
Scheme 3



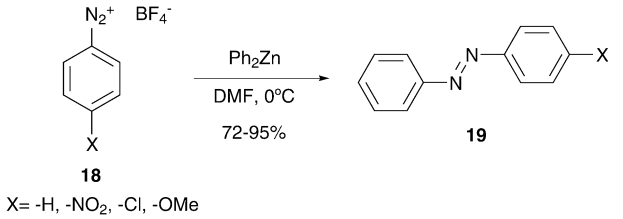
Scheme 4

a sulfonate group anchored on a polystyrene resin (Amberlyst A-15, resin-based sulfonic acid group and Amberlyst A-26 functionalized with tetraalkylammonium groups). The diazonium salt **12** generated through this exchange is on a polymeric support and is further coupled with an electron-rich aromatic component **13** to form the azo compounds **14**. This can be isolated without treatment or purification (Scheme 4).[19]

Azo coupling has permitted the introduction of the azo group in porphyrins,[20] metacyclophanes[21] and calixarenes.[22] In the example shown in Scheme 5, coupling of the diazonium salt **16** with calixarene **15** gives the azo compound **17** in 23% yield.



Scheme 5



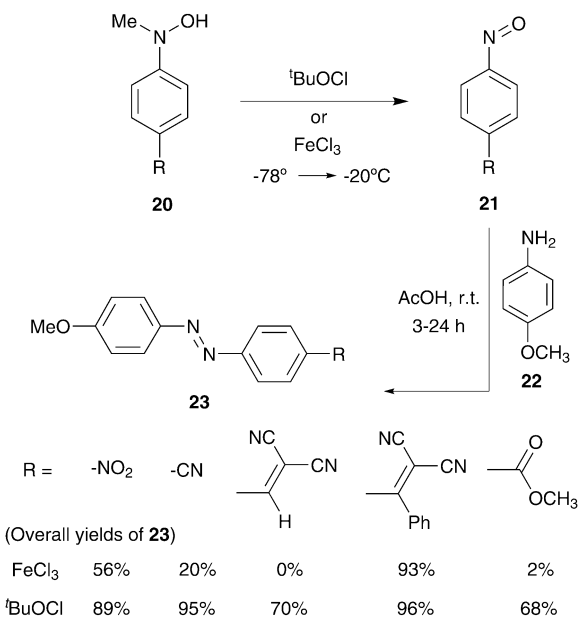
Scheme 6

The nature of the counterion of the diazonium salt also strongly influences its stability. Chlorides are unstable, they can decompose explosively above 5 °C. Tetrafluoroborates, disulfonimides, hexafluorophosphates and zinc chlorides are stable in the solid form and can be stored for long periods of time. These salts easily react with organometallic reagents by the simple addition of the organometallic to a diazonium containing solution.

Reactions of arenediazonium 2-benzenedisulfonimides with Grignard,[23] cadmium, mercury, lithium, zinc[24] and tin[25] reagents have been studied. The best yields of the azobenzenes (72–95% yields) have been obtained in reactions between arenediazonium tetrafluoroborates **18** and diphenylzinc (Scheme 6).

2.2 Mills reaction

The reaction of aromatic nitroso derivatives and anilines in glacial acetic acid gives in good yield the corresponding azobenzenes (Scheme 7).[26] The aromatic nitroso derivative **21** can be prepared by oxidation of an aromatic methylhydroxylamine **20** with *tert*-butyl hypochlorite. Such an oxidation reaction is fast and needs to be carried out at −78 °C with high dilution to prevent overoxidation. The reaction of nitroso derivatives **21** with aniline **22** leads to the azobenzenes **23** with good overall yields. Other oxidation agents like ferric chloride,[27] Caro's acid (H_2SO_5),[28] sodium or potassium dichromate and sulfuric acid,[29] acetic acid/H_2O_2,[30]



Scheme 7

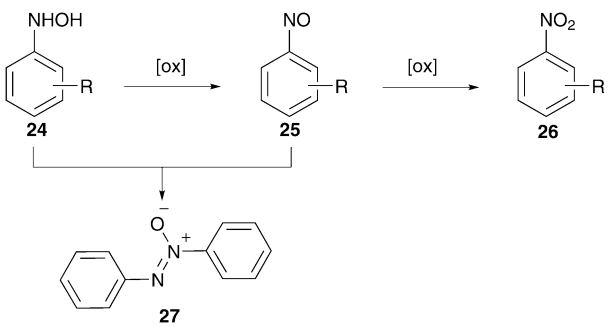
m-chloroperbenzoic acid,[31] potassium permanganate,[32] ferric chloride,[33] diethyl azodicarboxylate,[34] iodine/NaI/NaOAc,[35] silver carbonate,[36] (diacetoxyiodo)benzene,[37] 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ)[38] and peroxyformic acid[39] have been used to generate the nitroso aromatic derivative.

Hydrogen peroxide in the presence of rhenium,[40] tungsten[41] or molybdenum[42] catalysts also gives the nitrosoarenes with high yields. Other heterogeneous preparation procedures involve the use of tetrabutylammonium cerium (IV) nitrate,[43] iridium on carbon,[44] pyridinium chlorochromate,[45] potassium ferrate (VI)[46] and phenyl seleninic anhydride[47] as oxidants. These heterogeneous oxidation reactions are often slow and give low yields in cases where either the starting hydroxylamine or the nitrous product has limited stability and decomposes during the course of the reaction. Side reactions can also occur during the oxidation of the hydroxylamines **24**, such as the formation of nitro derivatives **26**, caused by further oxidation of the nitroso compounds **25**, and condensation reactions that yield azoxybenzenes **27** from the *N*-arylhydroxylamine intermediates **24** and nitroso compound **25** (Scheme 8).[17c] To a greater extent, these side reactions are commonly observed when poorly reactive anilines with electron-withdrawing substituents in either the *para* or *meta* position are reacted, and are favoured by prolonged reaction times as well.

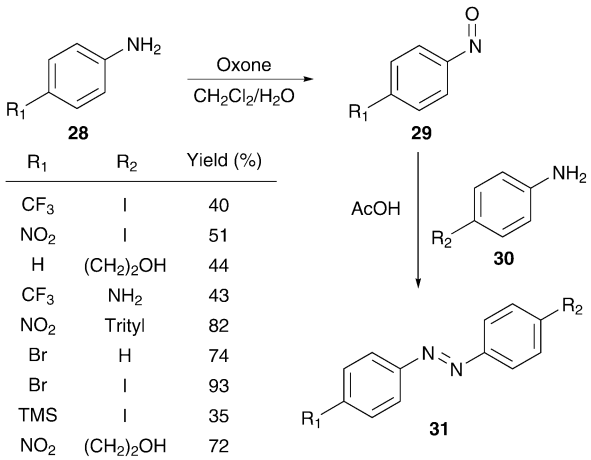
Two phase heterogeneous systems like Oxone® (*i.e.*, $2KHSO_5{\cdot}KHSO_4{\cdot}K_2SO_4$) in H_2O/CH_2Cl_2 are efficient to form nitrosoarenes **29** which condense with anilines **30** to give azobenzenes **31** in good yield.[48] These biphasic systems secure the separation of the generally less water-soluble nitroso compounds **29** from the *N*-arylhydroxylamine intermediates and aniline precursors **28** and thus prevent undesirable condensation reactions (Scheme 9).

The mechanism of the Mills reaction involves the attack of aniline **32** on the nitroso derivative **33** in acid media that leads to azobenzene **36** after dehydration of the intermediate **35** (Scheme 10).[49]

Recently, this method has been applied to the synthesis of alternating sequences of pyridine-2,6-dicarboxamides and 3-(phenylazo)-azobenzenes, which have been assembled into oligomers of four (**46**) and eight (**47**) azobenzene linkages (Scheme 11).[50] In the direct reaction between 2 equivalents of *N*-(2-nitrosophenyl)acetamide **37** and 3-phenylenediamine **38**, in the presence of acetic acid, only an unidentified mixture was obtained. Probably, the electron-rich nature of 3-phenylenediamine **38** causes the reaction to take place on the

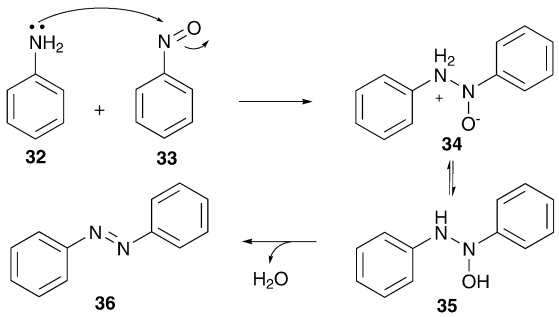


Scheme 8



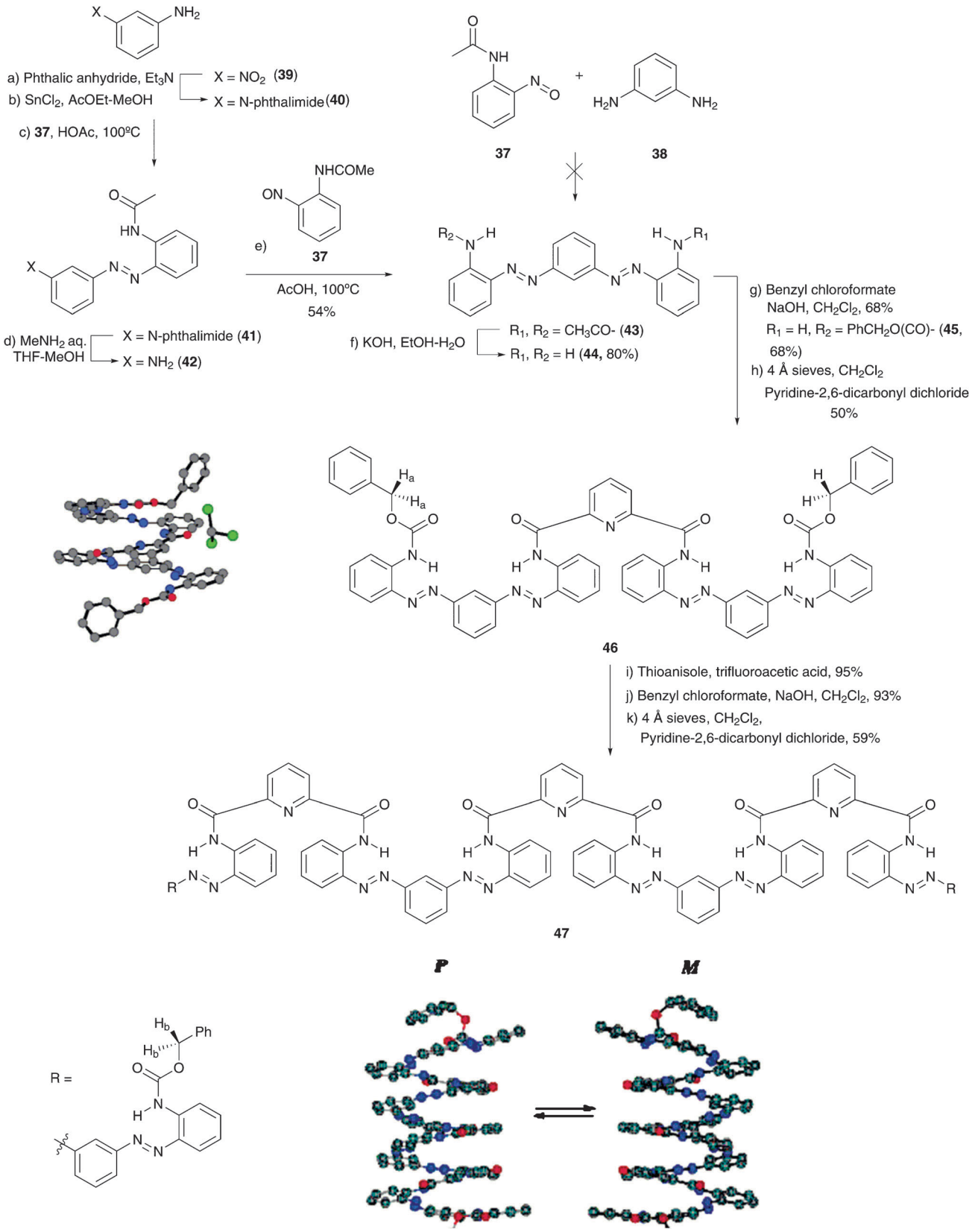
R_1	R_2	Yield (%)
CF_3	I	40
NO_2	I	51
H	$(CH_2)_2OH$	44
CF_3	NH_2	43
NO_2	Trityl	82
Br	H	74
Br	I	93
TMS	I	35
NO_2	$(CH_2)_2OH$	72

Scheme 9



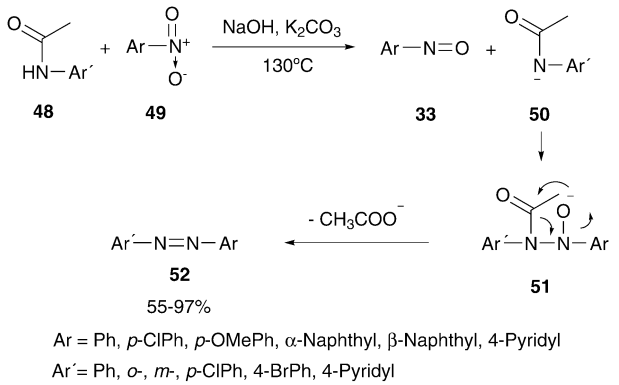
Scheme 10

aromatic ring and amino groups. When 3-nitroaniline **39** was used as the starting material, the corresponding azo compound was obtained in 60% yield. However, reduction of the nitro compound to the corresponding amine provided variable yields due to the competitive reduction of the azo group. To avoid reduction of the nitro group, 3-phthalimido derivatives **40** were investigated as electron-deficient analogues of 3-nitroaniline **39** that could be deprotected without competitive azo bond reduction. In the coupling reaction of 3-phthalimido derivatives **40** with nitroso compounds **37**, the azo compound **41** was obtained in high yield. Selective deprotection of the phthalimide group in **41** was carried out using aqueous methylamine. Subsequent condensation of amine **42** with nitroso derivative **37** afforded the corresponding azobenzene **43** in 54% yield. Hydrolysis of the acetamide groups with KOH and monoprotection with benzyl chloroformate provided the monoamine derivative **45**. Amidation of **45** with pyridine-2,6-dicarbonyl dichloride affords the oligomer **46** in 50% yield. The synthesis of the second generation oligomer **47** was carried out by repetition of the monoprotection/amidation sequence (Scheme 11). The oligomer **46** was shown to adopt a helical disposition in the solid state with intramolecular hydrogen bonds between the NH of the pyridine-*N* amide and an adjacent azo nitrogen. In the absence of a chiral perturbation, the helical conformations exist as an interconverting mixture of equal amounts of *M* and *P* helices. The helices undergo a dynamic *M*–*P* helical interconversion with energetic barriers that increase with helix length. This was



Scheme 11

evidenced by low temperature NMR studies in $CDCl_3$. Two different signals for H_a in **46** and H_b in **47** were observed due to the global conformation of the molecule. Increasing temperature caused the two doublets of both H_a to coalesce into a singlet by the average of the two protons undergoing exchange caused by the *M*–*P* helical interconversion.



Scheme 12

As shown in Scheme 12, the nitroso derivative **33** can be formed by deoxygenation of nitrobenzene **49**. This allows the preparation of asymmetrically substituted azo compounds **52** from the nitro compound **49** and an aromatic *N*-acylamine (Ar′NHAc) **48**.[51]

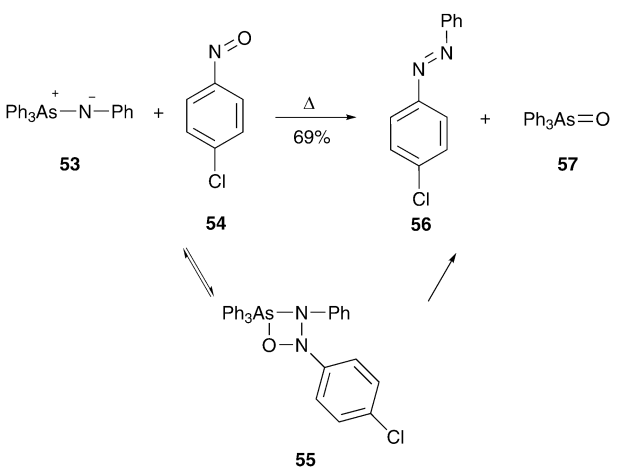
Once the nitroso derivative **33** is formed, the reaction with the nitrogen anion of the acetanilide salt **50**, formed under basic conditions, gives rise to the N–N bond. The azo compound **52** is finally formed in good yield from the intermediate **51** after elimination of the acetate ion. This method allows the synthesis of azo compounds in basic media.

Instead of aniline, the use of triphenylarsine phenylimine as a nucleophile has been described.[52] Thus heating of **53** with nitrosobenzene **54** leads to the azo compound **56** in 69% yield.

The mechanism proposed for this reaction is similar to the Wittig reaction. That is, the nucleophilic attack of the arsine imine **53** on the nitrogen atom of the nitroso derivative **54** is simultaneous to the attack of the oxygen of the nitroso group on arsenic. The cyclic intermediate **55** decomposes to the arsine oxide **57** and the azo compound **56** (Scheme 13).

2.3 Wallach reaction

The Wallach reaction involves the conversion of an azoxybenzene, accessible from the reduction of nitrobenzene with alcoholic potassium hydroxide/acetaldehyde,[53] sodium amalgam,[54] hydrogen/PbO[55] or MeONa[56] or the oxidation of aniline with hydrogen peroxide or permanganic acid/formaldehyde,[57] into a 4-hydroxy substituted azoderivative (or sometimes the 2-hydroxy isomer) by treatment with an acid. The 4-nitro derivative **58a** gave the 2-phenol **59a** as the main product. Whereas X = $COCH_3$ or COOH, the *ipso* rearranged product **60b** or **60c** respectively, is obtained (Scheme 14).[58]

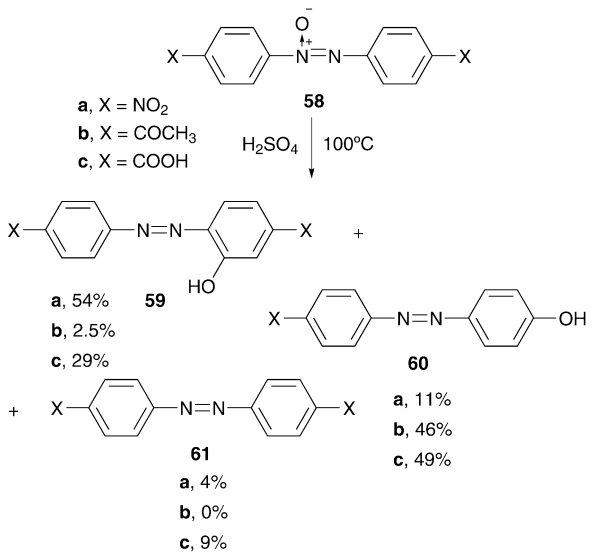


Scheme 13

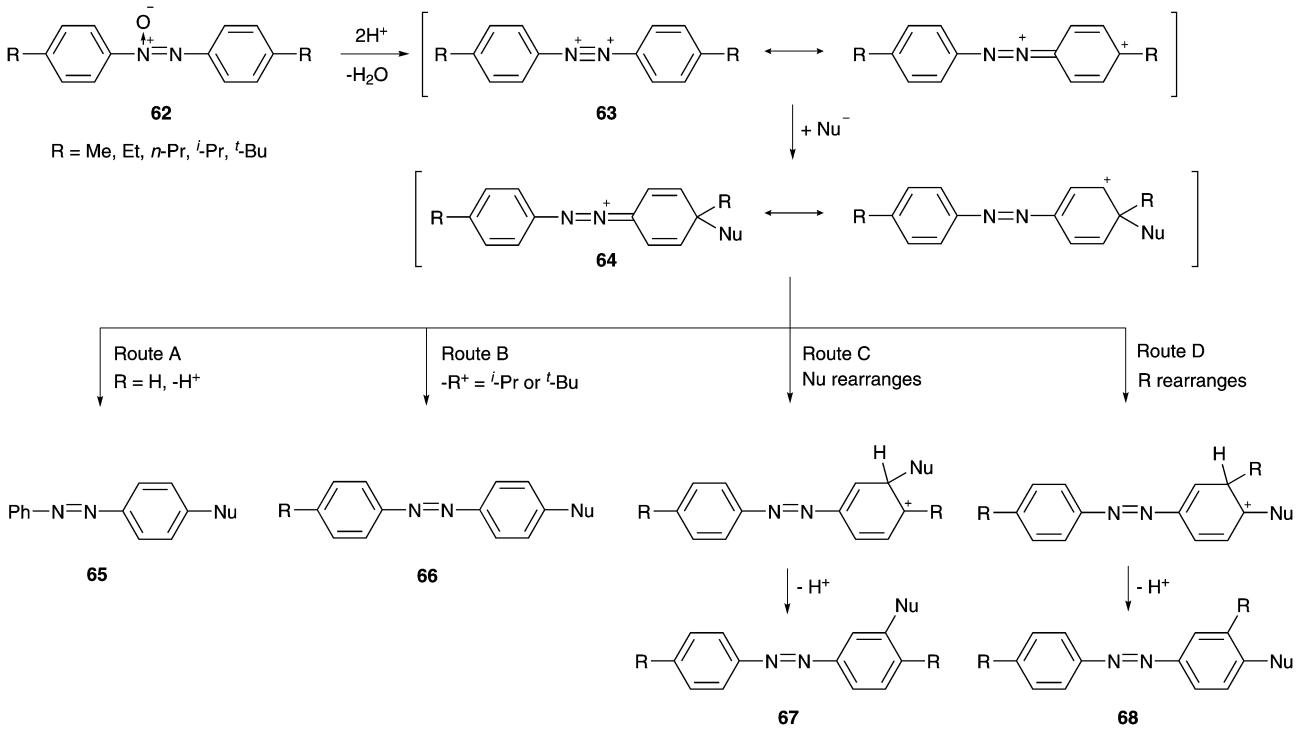
The reaction of 4,4′-dialkylazoxybenzenes with sulfuric acid leads to a mixture of products **65–68** (Scheme 15).[59] The ratios of these compounds are affected by the alkyl group type. The proposed mechanism for the Wallach rearrangement explains the formation of the mixture of azobenzenes. Data from isotopic labeling studies suggest an intermolecular pathway for the rearrangement. First, the azoxybenzene **62** is transformed into the dicationic intermediate **63** by diprotonation and dehydration. Subsequently, the nucleophile attacks the dication to form the intermediate **64**.

When R = H (route A), 4-hydroxyazobenzenes **65** are obtained. Compound **66** can be formed by the separation of an alkyl carbocation from the intermediate **64** (route B). This is favored when the carbocation is stable, such as, an isopropyl or *tert*-butyl cation. In such cases, compound **66** is the main product of the reaction. In route C, the nucleophilic group migrates to the *ortho* position in the intermediate **64**, followed by protonation, to obtain compound **67**. In route D, the azobenzene **68** is obtained after alkyl group migration to the *ortho* position in **64** and deprotonation (Scheme 15).

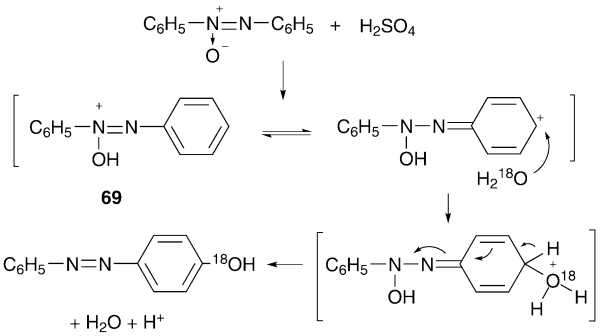
Another mechanism proceeds *via* the monocation **69**. In this reaction, the nucleophilic attack of water occurs at the *para* position of the aromatic ring (Scheme 16).[60] Shemyakin and coworkers described that the formation of 2-hydroxyazobenzenes **72** would proceed *via* an intramolecular oxygen shift (Scheme 17).[61] Already in 1925, Cumming observed the formation of 2-hydroxy azobenzene by irradiation of azoxybenzene solution in ethanol with UV light.[62] The oxygen atom of the azoxy group in azobenzene **70** is transferred to the benzene ring attached to the fragment –N═ of the azoxy



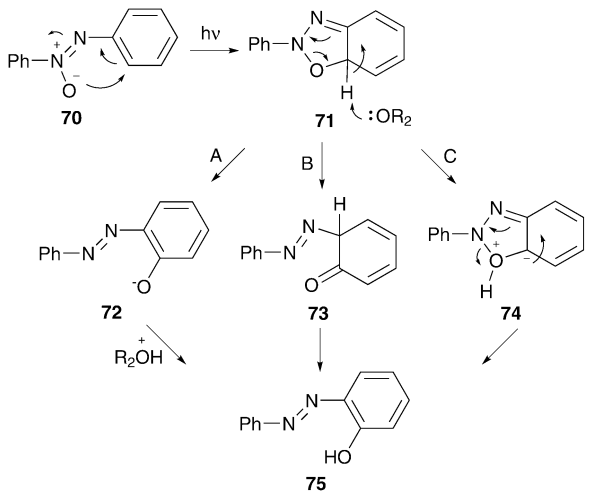
Scheme 14



Scheme 15



Scheme 16



Scheme 17

group upon exposure to light. Based on the structure of the azoxy group in the compound **70**, the oxygen atom that lies on the plane of the N=N bond is closer to the *ortho* position of the benzene ring that supports the other nitrogen atom. These facts indicate that the photochemical Wallach transposition has an intramolecular character. It is accepted that the intermediate **71** is formed in the rearrangement. The way to transform **71** in **75** is not known. There are some possibilities. One of them (A) is ring opening accompanying deprotonation by basic solvents. Another possibility (B) arises as follows. The formation of diazonium ions during irradiation of azoxy compounds in benzene solution has been described. The origin of the diazonium ion is attributed to an intermediate **73**, obtained from **71** by an intramolecular 1,2-hydrogen-atom shift and undergoing either scission to give the diazonium ion or prototropy to form **75**. The last possibility (C) for intramolecular H-migration which can lead to both **75** and diazonium ion formation is a [1,5]-sigmatropic migration of hydrogen across the face of the heterocyclic ring. Solvent-dependent migration of the LUMO of the H atom across the HOMO of the excited eight-electron ring system could bring the H atom to the oxygen (**74**) leading to **75** by prototropy (Scheme 17).[63] Another alternative for the *ortho* rearrangement is through an "intimate ion pair" **76** different from that proposed in the formation of 4-hydroxyazobenzenes (Fig. 1).[60]

Studies carried out on reactions of azoxybenzenes **77** with Lewis acids reveal the formation of 1 : 1 complex **78** in high yield. However they are highly hygroscopic, and their hydrolysis gives rise to the starting azoxybenzenes **77**.[64] The thermolysis of the complex formed with $SbCl_5$ in nitrobenzene leads selectively to 2-hydroxy substituted products **79**

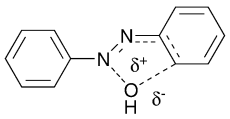


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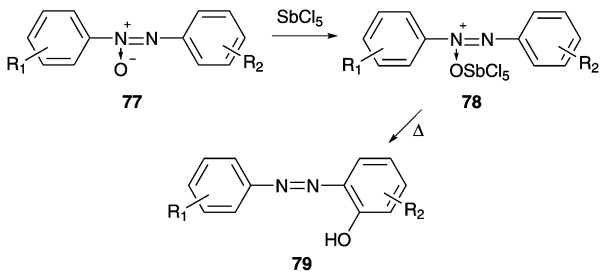
Fig. 1 Ortho rearrangement in Wallach reaction through an "intimate ion pair"



R_1 =	H	H	2-CH_3	3-CH_3	H	4-CH_3	4-Cl	4-Br	4-NO_2
R_2 =	H	2-CH_3	2-CH_3	3-CH_3	4-CH_3	H	H	H	H
Yield (1° Step)=	94	97	98	98	99	97	93	94	91
Yield (2° Step)=	64	34	13	16	73	32	12	47	7

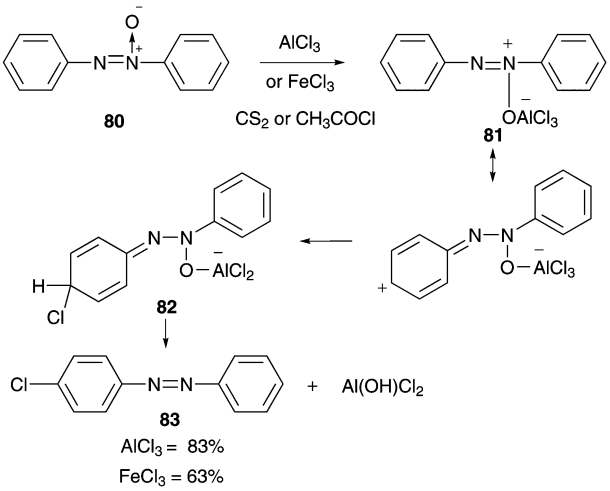
Scheme 18

(yields: 7–73%). Tarry products may also be formed. The product distribution of **79** and tarry products are highly temperature dependent. For instance, in the case of azoxybenzene, the yield of tarry products increases with increasing temperature. The maximum yield of azobenzene is obtained at *ca.* 85 °C (Scheme 18). With other Lewis acids, such as $TiCl_4$, $AlCl_3$, $FeCl_3$ and $ZnBr_2$, the complex formation followed by the thermal *ortho* Wallach reaction does not take place. When the Lewis acids are used in excess of azoxybenzene, mixtures of *p*-chloroazobenzene and azobenzene are obtained. The major reaction is deoxygenation to give the azobenzene. On the other hand, the thermal reaction of azoxybenzene **80** with $AlCl_3$ or $FeCl_3$ in carbon disulfide or acetyl chloride gives 4-chloroazobenzene **83** as the major product and traces of 2-hydroxybenzene. From the mechanistic point of view, it is assumed that the Lewis acid initially associates to the azoxy oxygen giving place to species stabilized by resonance such as **81**. The deficient *para* position of the intermediate is then attacked by a chloride ion leading to product **83** after deprotonation (Scheme 19).[65]

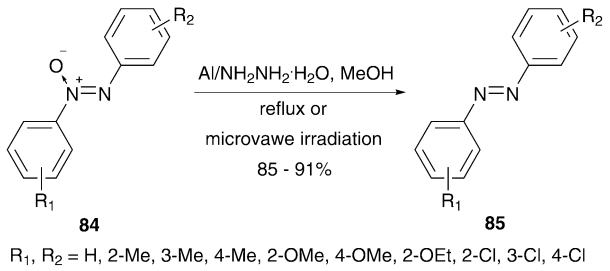
When azoxybenzenes are subjected to temperatures of *ca.* 245–250 °C, the thermal Wallach reaction is not synthetically useful since mixtures of 2-hydroxyazobenzenes, 2-hydroxyazoxybenzenes, 4-hydroxyazobenzenes and 4-hydroxyazoxybenzenes are obtained in low yield.

2.4 Reduction of azoxybenzenes

Azobenzenes can be also prepared by the reduction of azoxy derivatives. A method recently reported involves the treatment of azoxyarenes **84** with hydrazine hydrate in the presence of aluminium in methanol under reflux or microwave irradiation (Scheme 20).[66] The reaction is very fast, and the azoarenes **85** are obtained in excellent yield. The use of AlI_3[67] or $InCl_3$,[68] as



Scheme 19

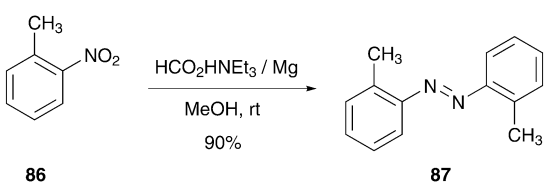


Scheme 20

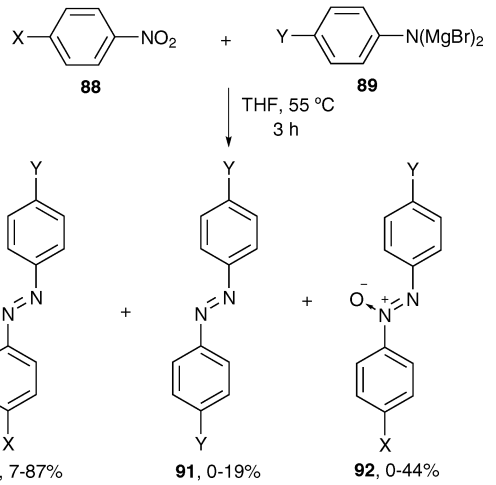
well as metallic triflates, such as $Zn(OTf)_2$ or $Cu(OTf)_2$,[69] also gives rise to the azo compounds in excellent yield. A reducing solution containing yeast–NaOH in ethanol and H_2O[70] is an efficient method for the rapid and selective reduction of azoxy compounds. Tertiary phosphines have also been used as reducing agents when the reaction is catalyzed by dichlorodioxomolybdenum (VI).[71] Tris-(dimethylamino) phosphine activated by iodine[72] and tertiary phosphites[73] generates the azo compounds from azoxybenzenes in very good yield as well.

2.5 Reductive coupling of aromatic nitro derivatives

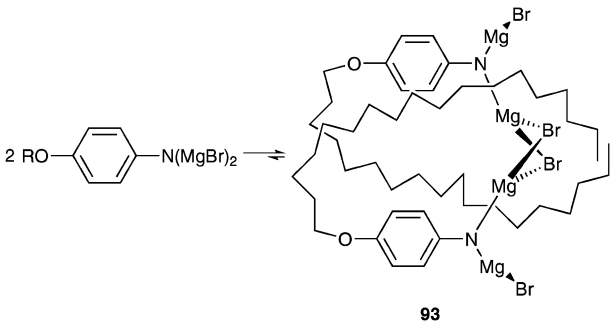
The reductive coupling of nitrobenzenes with reducing reagents, such as $LiAlH_4$,[74] $NaBH_4$,[75] sodium 2-hydroxy ethoxide in ethylene glycol,[76] KOH,[77] Zn/NaOH,[78] Bi,[79] Bi-KOH,[80] or Pb/HCO_2NH_4,[81] is a useful means to obtain exclusively symmetrical aromatic azo compounds. The reductive coupling of 2-nitrotoluene **86** using Mg/HCO_2HNEt_3 in methanol at room temperature gives 2,2′-dimethyl azobenzene **87** in 90% yield (Scheme 21).[82]



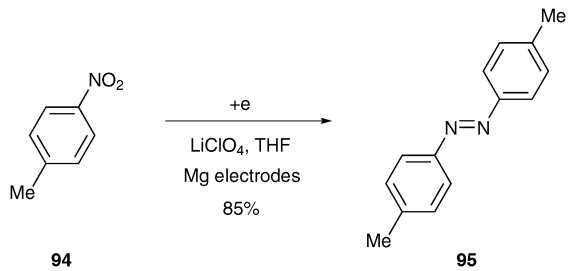
Scheme 21



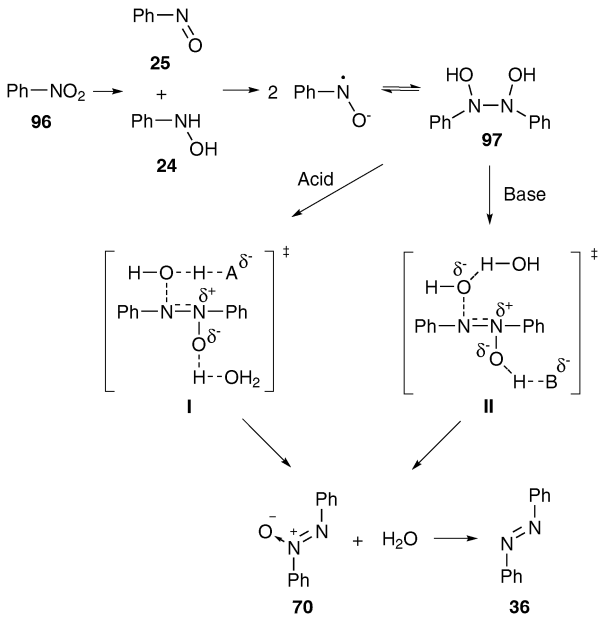
Scheme 22



Scheme 23



Scheme 24



Scheme 25

The reaction of aromatic nitro derivatives **88** with arylmethylenedimagnesium reagents **89** leads to mixtures of unsymmetrical and symmetrical azo (**90** and **91**) and azoxy compounds (**92**).[83] The synthetic utility of this procedure is limited by the lack of selectivity (Scheme 22). The yield of the corresponding azobenzene is higher when X = CH_3 and Y = *n*-$C_{12}H_{25}O$ and *n*-$C_{18}H_{37}O$. In these cases, the long chain is situated close to the nitrogen atom of the same molecule. Okubo *et al*. suggest that a long chain with more than eleven methylene groups twists around the –$N(MgBr)_2$ group of the other molecule to tie the dimer **93**, creating a synergy to enhance the yield of the azo compound **90** (Scheme 23).

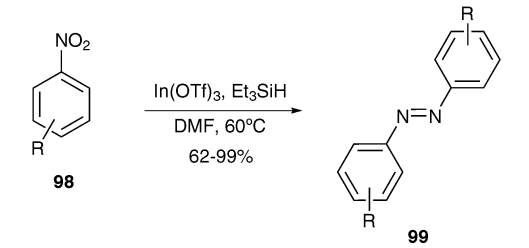
Other reducing agents that have been used, such as Al/NaOH under ultrasonic conditions,[84] $SnCl_2$/NaOH,[85] glucose/NaOH,[86] Pb/HCO_2HNEt_3,[87] Pb/$CH_3CO_2NH_4$,[88] $TiCl_4$/$LiAlH_4$,[89] $NaBH_4$/$(PhTe)_2$,[90] $Co_2(CO)_8$,[91] or $NiCl_2$·H_2O-Li-4,4′-di-tert-butylbiphenyl (DTBB),[92] for reductive coupling of nitroarenes, lead to the corresponding azobenzenes in yields ranging from 60 to 95%. Furthermore, magnesium diisopropylamide,[93] FeO, iron pentacarbonyl/CO[94] or the system MCl_n–Mg–THF[95] (where MCl_n = $TiCl_4$, VCl_3, $CrCl_3$, $MoOCl_3$, WCl_6 or $FeCl_3$) could be used for this aim as well.

The electrochemical reduction with magnesium electrodes has also been employed to prepare azo compounds like **95** in good yields (Scheme 24).[96]

The probable mechanistic proposal for these reductive couplings is the reduction of nitro compounds in the presence of the base or acid shown in Scheme 25.[97] Thus, the nitro aromatic compound **96** reacts with the reductant leading to a mixture of the nitroso derivative **25** and the corresponding hydroxylamine **24**. Both are later converted into radical anions that couple to generate a N–N bond leading to the *N*,*N*′-dihydroxy intermediate **97**. Dehydration of this intermediate is the single-rate determining step to form the azoxy compound **70**. The departure of the proton and hydroxide ion, in acid or basic media (**I** and **II**), is probably assisted by molecules of water. The resulting compound **70** is reduced to give the azo compound **36**.

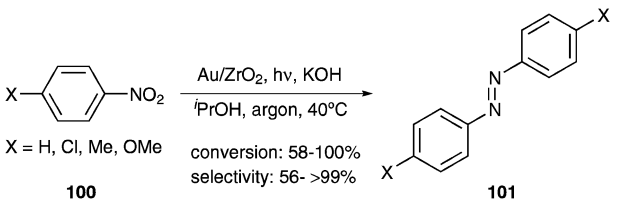
Recently, an example of this methodology has been described by Sakai and coworkers.[98] They used the system $In(OTf)_3$/Et_3SiH to obtain the azobenzenes **99** in 62–99% yields from nitro derivatives **98** (Scheme 26).

A disadvantage of this method is that the reducing agent is used in excess, and the by-products formed from the reducing reagent are not environmentally friendly. There is only one example of a catalytic process to obtain azobenzenes by reduction of nitroaromatic compounds. Zhu and coworkers



R = H, 2-Me, 3-Me, 4-Me, 4-Cl, 4-Br, 4-CN, 4-MeCO, 3-MeCO$_2$

Scheme 26



Scheme 27

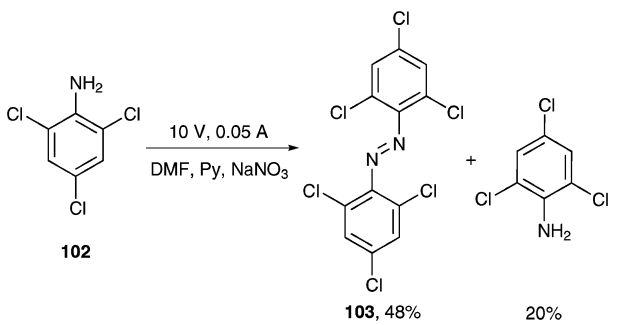
have described the reduction of nitrobenzenes **100** on gold nanoparticles supported on ZrO_2 with visible or ultraviolet light irradiation.[99] The azo compounds **101** are obtained with high selectivities at ambient temperature and pressure (Scheme 27).

2.6 Oxidation of anilines

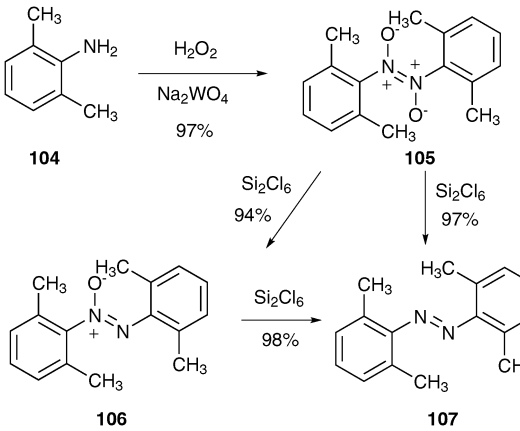
The electrolytic oxidation of aromatic amines was described in 1972 as a new method to obtain azobenzenes (Scheme 28).[100] However, this procedure gave azo compounds in low yields. Thus, for instance, the azobenzene **103** is obtained in 48% yield by electrolytic oxidation of aniline **102** with Pt electrode in dimethylformamide and in the presence of pyridine.

Additional different oxidizing agents were later reported to give azo compounds from aromatic amines like sodium perborate/acetic acid,[101] potassium permanganate supported on copper (II) sulfate pentahydrate[102] or $[C_{16}H_{33}N(CH_3)_3]Cr_2O_7$.[103] When H_2O_2/Na_2WO_4 is used, initial oxidation of aniline **104** to the azo dioxide **105** and its subsequent reduction with Si_2Cl_6 takes place. The azobenzene **107** is obtained in very good yield (Scheme 29).[104]

A variety of metallic and non-metallic reagents, such as Ag_2CO_3,[105] Ag_2O, AgO,[106] $AgMnO_4$,[107] MnO_2,[108] KO_2,[109] $NaBO_3$,[110] $Pb(OAc)_4$,[111] $BaMnO_4$,[112] $Ce(OH)_3O_2H$,[113] bis-(2,2′-bipyridyl)-copper (II) permanganate,[114] nickel peroxide,[115]



Scheme 28

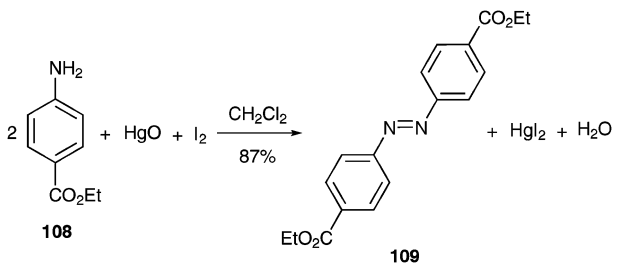


Scheme 29

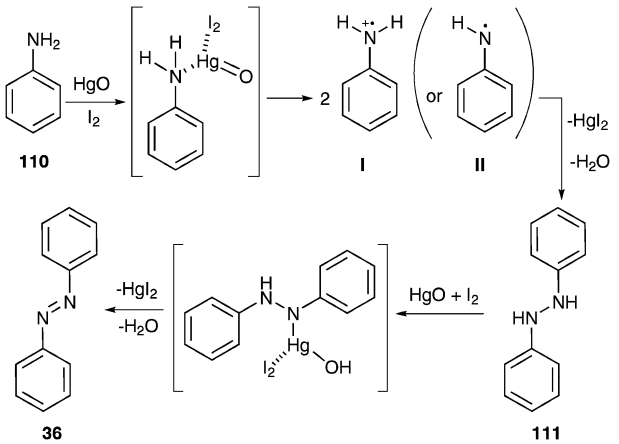
bispyridine silver permanganate,[116] $RuCl_3/H_2O_2$,[117] hypervalent iodine reagents such as $[PhI(OAc)_2]$,[118] Mn(tetraphenylporphyrin)Cl/$NaIO_4$,[119] galvinoxyl/$K_3Fe(CN)_6$,[120] or aerobic oxidation under different conditions (O_2–KO–^{t}Bu,[121] O_2/Co_3O_4,[122] peroxidase/H_2O_2[123] and $O_2/CuCl$[124]), have been used either stoichiometrically or in excess to synthesize azobenzenes from aromatic amines. In general, the azo compounds are obtained in low to moderate yields. The oxidation of ethyl-4-aminobenzoate **108** with HgO–I_2 leads to the azo compound **109** in 87% yield (Scheme 30).[125]

The reaction involves a N–N coupling of an initially formed cation radical **I** or **II**, which is probably produced by an one-electron transfer, followed by a two-electron oxidation of the resulting hydrazobenzene **111** to obtain the corresponding azobenzene **36** (Scheme 31).[125] This reagent has also been used in the photochemical oxidation of anilines **112** to obtain symmetrical azobenzenes **113** at room temperature in good yields (Scheme 32).[126]

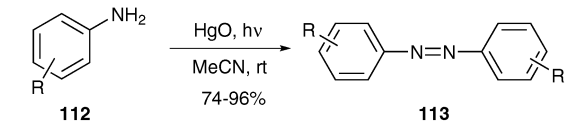
The mechanism of the photochemical synthesis of symmetrical azo compounds involves N–N bond coupling with the radical of aniline produced by one-electron transfer, followed by a two electron oxidation of hydrazobenzene **111** to give azo compound **36**. A hydrogen abstraction from the amino group by photoexcited mercuric oxide, followed by rapid electron transfer forming elemental mercury, is proposed by the authors (Scheme 33).[126] This photochemical oxidation of anilines is only useful to obtain symmetrical azobenzenes. When an equimolar mixture of two different anilines is irradiated in the presence of HgO, two symmetrical and one unsymmetrical azobenzenes are formed in moderate to low



Scheme 30

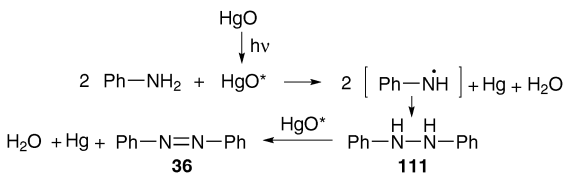


Scheme 31



R = H, 2-Me, 3-Me, 4-Me, 4-Et, 2-OMe, 3-OMe, 4-OMe, 2,4-$(OMe)_2$, 2-NO_2, 3-NO_2, 4-NO_2, 4-CN, 4-F, 2-I, 4-I, 2-Cl, 4-Cl, 2-Br, 4-Br, 2,4-Cl_2, 2,6-Cl_2, 2,4-Br_2, 2-NH_2, 3-NH_2, 4-NH_2, 4-NMe_2

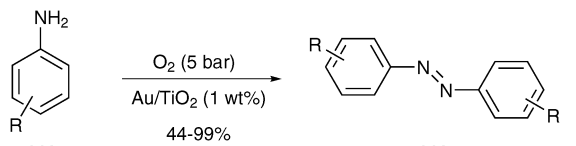
Scheme 32



Scheme 33

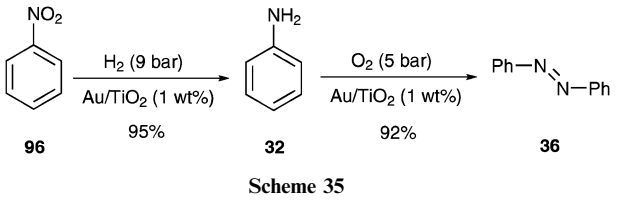
yield. The authors explain these results for the coupling of the different radical intermediates formed during the irradiation.

A drawback of this method is that the metal salts are used in stoichiometric amount and are not environmentally friendly oxidants. There are few examples describing catalytic procedures for this reaction to date. In 2008, Corma and coworkers reported that gold nanoparticles supported on titanium dioxide (TiO_2) catalyze the oxidation of anilines **112** using oxygen as oxidant to form azo compounds **113** with high selectivities and good yields (Scheme 34).[127] They also described the synthesis of azobenzenes from nitrobenzene **96** through a two step one-pot process: first, reduction of nitrobenzene **96** with hydrogen over Au/TiO_2 and second, oxidation of aniline **32** with the same catalyst to give azobenzene **36** in high yield (Scheme 35).

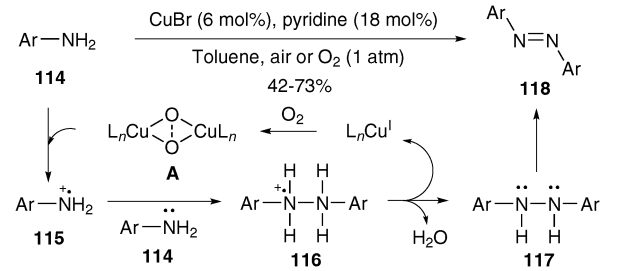


R = H, OCH_3, CH_3, Cl, $COCH_3$, $N(CH_3)_2$

Scheme 34



Scheme 35

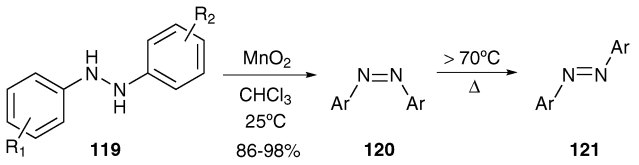


Scheme 36

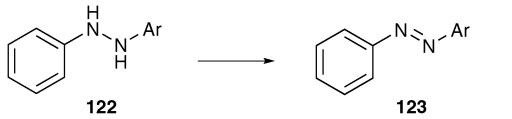
Zhang and coworkers have described the synthesis of azo compounds using air or dioxygen as the oxidant and a copper catalyst under mild conditions.[128] Copper (I) chelated with pyridine is oxidized by dioxygen to form a more active complex **A**. A single-electron oxidation of aniline **114** into the corresponding radical cation **115** followed by coupling of **115** with another molecule of **114** forms a three-electron sigma bond **116**. These species were pointed out by Pauling.[129] Instead of being the transition state for electron transfer between the components, a bonded, inner-sphere species is often lower in enthalpy than the separated components, and an intermediate for electron transfer between them. **116** donates two protons and one electron to form hydrazine **117**. The hydrazine formed is later oxidized by the copper (II) complex or dioxygen to generate the corresponding azo compound **118** (Scheme 36).

2.7 Dehydrogenation of arylhydrazines

Several examples of azo compounds obtained by dehydrogenation of the corresponding *N*,*N*′-diarylhydrazines have been reported. Oxidants used in stoichiometric amounts include $Pb(OAc)_4$,[130] $(NH_4)_2S_2O_8$,[131] *N*-bromosuccinimide in pyridine,[132] tetrabutylammonium cerium(IV) nitrate,[133] $K_3Fe(CN)_6$ in the presence of 2,4,6-triphenylphenol or 2,4,6-tri-*tert*-butylphenol,[134] $CuCl_2$,[135] air/NaOH,[136] $(PhSeO)_2O$[137] or $PhSeO_2H$,[138] arylsulfonyl peroxide reagents,[139] $NaNO_2$ in acetic anhydride[140] and $NaNO_2/NaHSO_4$ on silica.[141] Generally, the yields from the dehydrogenation are good (72–99%) for short reaction times (5 min–2 hours). When MnO_2 is used as an oxidant at room temperature and in the absence of light, starting from *ortho* and/or 3-substituted hydrazobenzenes **119**, the corresponding *cis*-azobenzenes **120** are obtained in good yield (Scheme 37). On the other hand, thermal isomerization of *cis*-azobenzenes **120** to *trans*-azobenzenes **121** takes place at temperatures above 70 °C. *cis*-Azobenzenes **120** are obtained with exception of systems with strongly conjugated 4-substituents such as NHAc, OAc, OMe, where *trans*-azobenzenes **121** are obtained.[142]

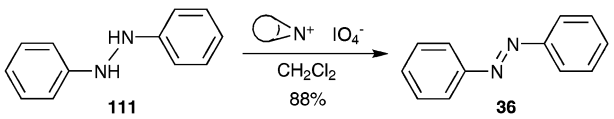


Scheme 37



Ar	$TiCl_3$/HBr	NH_4VO_3
C_6H_5	95	96
2,4-$(NO_2)_2$-C_6H_3	88	47
4-OMe-C_6H_4	95	82

Scheme 38



Scheme 39

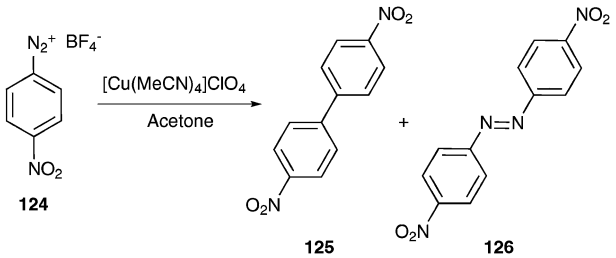
There are only few examples of catalytic oxidation of arylhydrazines to the corresponding azo compounds. Using oxygen or H_2O_2 as an oxidant, NH_4VO_3[143] and Co(II) complexes[144] are able to catalyze this transformation. Moreover, $FeSO_4$ has shown to function as a hydrazo group oxidation catalyst when a mixture of $KClO_3/H_2SO_4$ is used as an oxidant.[145] The system $TiCl_3$/HBr, with H_2O_2 as the oxidant,[146] is able to catalyze the oxidation of hydrazo derivatives **122** to the corresponding azo compounds **123** in very good yields. This system is more effective than NH_4VO_3 (Scheme 38).

Recently, azobenzene **36** has been synthesized from hydrazobenzene **111** in 88% yield using a periodate containing polyethylene imine resin (Scheme 39).[147]

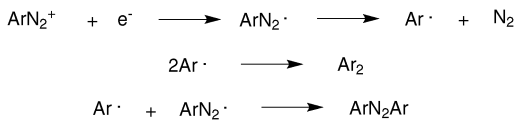
2.8 Dimerization reaction of diazonium salts

Aromatic azo compounds have been obtained by dimerization of diazonium salts when treated either with copper metal and an acid (Gatterman's method) or with copper(I) salts.[148] This process is highly dependent on the nature of the aryl groups. When the aromatic rings have electron-withdrawing substituents such as **124**, a C–C coupling occurred to give the biaryl **125** as the main product. In contrast, electron-donating substituted diazonium salts gave mainly the azo compound analogues of **126**.[149] The biaryl : azo compound ratio increases when the concentrations of the diazonium salt and copper(II) increase and the concentration of copper(I) decreases (Scheme 40).

The mechanism of this dimerization probably involves free radicals formed by the initial transfer of one electron to the diazonium salt. An aryl radical formed from the elimination of



Scheme 40



Scheme 41

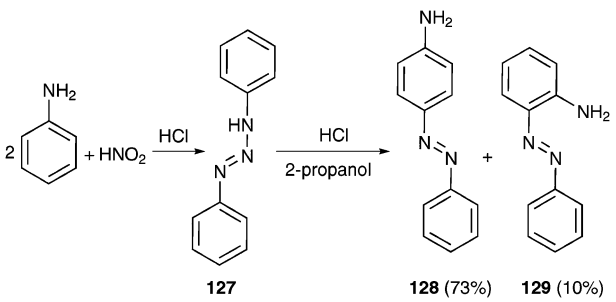
nitrogen in the diazonium radical can couple itself to obtain the biaryl or with the diazonium radical to give the azo compound (Scheme 41).[148]

2.9 Triazene rearrangement

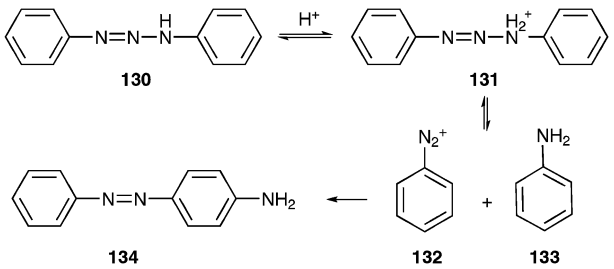
The reaction was originally discovered by Nietzki in 1877. In an acid media triazene **127** gives the azo compound **128** in 73% yield and the isomer **129** in 10% yield. This latter compound results from the *ortho* rearrangement.[150] Yields are normally low because of homolytic side reactions. The addition of small amounts of radical scavengers like acrylonitrile or methacrylates reduces the side reactions. Formation of triazene and the rearrangement are carried out in a single step (Scheme 42).

An intermolecular mechanism was proposed for this reaction.[151] Friswell–Green's mechanism consists of three steps: first, the protonation of the triazene **130**, second, the dissociation to the diazonium ion **132** and aniline **133** and third, the C-coupling of these species to obtain the azo compound **134** (Scheme 43).

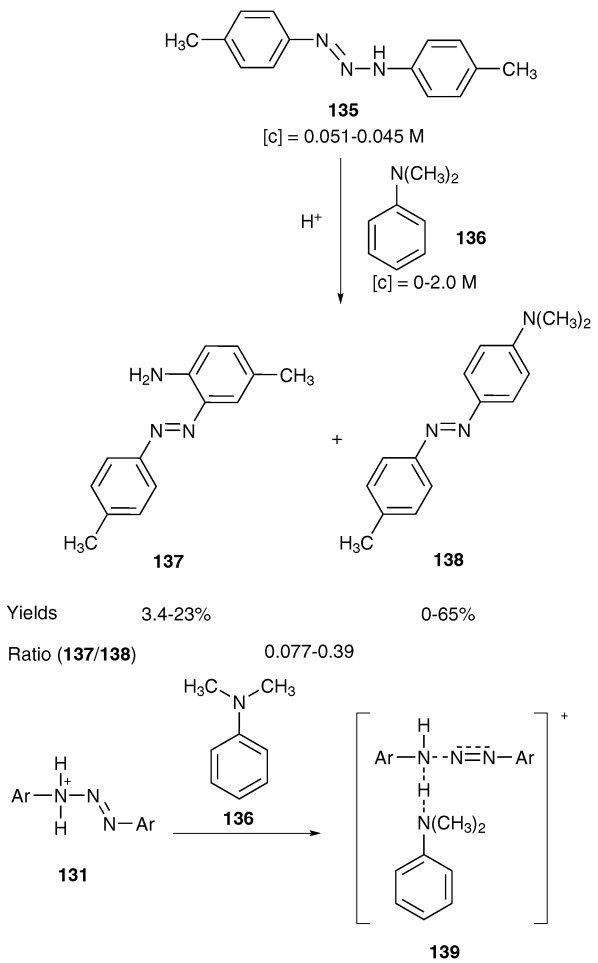
A study on the effect of *N*,*N*-dimethylaniline (DMA) **136** as a trapping agent for the diazonium ion intermediate **132** suggested a partial intramolecular character of the rearrangement.[150] The rearrangement provides a mixture of azobenzenes **137** and **138** in low to moderate yields (0–65%) and ratios **137**/**138** between 0.077 and 0.39 depending on [DMA]. The ratio **137**/**138** decreases until [DMA] = 0.75 M, but with increasing [DMA] > 0.75 M, the ratio **137**/**138** increases to 0.25. There is an increase of intramolecular nature



Scheme 42



Scheme 43

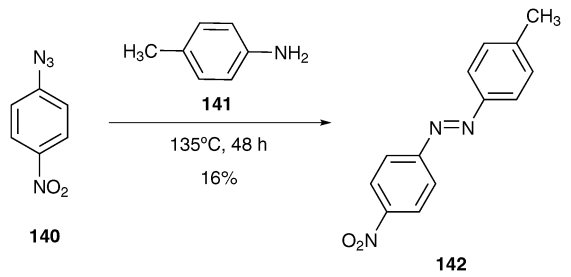


Scheme 44

of the rearrangement at very high [DMA]. The authors proposed that an increased nucleophilicity of the complex **139**, formed from the conjugate acid **131** of the triazene, may be due to hydrogen bonding with *N*,*N*-dimethylaniline **136** (Scheme 44). High viscosity solvents favor such *ortho* migration.

2.10 Thermolysis of azides

Aromatic azides when heated in the presence of anilines lead to unsymmetrical azo compounds in low yields. For instance, the decomposition of 4-nitrophenyl azide **140** at 135 °C in the presence of 4-methylaniline **141** gives the azobenzene **142** in 16% yield (Scheme 45).[152]



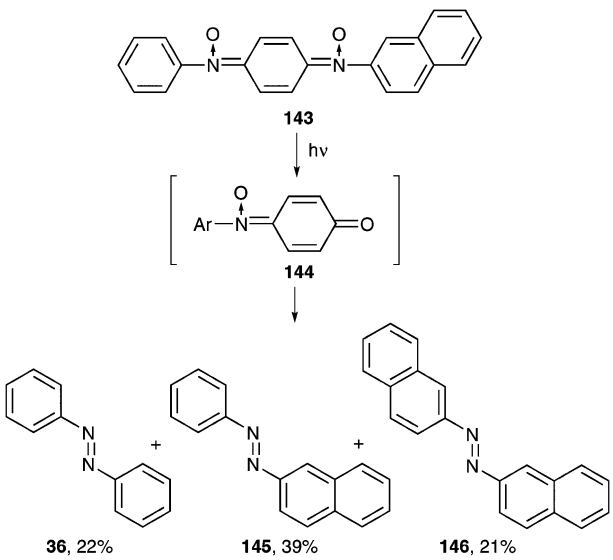
Scheme 45

Such a reaction is more efficient when the electronic effects of the substituents on the two rings oppose each other. The nature of the substituent is more crucial in azide than in aniline. The usefulness of this method is limited since the azides are explosive compounds and difficult to handle.

2.11 Decomposition of *N*,*N*′-*p*-benzoquinonediimine dioxides

Dialkyl or diarylsubstituted *N*,*N*′-4-benzoquinonediimines dioxides are very sensitive to light. They decompose quickly and quantitatively to generate 4-benzoquinonimines *N*-oxides, which in turn, transform into *p*-benzoquinone and azo compounds.

Formation of the latter depends upon the substituents on the nitrogen atoms. If the substituents are different but similar in nature, the nitrogens are activated to the same extent, and three different azo compounds are formed. The photochemical decomposition of *N*-phenyl-*N*′-(2-naphthyl)-4-quinonedimine-*N*,*N*′-dioxide **143** gives a mixture of three azobenzenes: azobenzene **36**, 2-(phenylazo)naphthalene **145** and 2,2′-azonaphthalene **146** (Scheme 46).[153] If the substituents on the nitrogen atoms are of aliphatic and aromatic nature, the aryl nitrogen is activated more easily than the aliphatic nitrogen and the symmetrical aromatic azo compound is formed. As for the previous case (Section 2.10), the preparative interest of this method is quite limited.



Scheme 46

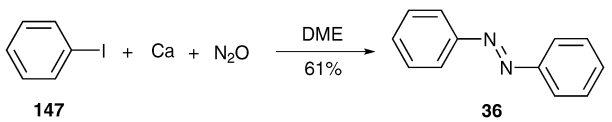
2.12 Reaction of arylcalcium derivatives with nitrous oxide

Arylcalcium derivatives constitute good starting materials to synthesize azobenzenes. The reaction between iodobenzene **147**, calcium metal and nitrous oxide in dimethoxyethane leads to azobenzene **36** in 61% yield (Scheme 47).[154] When the reaction is carried out with organolithium compounds instead, the yield of the target compound is very low (7–16%).[155] Phenylcalcium iodides are generated from iodobenzenes or substituted iodobenzenes and calcium under reflux in ethereal solvents.

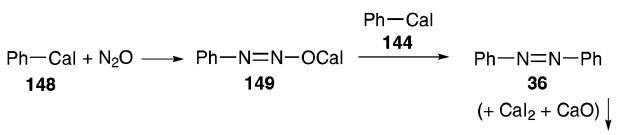
The mechanistic process to form C–N bonds in this reaction is not well understood. Diazotate **149** is formed directly from the reaction between phenylcalcium iodide **148** and nitrous oxide, and could be the key intermediate in the reaction. A subsequent attack of another molecule of phenylcalcium iodide **148** would generate the second C–N bond (Scheme 48).[156] Alkyl and arylcalcium halides are susceptible to disproportion by the Schlenk equilibrium. An alternative explanation for the formation of azo compounds could involve the diphenylcalcium species $(C_6H_5)_2Ca$ **150**, where insertion of N_2O into the Ca–C bond leading to **151** followed by intramolecular phenyl migration would afford the azobenzenes **36** (Scheme 49).

2.13 Metal catalyzed coupling of arylhydrazines

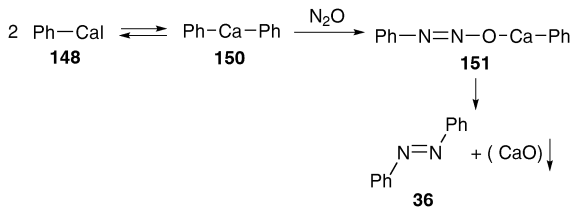
The palladium catalyzed coupling reaction of *N*-Boc arylhydrazines **152** with aryl halides **153** was described in 2003 as a new method for the synthesis of azo compounds **154** (Scheme 50).[157] The resulting diaryl hydrazines were directly oxidized with NBS/pyridine in dichloromethane at room temperature to give the azobenzenes **154** in good yields. In a subsequent report,[158] the authors described the coupling reaction catalyzed by $Pd(OAc)_2$ of *N*,*N*′-bis-Boc arylhydrazine **155** with aryl halide **156** to obtain *N*,*N*′-bis-Boc diaryldihydrazine **157**, which was oxidized to the azobenzene **158** in the presence of copper(I) and a base in 60% yield (Scheme 51).



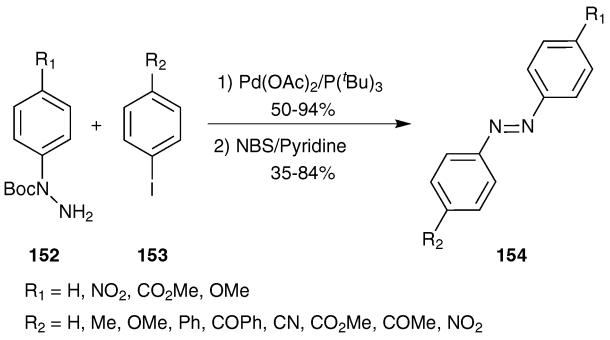
Scheme 47



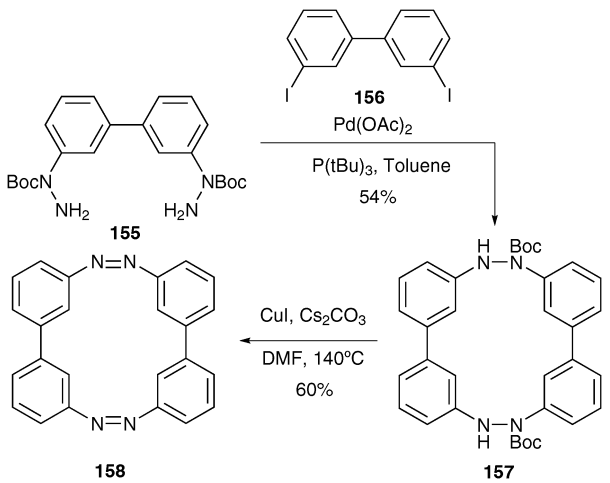
Scheme 48



Scheme 49



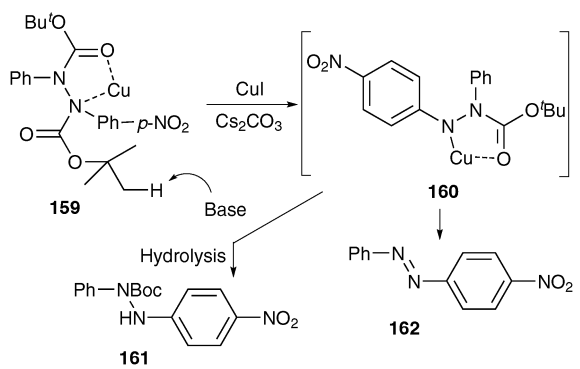
Scheme 50



Scheme 51

The mechanism of this reaction has not been completely elucidated. However, it is argued that the oxidation step proceeds through the initial elimination of the Boc group. By thin-layer chromatography, the initially formed *N*-Boc diaryl hydrazine **159** evolves into a more polar product whose structure could correspond to **160**. The mono-Boc protected diarylhydrazine **161** has been isolated from the reaction following hydrolysis, before the conversion to less polar azo compound **162** (Scheme 52).[159]

The synthesis of 1,3,5-tris-azobenzenes from 1,3,5-trihalobenzenes by Pd-catalyzed coupling of *N*-Boc arylhydrazines and further oxidation with Cu(I) has been reported. The oxidation of the tris-arylhydrazide initially formed produces



Scheme 52

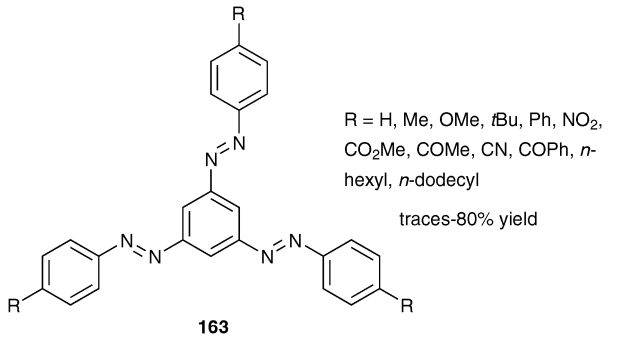


Fig. 2 1,3,5-tris-azobenzenes

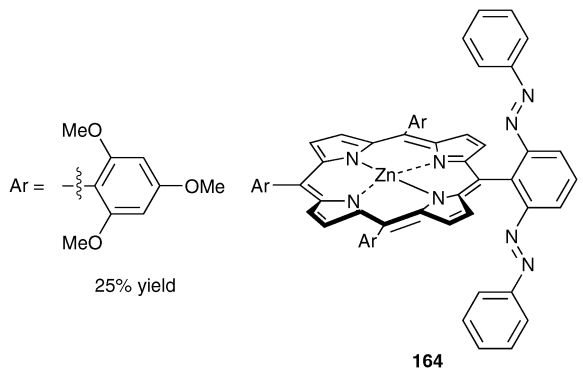


Fig. 3 Zn-Phorphyrin

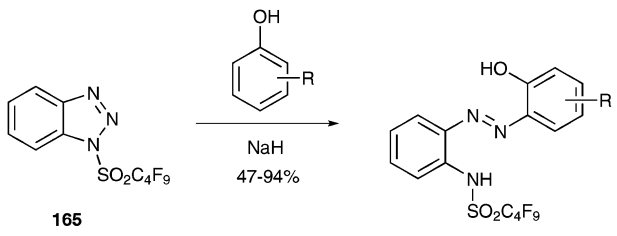
the azobenzene **163** as a mixture of four *E*/*Z* isomers of the 1,3,5-tris-azobenzene (Fig. 2).[160]

Recently, Hecht has described the incorporation of azobenzene units into tetraphenylporphyrin skeletons using this method.[161] The final compound **164** has a geometry where the phenylazo groups are above and below the plane of the macrocycle (Fig. 3).

2.14 Opening of benzotriazoles

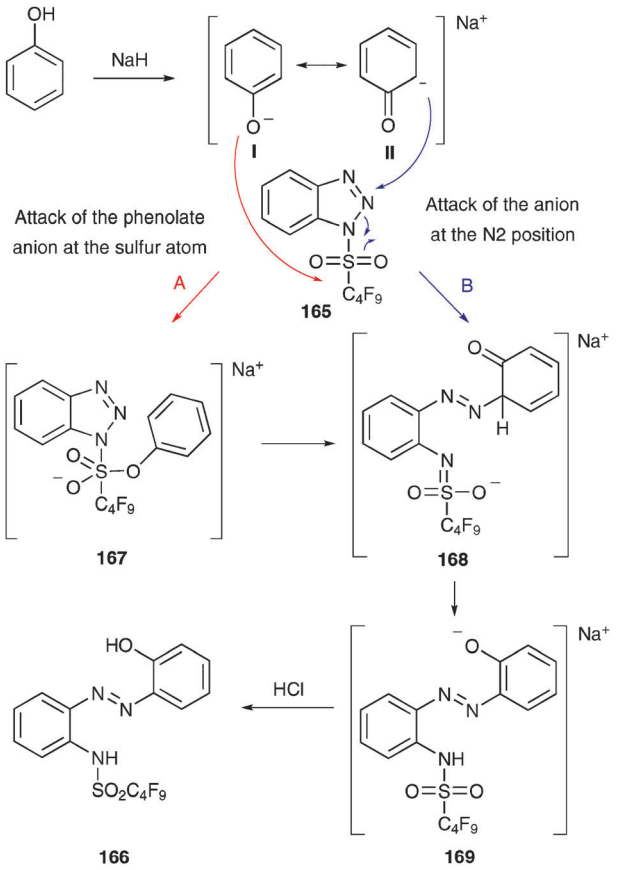
Ziegler and Subramanian have described a direct approach to prepare 2-hydroxyazobenzenes **166**, from benzotriazoles **165** by reaction with phenols (Scheme 53).[162] Due to the presence of the strongly electron-withdrawing nonafluorobutanesulfonyl group, the opening of the heterocyclic ring occurred easily. The azo compounds **166** are formed after acid hydrolysis in yields ranging between 47–94%.

The reaction mechanism leading to the formation of azobenzene **166** is shown in Scheme 54 (pathway A). Nucleophilic attack

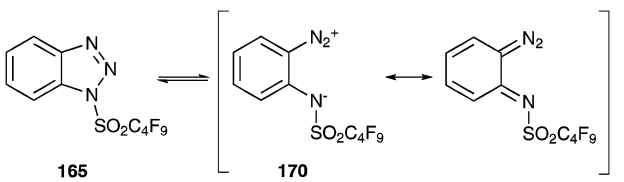


R = H, 2-methoxy, 4-methyl, 3-butyl, 4-hydroxy, 1-napthyl, 2-naphthyl

Scheme 53



Scheme 54



Scheme 55

of the phenolate anion **I** at the sulfonyl group of **165** results in ring opening of the triazole moiety giving rise to compound **167**. This is followed by a rearrangement to intermediate **168**. However, this process only leads to the 2-substituted azobenzene **166**.

A second possible path for the formation of the azo compound is the attack of the phenoxide anion **II** on the *N*-2 position of **165**, inducing the opening of the triazole ring and formation of the azo compound **168** that evolves to obtain the azobenzene **166** (Scheme 54, pathway B).

A third proposal, shown in Scheme 55, involves a free diazonium intermediate **170** that would exist in equilibrium with benzotriazol **165** (Scheme 55).[162] The existence of free diazonium species in equilibrium with the 1,2,3-triazole ring is known for the parent 1,2,3-triazole substituted with a sulfonyl group at *N*-1. This equilibrium has been confirmed by ^{1}H-NMR studies.[163] The stability of these species is enhanced by charge delocalisation into the aromatic ring.

2.15 Reaction of quinones with arylhydrazines

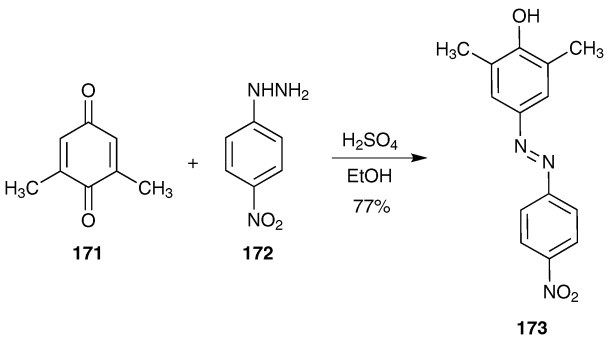
The reaction of quinone **171** with phenylhydrazine **172** in acid medium to give azo compound **173** in 77% yield has been described (Scheme 56).[164]

In 1963, Hecker and Lattrell reported the oxidation of alkylphenols with thallium triacetate to 4-alkyl-4-hydroxycyclohexadienones.[165] These compounds react with 2,4-dinitrophenylhydrazine in the presence of either acetic acid or sulfuric acid to give the corresponding azobenzenes in low yield. In 1978, McKillop and Taylor described a similar method to replace a phenolic hydroxy group by the N=NAr group.[166] The oxidation of 4-methoxyphenol **174** with thallium(III) nitrate in methanol gives rise to monoketal *p*-benzoquinone **175**. The subsequent addition of an arylhydrazine **176** in the presence of an acid ($BF_3{\cdot}Et_2O$) forms hydrazone **177**, having lost an acidic hydrogen in the α position to C=N in a spontaneous aromatization by elimination of MeOH obtaining the azo compound **178** in 99% yield (Scheme 57).

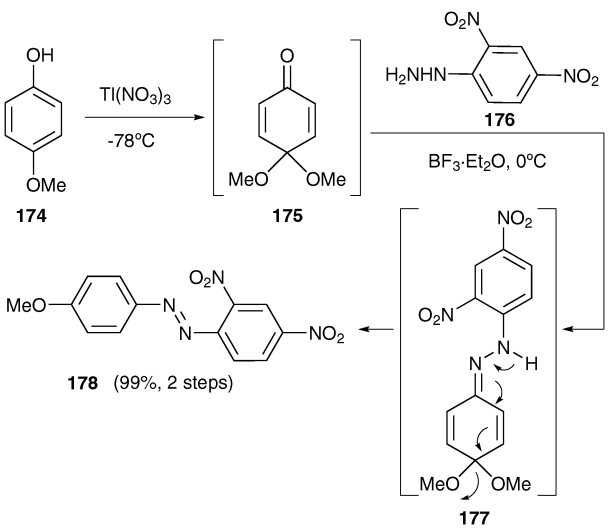
For the example shown in Scheme 58, the reaction between *p*-benzoquinone-crown ether **179** and 2,4-dinitrophenylhydrazine **176**, in the presence of H_2SO_4, gave the azophenolic crown ether **180** in 81% yield.[167]

2.16 Reaction of quinone acetals with arylhydrazines

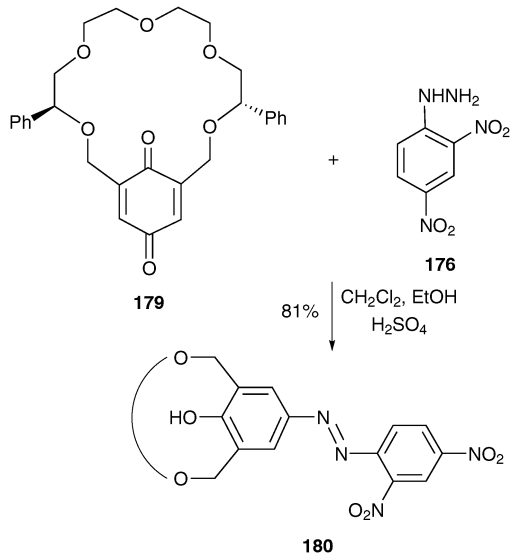
Carreño *et al*. reported in 2004, the reaction of quinone acetals **181**, which are easily obtained by anodic oxidation of



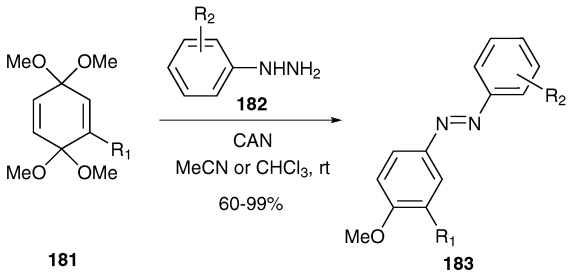
Scheme 56



Scheme 57



Scheme 58



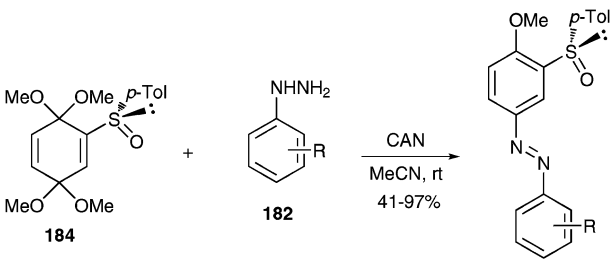
R_1 = H, OMe, SO*p*-Tol

R_2 = 2,4-$(NO_2)_2$, *o*-NO_2, *p*-NO_2, *o*-Br, *o*-CF_3, 2,5-F_2, 2,3,4,5,6-F_5, 2,3,5,6-F_4-4-CF_3, H, *p*-OMe

Scheme 59

1,4-dimethoxybenzenes, and aryl hydrazines **182** provided azobenzenes **183** in good yields (Scheme 59).[168] The presence of catalytic amounts of cerium ammonium nitrate ($(NH_4)_2[Ce(NO_3)_6]$, CAN) reduced the reaction times. When the bisacetal core has one substituent only one regioisomer is obtained.

The regioselective synthesis of optically pure *p*-tolylsulfinyl azobenzenes **185** from *p*-tolylsulfinyl functionalized *p*-quinone bisketals **184** and arylhydrazines **182** was later reported by the same authors (Scheme 60).[169] The study of their photoresponsive behavior by circular dichroism evidenced that the position of the sulfoxide group in the azobenzene causes two different



R = 2,5-F_2, 2,3,4,5,6-F_5, *o*-Br, *p*-Br, 2,4-$(NO_2)_2$

Scheme 60

chiral responses. Thus, the presence of the *p*-tolylsulfinyl group at C-3 induced a transfer of chirality from the stereogenic sulfur to the N=N group in both the *trans* and *cis* isomers. However, when the sulfoxide is at C-2, this transfer of chirality only occurred in the *cis* isomers. This different chiroptical response is a consequence of a conformation fixed by the sulfoxide, as deduced by NMR studies. Choosing the appropriate location of the sulfoxide in the azobenzene, a conformational change could be induced in a controlled manner by irradiation, and the overall disposition of the systems can be controlled during the *trans* to *cis* N=N double bond isomerization.

The inhibition of this reaction with triethylamine suggested the possible existence of acidic species triggering the reaction. The suspected active species could be a radical cation from the one-electron oxidation of arylhydrazine by air. This acidic species should catalyze the condensation of hydrazine with one of the acetal groups forming a hydrazone intermediate, which provides the azo compound by methanol elimination. In this way, the addition of catalytic amounts of CAN, an one-electron oxidant, increases the reaction rate. No reaction was observed with alkylhydrazines such as benzyl or *N*,*N*-dimethylhydrazine. These observations also point to the existence of an intermediate radical cation as a possible catalyst which is easily formed from aromatic hydrazines.[170]

3. Conclusions

The azobenzenes are very important compounds due to their wide range of properties and applications. This review summarizes the methods of synthesis of azo compounds described in the literature at present time. The most used methods have been the azo coupling, the Mills reaction and the Wallach reaction. These methods present some disadvantages. In the case of the azo coupling, the diazonium salts used can be explosive and it is necessary to control the temperature of the reaction. In the Mills reaction, and the Wallach reaction to synthesize the nitroso compounds and the azoxybenzenes stoichiometric or excess amounts of oxidant or reductant reagents are necessary and subproducts are obtained. In the reduction of azoxybenzenes, also is necessary an excess of reductant reagent. Only a few catalytic strategies have been described in the synthesis of azobenzenes by reductive coupling of aromatic nitro derivatives, oxidation of anilines, and dehydrogenation of arylhydrazines. In these cases, symmetrical azobenzenes are obtained. The opening of benzotriazoles only allows to obtain 2-hydroxy azobenzenes. By dimerization of diazonium salts, triazene rearrangement, thermolysis of azides, reaction of arylcalcium derivatives with nitrous oxide and decomposition of *N*,*N*′-*p*-benzoquinone-diimine dioxides, the azo compounds are obtained in low yields and the preparative interest of these methods is limited. Azobenzenes are synthesized in good yields by metal catalyzed coupling of arylhydrazines. The reaction of quinones and quinone acetals with arylhydrazines allows under mild conditions to synthesize azo compounds in high yields. Although there are different methods to obtain azobenzenes, they present limitations. It is necessary to continue researching to find new efficient methods of synthesis.

Acknowledgements

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