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HETEROPENTALENE MESOMERIC BETAINES OF TYPE C: PROGRESS SINCE THE EARLY 1980s

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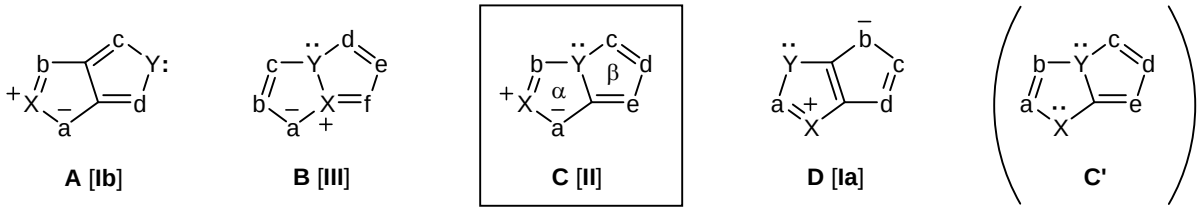
Abstract – This account briefly summarizes the achievements made in the last twenty-five years. Synthesis, properties, and reactivity are dealt with here.

INTRODUCTION

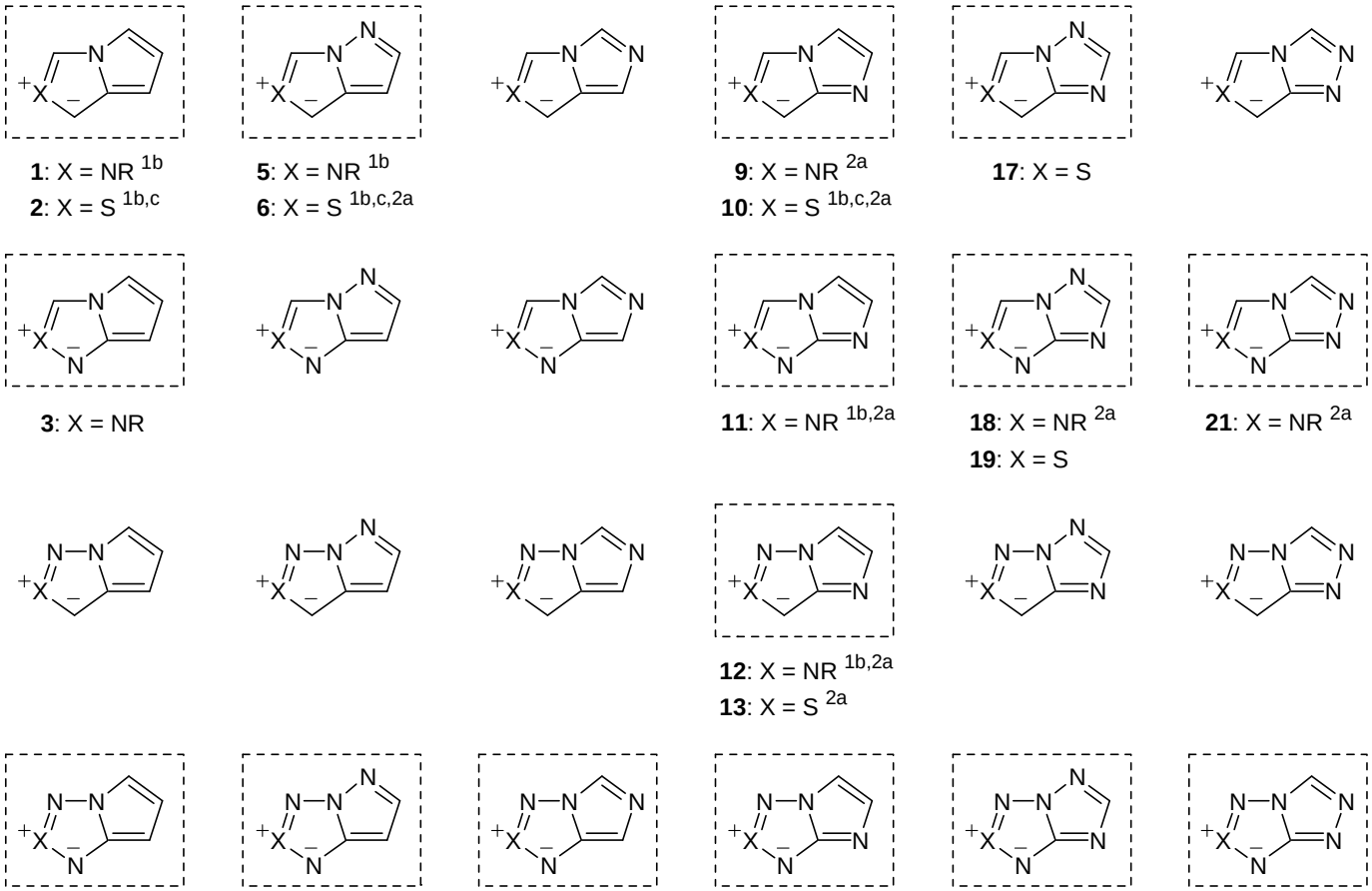
The term 'heteropentalene mesomeric betaine'[1a,b] describes a heterocyclic system that is isoconjugate with the pentalene dianion and that cannot be represented by a classical Kekulé structure (hence the shorter name 'non-classical heteropentalen'[1b]). Within this class of compound four general types are discerned, denoted as **A**, **B**, **C**, and **D**[1a,b] (corresponding to **Ib**, **III**, **II**, and **Ia** after a less common classification[2b]) (Figure 1). When the interesting field was surveyed for the last time in the early 1980s,[1b,c] the title system (**C**) was comparatively new[3] and findings were of limited number (see also *passim*[2a]). However, studies have been intensified since, and results have grown to such an extent as to warrant a separate review. Out of 24 conceivable scaffolds[4] grouped in Figure 2, no less than 15 variants are known to date (see framed structures); some exhibit different atoms or units for X, thereby affording the individual systems (**1–22**).[5] Certain representatives, *viz.* **1**, **2**, **5**, **6**, **9–13**, **15**, **16**, **18**, and **21**, already existed at the time of the previous surveys,[1b,c,2a] but fresh material on most systems requires treatment again. Two series appear 'complete,'



X,Y = 2π-donor atom; a-f = 1π-donor atom

Figure 1. The 4 types of non-classical heteropentalenes after Ramsden[1a,b] [and Chuiguk [2b]]
(in parentheses: the most important 'neutral' isomer of the title class)

i.e. those having (i) as α half-ring a tetrazole (**4**, **7**, **8**, **14**, **20**, **22**) and (ii) as β half-ring a *b*-fused imidazole (**9**, **11**, **12**, **14**). Conversely, members having as α half-ring either a 1,2,3-triazole (**12**) or a 1,2,3-thiadiazole (**13**) are still rare; the same applies to those bearing as β half-ring a *c*-fused imidazole (**8**).

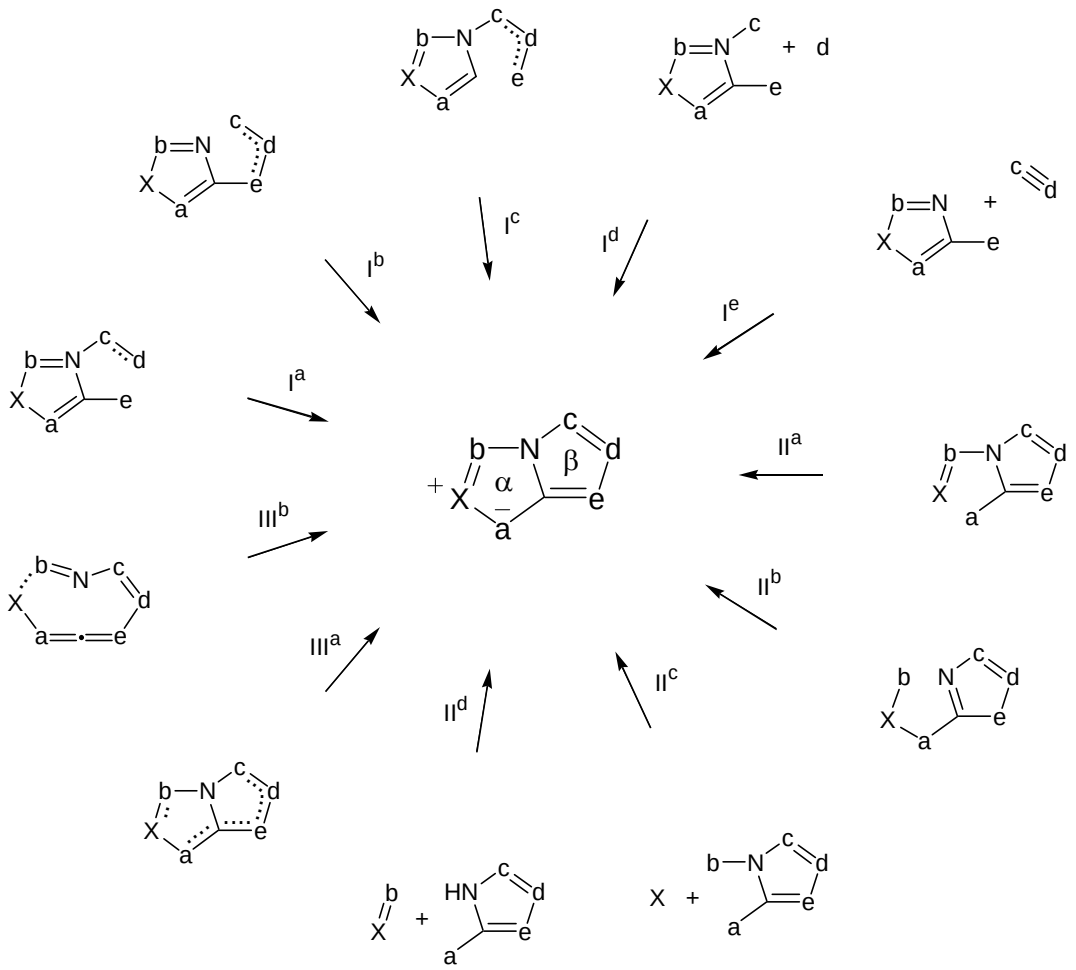


Method (Scheme 1)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
I[a]			+	+					+	?	+	+	+	+			+					
I[b]		+			+	+				+												+
I[c]																		+				
I[d]			+	+										+								
I[e]								+														
II[a]																			+			
II[b]																					+	
II[c]										+			+		+	+						
II[d]	+																					
III[a]	+	+		+		+	+			+								+		+		
III[b]													+									

Figure 2. Survey of known type C systems and methods for their construction

SYNTHESIS

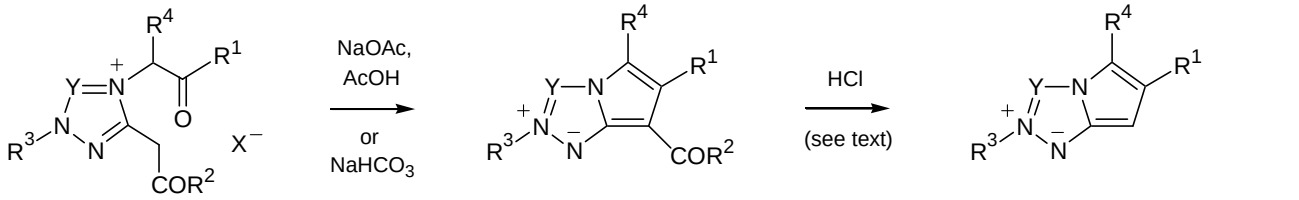
Presentation of material in this chapter is organized according to preparative methods rather than to products. As illustrated by Scheme 1, a total of 11 synthetic principles are encountered; they may be divided into three major categories: (i) Cyclization of a functionalized monocycle that provides the α half-ring of the required bicycle; here five modes exist, three of them represent an intramolecular ring closure (I^a, I^b, I^c), whereas the remainder are characterized by incorporation of an external component (I^d, I^e); (ii) application of the preceding concept based on the β half-ring to include the variants (II^a, II^b) and (II^c, II^d), respectively; (iii) transformation of a non-aromatic heteropentalene or an aromatic heteropentalene anion (III^a) and, secondly, ring closure of an eight-membered scaffold lacking the bicycle′s central bond (III^b). It should be recalled that, using appropriate educts, some of these principles match those leading to the 'neutral' type C' system.



Scheme 1. Synthetic principles applied (formal charges of educts omitted)

Method I^a: Here application of the Tschitschibabin reaction and its nitrogen variant prevails (Scheme 2): The process – established as an efficient tool for constructing type C' pyrrolo- and imidazoazoles[6] – has

turned out suitable for making quite a number of non-classical congeners. Systems already described in the previous reviews include: (i) imidazo[1,2-*c*]thiazole (**10**);[1b, 2a] (ii) the couple of imidazo[1,2-*c*][1,2,3]-triazole (**12**)[1b, 2a] and imidazo[1,2-*c*][1,2,3]thiadiazole (**13**);[2a] (iii) imidazo[1,5-*a*]imidazole (**9**) and imidazo[2,1-*c*][1,2,4]triazole (**11**) as the relevant moieties of imidazo[1',2':3,4]imidazo[1,2-*a*]pyridine [2a] and imidazo[2',1':3,4][1,2,4]triazolo[1,5-*a*]pyridine/pyrimidine,[1b, 2a] respectively. Regarding access to the latter, *viz.* **11a**, the short note[7a] cited by the former reviewers[1b, 2a] was followed by a detailed description a few years later.[7b] Of more recent vintage are derivatives of pyrrolo[2,1-*c*][1,2,4]triazole (**3a**),[8a] pyrrolotetrazole (**4a**),[9a] and imidazo[1,2-*d*]tetrazole (**14a**),[10] most of which were obtained in reasonable yield. The acceptor (COR^2) in **23** and **24** is compulsory since an unsubstituted methyl group is inactive in both cases;[11, 12] from **3a** (R^2 = OEt) and **4a** (R^2 = Me, OMe) the auxiliary function is removed with mineral acid to give **3b** and **4b**. Contrasting with **24** (R^1 = Me, R^4 = H), the congener (**26**; R = Me) could not be cyclized.[9c] A process that is formally related to the Tschitschibabin reaction constitutes ring closure of the thiazolium salts (**27**)[13] (Scheme 3). These species once formed from the open-chain compounds shown cyclize to the benzenesulfonates of the thiazolo[3,4-*b*][1,2,4]triazoles (**17a**). The latter salts were converted into the perchlorates which on treatment with base gave the free heteropentalenes in fair yield.

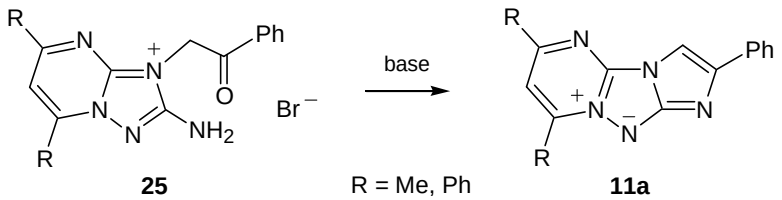


23: Y = CH, CMe; R^4 = H; X = Br
24: Y = N; R^4 = H, Me; X = BF_4, $MeOSO_3$

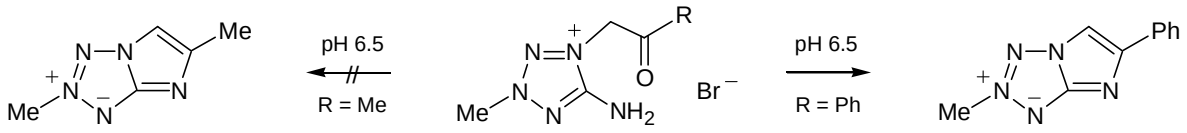
3a: Y = CH, CMe; R^4 = H
4a: Y = N; R^4 = H, Me

3b: Y = CMe; R^1= R^3 = Ph; R^4 = H
4b: Y = N; R^1= Me, Ph, 4-BrC_6H_4; R^3 = Me, Ph; R^4 = H, Me

R^1 = Me, Ph, 4-BrC_6H_4; R^2 = Me, OMe, OEt; R^3 = Me, Ph

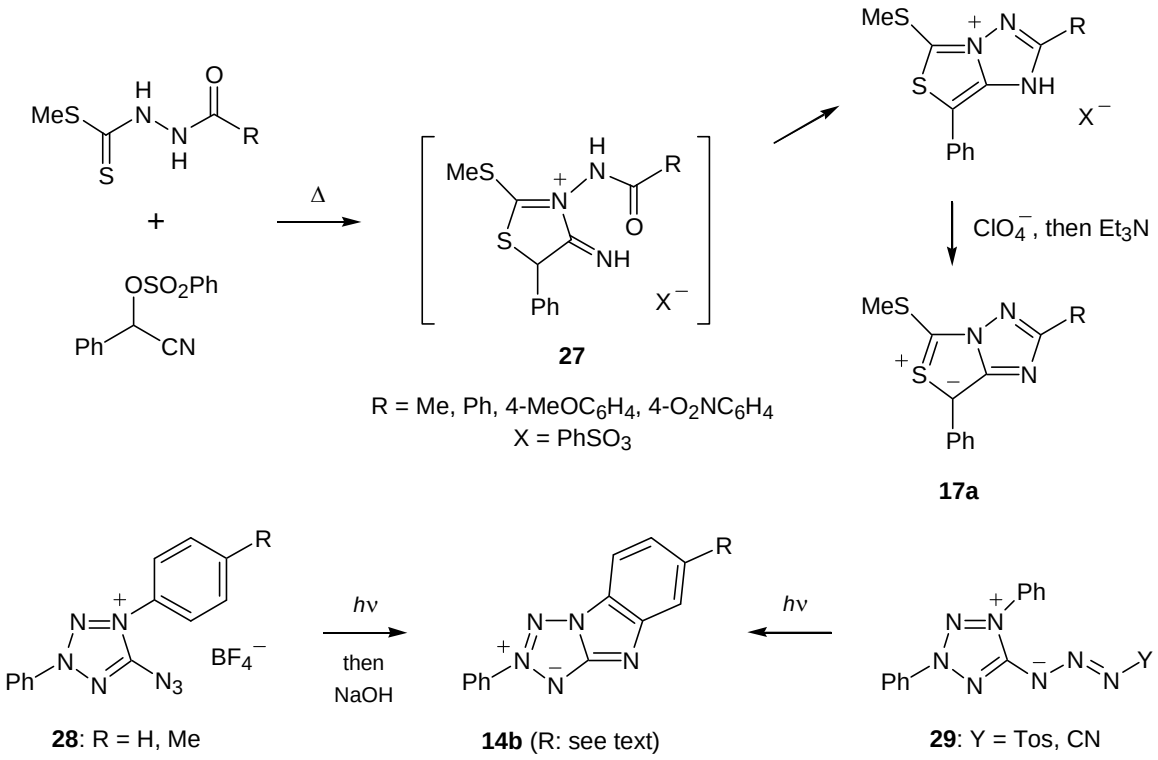


25 R = Me, Ph **11a**



26: R = Me, Ph **14a**

Scheme 2

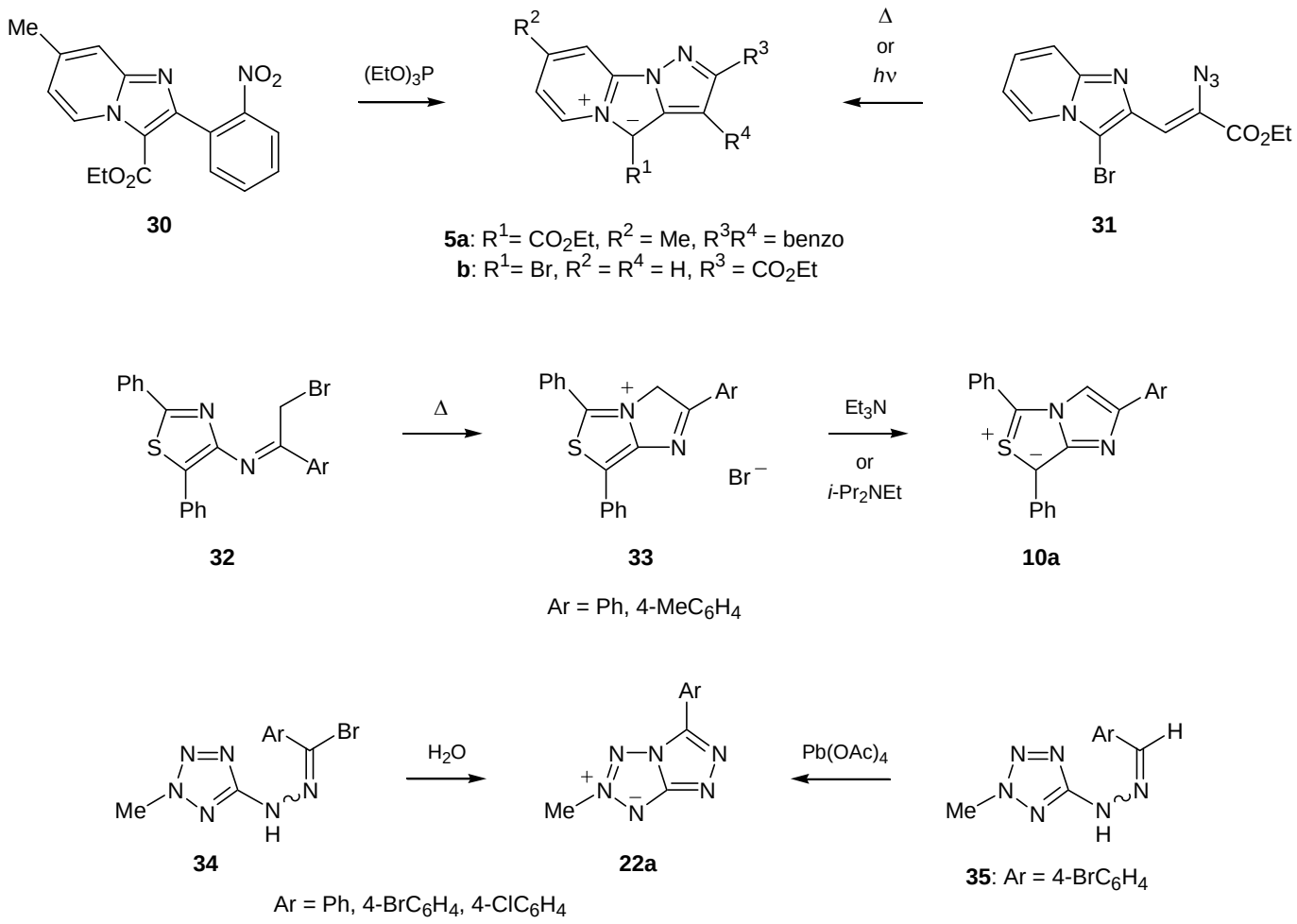


Scheme 3

A final I[a] type reaction gives rise to benzo-fused derivatives of imidazo[1,2-*d*]tetrazole (**14**), *viz.* the tetrazolo[1,5-*a*]benzimidazoles (**14b**; R = H, Me). Here intramolecular cyclization consists in nitrene insertion into aromatic C–H. Thus, photolysis of the azidotetrazolium salts (**28**; R = H, Me) conducted in acetonitrile as solvent led to the corresponding tricycles in 35 and 22 % yield, respectively.[14a] Using methanol, a mere 20% of **14b** (R = H) was obtained while, owing to the action of triplet nitrene, 1,3-diphenyltetrazolium-5-aminide (23%) was produced as a major side component. Formation of **14b** (R = H) occurs also on irradiation of the triazenides (**29**); again acetonitrile turned out to be superior, affording the heteropentalene in 32% (Y = Tos) and 9% yield (Y = CN), respectively.[14b]

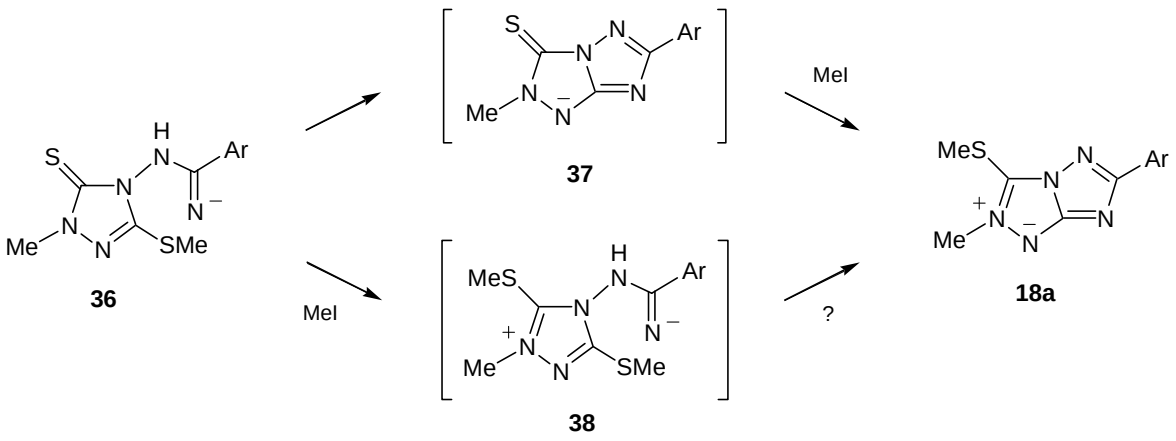
Method I[b]: This kind of intramolecular ring closure includes two types of reaction: (i) Attack of a nitrene on pyridine-like nitrogen to afford a pyrazole as β half-ring, and (ii) alkylation or hydrazonoylation followed by proton loss to give, depending on the side chain, a pyrrole, an *a*-fused imidazole or a *c*-fused 1,2,4-triazole half-ring.

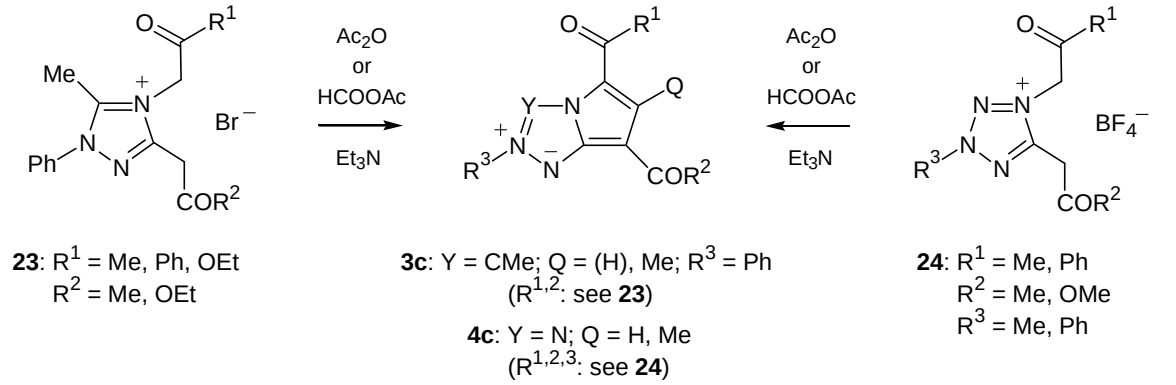
(i) Utilized earlier as an entry to the pyrazolo[1,5-*c*]thiazole scaffold (**6**), *i.e.* to thiazolo[3,4-*b*]indazole[3] (covered by refs.[1b, 2a]), this route was followed to construct the imidazo[1,5-*b*]pyrazole system (**5**) present in the tricycles (**5a**)[15] and (**5b**)[16] (Scheme 4). As expected, N–N bond formation occurs only when C(3) of **30** and **31** carries a substituent, otherwise the nitrene inserts into C–H giving a pyrido[2',1':2,3]imidazo-[4,5-*b*]indole.[15,16] While the amount of **5b** has not been specified,[16] **5a** was obtained in 31% yield.[15]

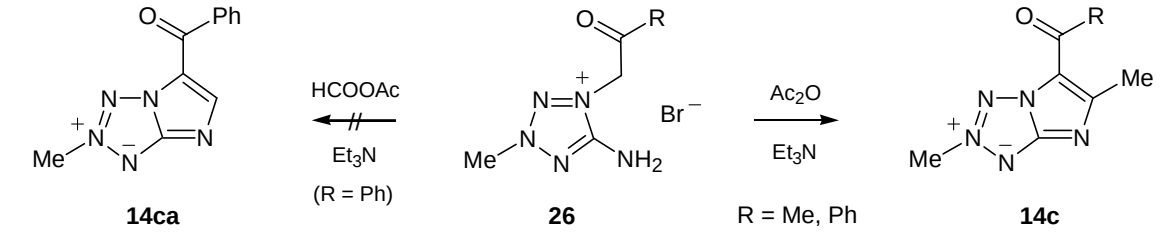


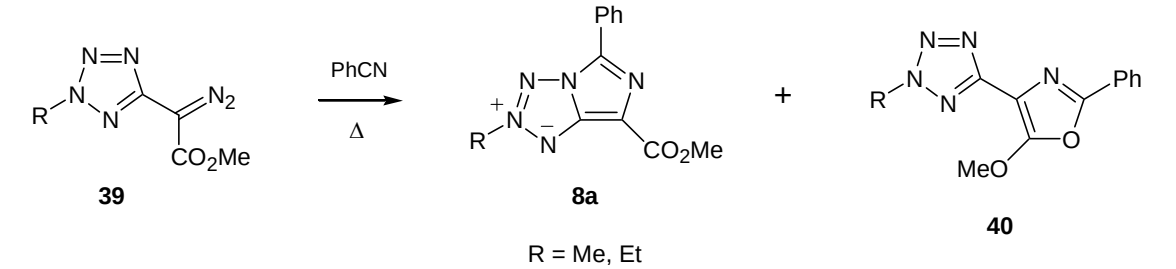
Scheme 4

(ii) In analogy to the earlier synthesis of thiazolo[4,3-*a*]isoindole – a benzo derivative of the pyrrolo[1,2-*c*]thiazole system (**2**),[17a] heating of the (ylidenamino)thiazole (**32**) affords the imidazo[1,2-*c*]thiazolium salts (**33**) as precursors to **10**: The derivative (**10a**; Ar = 4-MeC_6H_4), in contrast to its phenyl congener,[18] was prepared in one stage without isolation of the respective salt (**33**) (75% yield);[19,20] compound (**33**; Ar = Ph) resulted in 83% yield, it gave the free heteropentalene quantitatively.[18] Another ring closure of this category, comprising two variants, leads to the [1,2,4]triazolo[4,3-*d*]tetrazole system (**22**). Solvolysis of the hydrazonoyl bromides (**34**) in dioxane/water generates the derivatives (**22a**) as main products (60–73% yield). These compounds were the first type C heteropentalenes to be prepared but were erroneously viewed as 3*H*-isomers of **22a**.[21a] Their actual constitution was recognized only fifteen years later by other researchers engaged in studies on 3*H*-azolotetrazoles;[22] the unexpected revelation caused the original workers to contribute an X-ray analysis of **22a** (Ar = 4-BrC_6H_4) for confirmation.[21b] Compared to the ring closure of **34**, dehydrogenation of the hydrazone (**35**) is much less efficient (also with respect to the behaviour of the 1*H*-isomeric tetrazolylhydrazones[23]): The corresponding bicycle (**22a**) was obtained in 2% yield only, while as a major product the (open-chain) *N*′-acetylated benzohydrazide was found.[21a]









Scheme 5

Method I[c]: Understanding the high-yielding one-pot synthesis of [1,2,4]triazolo[4,3-*b*][1,2,4]triazoles (**18a**) from **36** and methyl iodide (Scheme 5),[24] the authors considered two modes: (i) A reaction course

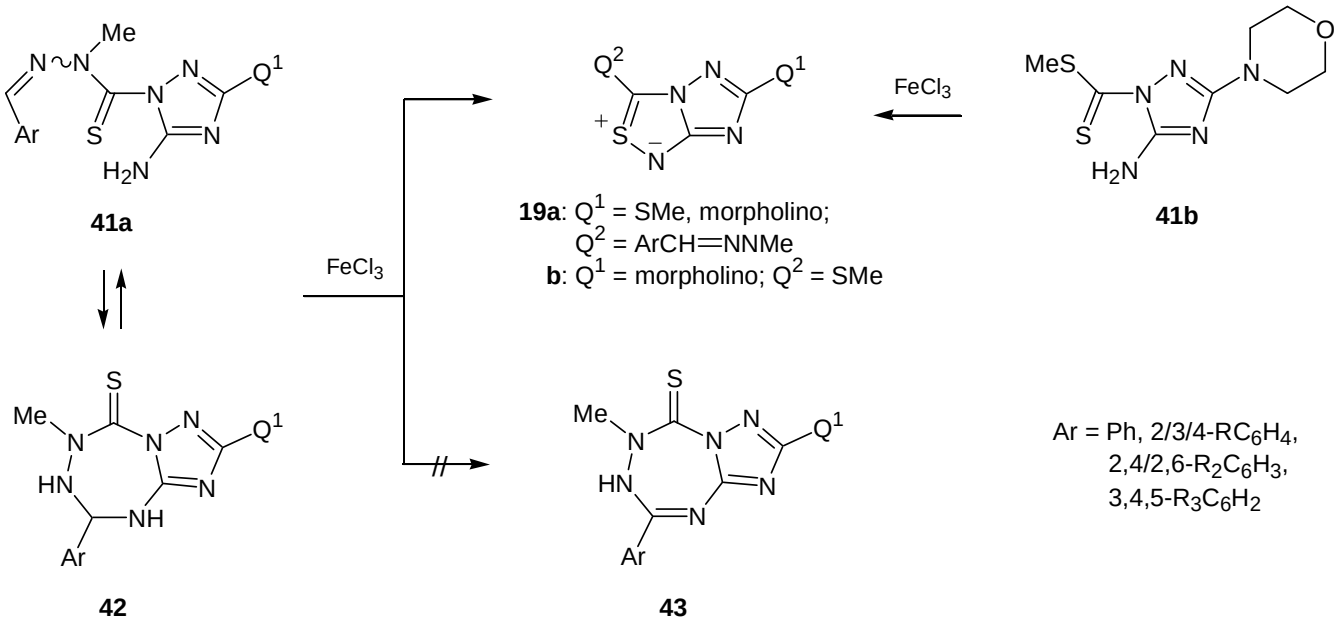
via the bicycle (**37**) (which requires the final step to be classified as III[a] rather than I[c]), or (ii) a pathway showing *S*-methylation to precede ring closure (the latter process matches I[c]). Looking at these alternatives critically, it occurs that a species like **38** should loose methanethiolate anion also (if not exclusively) from C(5) and, hence, give rise to the the type C' isomers of **18a**.

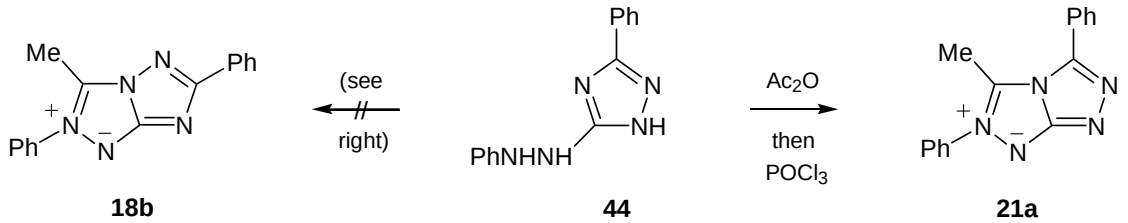
Method I[d]: This kind of cyclization is represented by three related reactions, *viz.* **23** → **3c**,[8a] **24** → **4c**,[9a] and **26** → **14c**,[10] leading directly to 5,7-diacylated pyrrolo[2,1-*c*][1,2,4]triazoles and pyrrolotetrazoles and to 6-acylated imidazo[1,2-*d*]tetrazoles (Scheme 5). The process commences with acylation of the most acidic functionality [*i.e.* that at C(5)], followed by attack from the *N*-linked methylene group. The entire sequence has been monitored by NMR in the case (**24** → **4c**; Q = R^2 = Me, R^1 = R^3 = Ph),[8b] showing that the pathway corresponds to that observed with type C' heteropentalenes.[9a,25] Because of reasonable yields this ring closure is a good complement to the Tschitschibabin reaction (*cf.* Scheme 2); deacylation is feasible with **3c** (R^1CO)[8a] and certain derivatives of **4c** (R^1CO, R^2CO)[9a] but fails with **14c**.[9c] Cyclization of **23** (R^1 = Ph, R^2 = Me) with acetic formic anhydride worked only sparingly[8b] (in contrast to the behaviour of **24**), and the analogous reaction with **26** (R = Ph) to give **14ca** could not be accomplished at all.[9c]

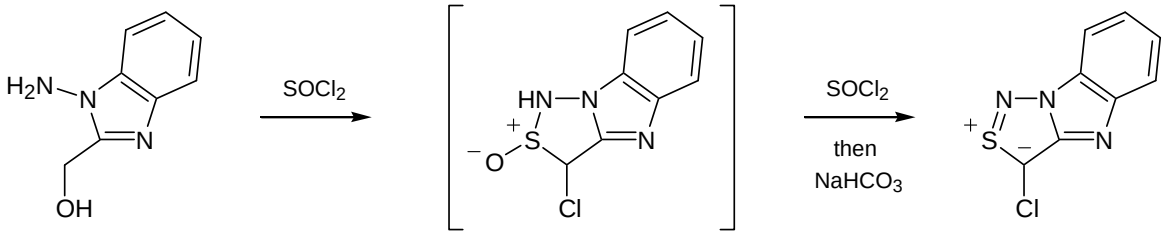
Method I[e]: This still rare synthetic route to type C non-classical heteropentalenes has been followed to enter the imidazo[1,5-*d*]tetrazole series (**8**): Thermolysis of the tetrazol-5-yl substituted diazo esters (**39**) performed in the presence of benzonitrile gives rise to the bicycles (**8a**) in *ca.* 25% yield.[26] In addition to **8a**, oxazole derivatives (**40**) are formed as a consequence of a competing nitrile to acylcarbene cycloaddition, and compounds of this type are the sole products when **39** is thermolyzed in acetonitrile. The latter observation contrasts with the behaviour of the 1*H*-congeners of **39** which exclusively produce the appropriate type C' heteropentalenes, irrespective of the particular nitrile used.[27]

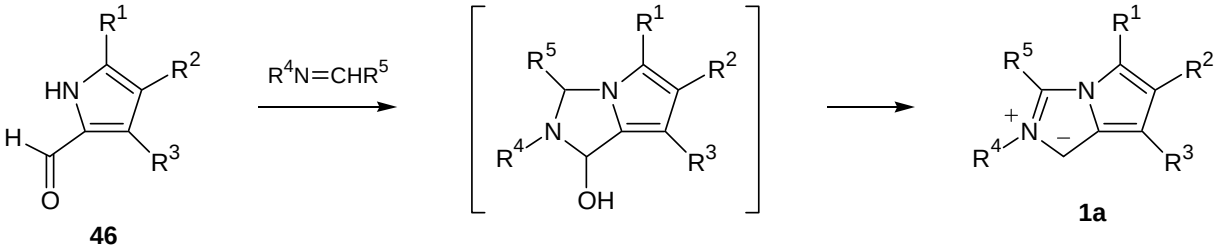
Method II[a]: An example that matches this kind of ring closure constitutes the formation of the [1,2,4]triazolo[5,1-*c*][1,2,4]thiadiazole system (**19**): Fe(III)-mediated cyclization of the difunctionalized triazoles (**41a**) leads to the derivatives (**19a**) in medium to high yield (Scheme 6).[28] Oxidative N–S bond formation is an established route to 1,2,4-thiadiazoles; however, in the present case something else was expected: The starting compounds (**41a**) were found to be capable of undergoing ring-chain tautomerism to give the bicycles (**42**); in order to stabilize them by dehydrogenation the authors used the said oxidant, but instead of the required products (**43**) they obtained **19a**. Ring closure of **41b** into **19b** proceeds equally well.[28]

Method II[b]: To the present mode we will attribute a process giving the [1,2,4]triazolo[3,4-*c*][1,2,4]triazole derivative (**21a**). This compound was obtained in two stages from the (β-phenylhydrazino)triazole (**44**)









R^1= Ac, CO_2R, CN; R^2 = Me, Et; R^3 = Ac, CO_2R;
R^4 = Me, Pr, Bu, *c*-C_6H_{11}, PhCHMe; R^5 = subst. pyrrol-2-yl, Ph, 2-$MeOC_6H_4$

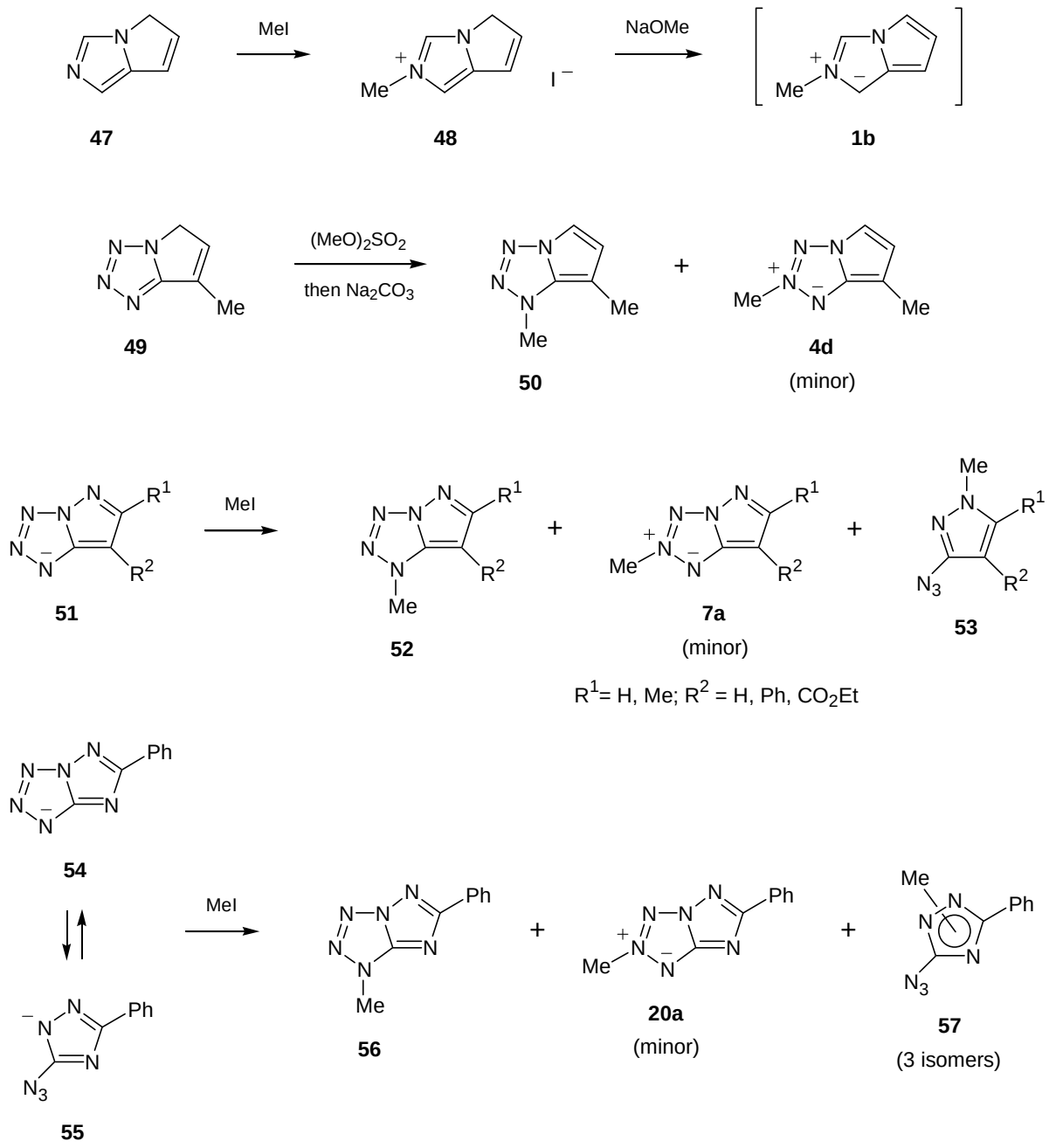
Scheme 6

as reviewed earlier.[2a] Yet, two points mentioned in the original literature[29] may be added for completion: (i) The reaction proceeds *via* a diacetyl derivative of **44** (61% yield; structure not elucidated, one acetyl group should of course reside at the β nitrogen); this material, on being heated with phosphoryl chloride, yields the above heteropentalene quantitatively; and (ii) regarding the isomeric bicycle (**18b**), the authors ruled out its presence, arguing that the ^{1}H NMR spectrum of the actual product lacked an aromatic multiplet which ought to be found in that case because of the unhindered *C*-phenyl group; instead a ten proton singlet was observed for both phenyl groups.

Method II^c: This concept seems especially useful for closing the α half-ring with an external sulfur (or selenium) reagent, giving the systems of imidazo[1,2-*c*]thiazole (**10**),[1b, 2a] imidazo[1,2-*c*][1,2,3]thiadiazole (**13**),[2a] and imidazo[1,2-*c*][1,2,3,5]thia(selena)triazole (**15**, **16**) [2a] as surveyed previously. A more recent example concerns the synthesis of **13a**: When the 1,2-difunctionalized benzimidazole (**45**) is heated with thionyl chloride, the hydrochloride salt of **13a** results (50% yield); treatment with hydrogencarbonate ion gives the free heteropentalene in 85% yield.[30a] This sequence has also been applied to prepare a 1,4-dioxine-fused congener of **13a** (one-pot reaction, 21% yield).[30b]

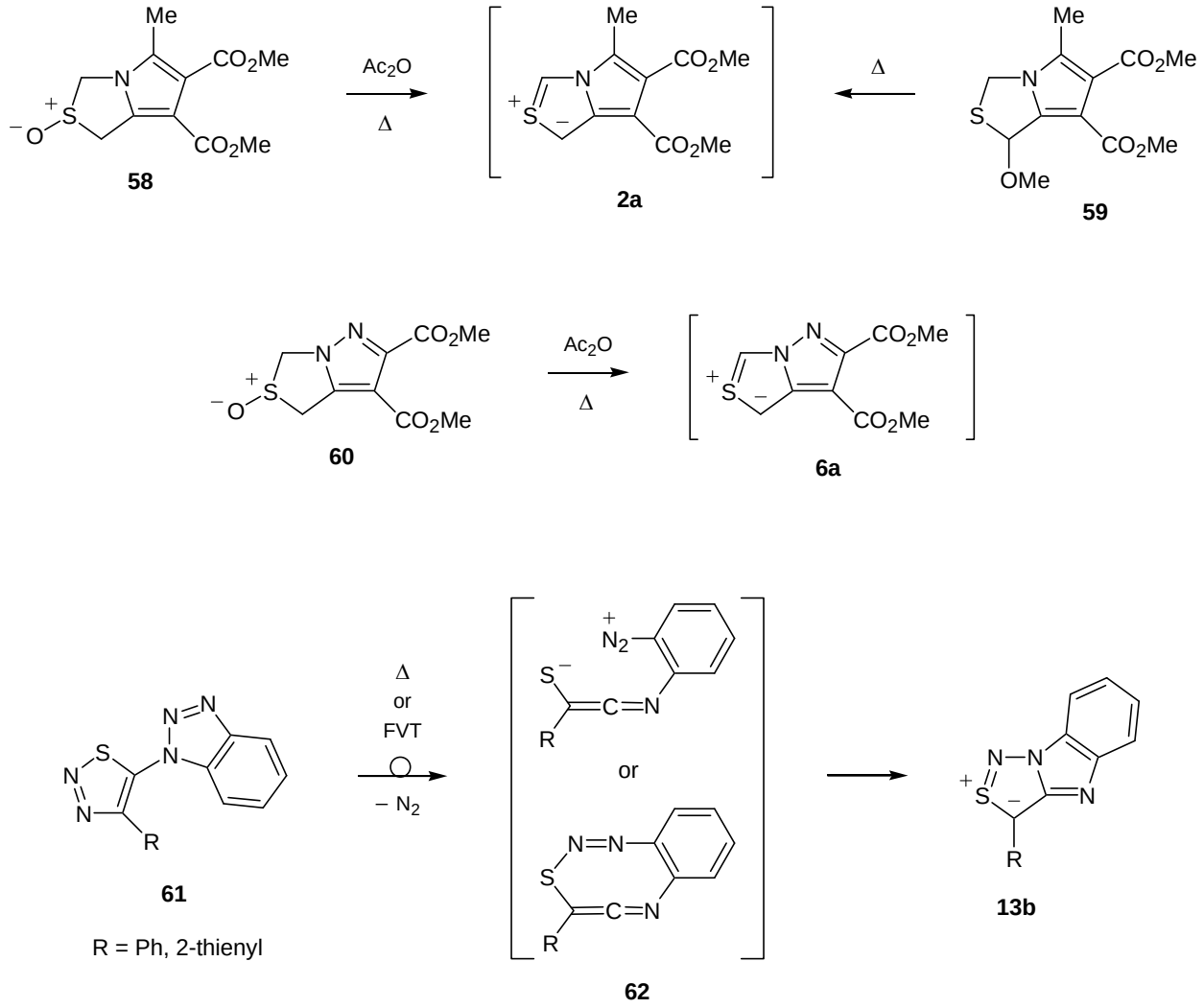
Method II^d: This kind of approach is represented by the elegant entry into the pyrrolo[1,2-*c*]imidazole series (**1**): In a one-stage procedure excess pyrrole-2-carbaldehydes (**46**) bearing electron-withdrawing substituents at C(3) and C(5) are condensed with aliphatic amines to the respective imines (R^5 = subst. pyrrol-2-yl) which, as transient species, react immediately with unconsumed aldehyde to afford the derivatives (**1a**; R^5 = subst. pyrrol-2-yl; yields up to 89%).[31a] Bicycles of this series with R^5 = Ph or 2-$MeOC_6H_4$ are accessible too (fair yields), but in this case, **46** has to be reacted with the separately prepared imine.

Method III^a: Quite a number of examples illustrate this mode [Schemes 7 and 8 (upper half)]. Quaternization of 5*H*-pyrrolo[1,2-*c*]imidazole (**47**) with methyl iodide affords the bicyclic salt (**48**) which on treatment with sodium methoxide gives the free base (**1b**).[32] This compound, for lack of stabilizing acceptor groups, is an unisolable species (in contrast to **1a**) but can be trapped with a dipolarophile (see later). An analogous reaction has been carried out with the 5*H*-pyrrolotetrazole (**49**). Since this substrate is an ambident nucleophile, two quaternary products are formed; the salt leading to **4d** occurs as a minor component.[33] Methylation of the azolotetrazolide anions (**51**) and (**54**) performed in DMSO gives rise to the pyrazolo[1,5-*d*]tetrazoles (**7a**)[34] and the [1,2,4]triazolo[1,5-*d*]tetrazole (**20a**),[35] respectively. These compounds were obtained in small quantities from complex mixtures containing the type C' bicycles (**52**) and (**56**) and the azidoazoles (**53**) and (**57**). It is important to note that **7a** and **20a** have originally been viewed as 3*H*-isomers,[34,35] their non-classical structures were established only later (*cf.* above **22a**).[22] Contrasting



Scheme 7

with **51** and **54**, the imidazo[1,2-*d*]tetrazolide ion cannot be used as a source for a type C heteropentalene [*i.e.* for system (**14**)]: Methylation conducted under the same conditions exclusively affects the β half-ring affording 2-azido-1-methylimidazole.[36] A further type III[a] reaction – covered by ref.[2a] – proceeds when 6-methyl-[1,2,4]triazolo[4,3-*b*][1,2,4]triazol-3-amine is heated with various 1,3-diketones to furnish the appropriate pyrimido-fused derivatives of system (**18**). Finally, dehydration of the sulfoxides (**58**) and (**60**) with acetic anhydride gives rise to the pyrrolo[1,2-*c*]thiazole (**2a**) and the pyrazolo[1,5-*c*]thiazole (**6a**),[37a] respectively (Scheme 8); this matches the earlier finding with **2a**[37b] reviewed in ref.[1b] An alternate route to **2a** consists in thermolyzing the derivative (**59**).[37a] Both heteropentalenes are generated *in situ* and can be intercepted with a dipolarophile (see later).



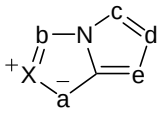
Scheme 8

Method III[b]: Heating of the compounds (**61**) in DMF at 150–170 °C causes rearrangement to the benzo-annelated imidazo[1,2-*c*][1,2,3]thiadiazoles (**13b**) which were isolated in fair yield.[38a] In a further study the derivative (**61**; R = Ph) was submitted to flash vacuum thermolysis between 200–300 °C, giving the product in yields that increased (18–72%) as the temperature was raised.[38b] The reaction is believed to commence with loss of molecular nitrogen from the thiadiazole moiety; the resultant diradical (not shown) would induce opening of the benzotriazole ring to produce an eight-membered framework (**62**) which by transannulation affords (**13b**; R = Ph).[38b]

PROPERTIES

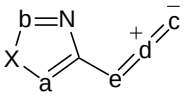
Quantum-chemical investigations have shown that non-classical type C heteropentalenes are thermodynamically less stable than their type C' isomers. This follows from a semiempirical study (MINDO/3) on the pyrazolo[1,5-*d*]tetrazole (**7**; R = Me) and its 1*H*-isomer[22] and, more recently, from a Density Functional

Table 1. Relative Energies (kcal/mol) of Isomeric Heteropentalene Models (Including Diazomethyl and Azido Valence Bond Tautomers) [a]



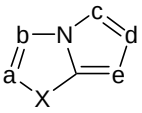
(Ia):

1-**11**
14, **15**, **20**, **22**
23-**29**



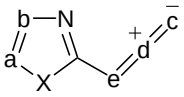
(Ib):

23o-**29o**



(IIa):

1'-**11'**
14', **15'**, **20'**, **22'**
23'-**29'**



(IIb):

23'o-**29'o**

Compd	a	b	c	d	e	X	(Ia) / (Ib) // (IIa) / (IIb)
1 // **1'** [b]	CH	CH	CH	CH	CH	NMe	12.41 – 0.00 –
2 // **2'**	CH	CH	CH	CH	CH	S	17.84 – 0.00 –
3 // **3'** [c]	N	CH	CH	CH	CH	NMe	9.64 – 0.00 –
4 // **4'** [c]	N	N	CH	CH	CH	NMe	4.07 – 0.00 –
5 // **5'**	CH	CH	N	CH	CH	NMe	10.14 – 0.00 –
6 // **6'**	CH	CH	N	CH	CH	S	15.78 – 0.00 –
7 // **7'**	N	N	N	CH	CH	NMe	2.52 – 0.00 –
8 // **8'**	N	N	CH	N	CH	NMe	4.53 – 0.00 –
9 // **9'**	CH	CH	CH	CH	N	NMe	12.97 – 0.00 –
10 // **10'**	CH	CH	CH	CH	N	S	15.33 – 0.00 –
11 // **11'**	N	CH	CH	CH	N	NMe	10.23 – 0.00 –
14 // **14'**	N	N	CH	CH	N	NMe	4.57 – 0.00 –
15 // **15'**	N	N	CH	CH	N	S	0.00 – 0.73 –
20 // **20'**	N	N	N	CH	N	NMe	3.42 – 0.00 –
22 // **22'**	N	N	CH	N	N	NMe	5.77 – 0.00 –
23 / **23o** // **23'** / **23'o**	CH	CH	N	N	CH	NMe	16.22 0.00 6.26 0.46
24 / **24o** // **24'** / **24'o**	CH	CH	N	N	CH	S	18.82 1.42 2.05 0.00
25 / **25o** // **25'** / **25'o**	CH	CH	N	N	N	NMe	21.84 0.43 10.72 0.00
26 / **26o** // **26'** / **26'o**	CH	CH	N	N	N	S	22.42 0.17 7.20 0.00
27 / **27o** // **27'** / **27'o**	N	CH	N	N	N	NMe	26.76 0.27 17.92 0.00
28 / **28o** // **28'** / **28'o**	N	CH	N	N	N	S	27.33 0.54 [d] 12.74 0.00
29 / **29o** // **29'** / **29'o**	N	N	N	N	CH	NMe	21.06 0.00 [e] 18.17 4.80

[a] Calculated at the B3LYP/6-311+G** level of theory (gas phase); heteropentalenes having X = S are fully planar, whereas in the case X = NMe some derivatives show minute deviations from planarity such as **1**, **3'**, **4**, **5**, **8**, **9**, **9'**, **11'**, **25'**, **27'** (ring atoms by ≤ 1° and methyl group by 2–7°; regarding **3'**, **4**, these details have been omitted in ref.[8a]). [b] Ref.[8b] [c] Ref.[8a] [d] For *sp* conformer found: -0.02. [e] For *sp* conformer found: -0.03.

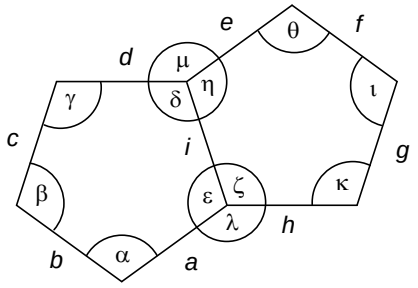
Theory calculation (B3LYP/6-311+G**) on the pyrroloazoles (**1** // **1'**, **3** // **3'**, and **4** // **4'**; R = Me).[8] The latter investigation also illustrates the stabilizing role of pyridine-like nitrogen in the α half-ring: On going from **1** // **1'** *via* **3** // **3'** to **4** // **4'**, the energy difference between the isomers is decreasing (Table 1). Some further comparisons such as (i) **5** // **5'** → **7** // **7'**, (ii) **9** // **9'** → **11** // **11'** → **14** // **14'**, and (iii) **10** // **10'** → **15** // **15'** reveal that this effect is general; quite interestingly, the sulfur-containing compound (**15**) ap-

pears even slightly more stable than its 'neutral' isomer (**15'**). As regards the role of pyridine-like nitrogen in the β half-ring, there is an energy-lowering effect throughout if this nitrogen is placed adjacent to the ring junction nitrogen (see **1** // **1'** → **5** // **5'**, **2** // **2'** → **6** // **6'**, or **4** // **4'** → **7** // **7'**); however, if located besides the bridgehead carbon, it exerts such an influence only in the azolothiazole series (see **2** // **2'** → **10** // **10'**) whereas with X = NMe the energy difference slightly increases (see **1** // **1'** → **9** // **9'**, **3** // **3'** → **11** // **11'**, or **4** // **4'** → **14** // **14'**). With heteropentalenes having as β half-ring a 1,2,3-triazole (**23** // **23'** – **25** // **25'**) or tetrazole moiety (**26** // **26'** – **29** // **29'**), an important point concerns valence bond tautomerism [(Ia) ⇄ (Ib) // (IIa) ⇄ (IIb)]. Comparing cyclic and open-chain species, the former are constantly higher in energy and here the difference between **23**–**29** and **23o**–**29o** exceeds that between **23'**–**29'** and **23'o**–**29'o**. According to their relatively low energies the bicycles (**24'**)[39] and (**26'**)[40] are isolable compounds,[41] whereas the azidoazoles (**25'o**)[40] and (**27'o**)[42] and the diazomethyl derivative (**29'o**)[43] do not tend to cyclize. In view of these relationships non-classical type C heteropentalenes such as **23**–**29** are expected to be highly elusive: The equilibrium should be entirely on the azide/diazomethyl side as observed, for example, with **26o**,[44] **27o**,[42] **28o**,[45] and **29o**.[43]

Theoretical interest has also been directed toward the electronic structure of the title systems. Pertinent studies include: (i) AM1, MNDO, and CNDO calculations on the pyrrolotetrazoles (**4**; R = H, Me)[9b,c] and the imidazo[1,2-*d*]tetrazoles (**14**; R = H, Me);[9c, 10] (ii) DFT computations (B3LYP/6-311+G**) on the pyrrolo[1,2-*c*]imidazole (**1**; R = Me),[8b] the pyrrolo[2,1-*c*][1,2,4]triazoles (**3**; R = Me; 7-H, 7-COMe),[8a] and the pyrrolotetrazoles (**4**; R = Me; 7-H-, 7-COMe);[8a] (iii) PPP[51] and CNDO/2 approximations [52] on the thiazolo[3,4-*b*][1,2,4]triazole (**17**; 6-SH). Of particular importance is the finding that C(5) of **1**, **3**, and **4** and also C(6) of **14** exhibit a greater π density than the respective atoms of the type C' isomers; this has been associated with an enhanced proclivity for electrophilic substitution reactions (see below). Further theoretical work concerns: (i) calculation of an aromaticity index for the pyrazolo[1,5-*d*]tetrazole (**7**; R = Me; 7-Ph) by statistical evaluation of the deviations in peripheral bond orders;[53] (ii) PM3 computations of the HOMO and LUMO energies of pyrrolo[1,2-*c*]thiazole (**2**) and pyrazolo[1,5-*c*]thiazole (**6**).[37a]

Regarding experimental structural methods, literature data on bond lengths and angles are available for only a limited number of systems (Table 2). The examples listed are planar aromatic molecules; with **18aa** / **18aa'** the torsional angle between the phenyl ring and the bicyclic plane was found to be -26.7 and -4.3°, respectively. Spectral data, however, are abundant (for a selection, see Table 3 / Figure 3); while the majority were recorded for characterization purposes, systematic studies like the detailed mass spectral investigation of compounds (**17a**) are still an exception.[52] Attention is drawn to differences that

Table 2. Bond Distances (Å) and Angles (°) from X-ray Diffraction [a]

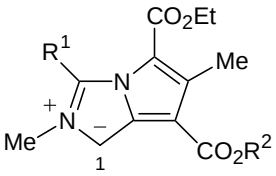


Compd	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*
7aa [b]	1.344	1.328	1.321	1.337	1.350	1.350	1.405	1.403	1.360
13aa [c]	1.374	1.685	1.636	1.349	1.391	1.388	1.386	1.414	1.326
13ab [d]	1.386	1.702	1.642	1.342	1.405	1.412	1.388	1.467	1.339
18aa [e]	1.358	1.377	1.338	1.343	1.377	1.322	1.366	1.353	1.348
18aa' [e]	1.361	1.375	1.338	1.346	1.377	1.330	1.356	1.350	1.330
19b [f]	1.359	1.655	1.705	1.322	1.398	1.337	1.369	1.354	1.329
22aa [g]	1.356	1.329	1.296	1.384	1.375	1.329	1.397	1.331	1.359

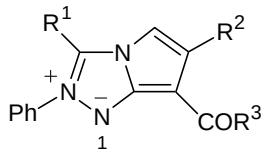
Compd	α	β	γ	δ	ε	ζ	η	θ	ι	κ	λ	μ
7aa [b]	102.3	118.0	100.0	112.2	107.5	106.3	115.2	100.7	115.8	101.9	146.1	132.6
13ab [d]	107.0	98.57	105.72	119.7	109.0	112.4	107.5	103.6	112.8	103.7	138.6	132.8
18aa [e]	101.9	114.3	104.1	108.1	111.6	108.7	111.8	99.7	117.5	102.2	139.6	140.1
18aa [e]	102.2	114.1	104.4	108.0	111.3	109.6	111.2	100.1	117.1	102.0	139.1	140.8
19b [f]	107.4	96.5	106.7	114.5	114.8	110.1	110.4	99.4	118.6	101.4	?	?
22aa [g]	101.5	120.3	99.1	111.1	108.0	112.4	106.9	105.6	112.6	102.5	139.6	142.0

[a] Generalized formula oriented according to structures shown in Figure 3. [b] Ref.[22] [c] Ref.[30a] [d] Ref.[38a] [e] Ref.[24] (two independent molecules observed). [f] Ref.[28] [g] Ref.[21b]

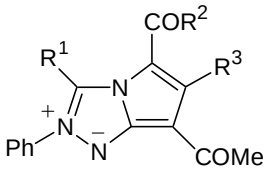
have been observed between type C and type C' isomers (*cf.* ref.[40]): (i) ^{13}C NMR: the bridgehead carbon atom of title systems (C) resonates at lower field; *e.g.* **3aa**: δ 154.4 *vs.* 141.3,[8b] **4ba**: δ 146.6 *vs.* 129.6,[9a] **7ab**: δ 147.8 *vs.* 134.9,[34] **8aa**: δ 150.4 *vs.* 139.4,[26] **14a**: δ 156.3 *vs.* 145.4,[10, 54] **20a**: δ 156.2 *vs.* 150.2;[35] (ii) UV/VIS: title compounds are characterized by a pronounced bathochromic shift of the longest wavelength (nm); *e.g.* **4ab**: 356 *vs.* 302,[9a] **4bd**: 377 *vs.* 324,[9a] **7ab**: 346 *vs.* 298,[34] **14a**: 328 *vs.* 289;[10] (iii) certain title compounds display fluorescence (nm): *e.g.* **1aa**: 463 (CH_2Cl_2),[31a] **1ab**: 500 (CH_2Cl_2),[31a] **4ab**: 481 (CCl_4),[9a] **4bd**: 520 / 495 (CCl_4);[9a] (iv) MS: acetyl derivatives and methyl esters of type C azolotetrazoles have been found to give intense [M–15] and [M–31] peaks (%): *e.g.* **4ab**: 44 *vs.* 2,[9a] 5-acetyl derivative of **4bd**: 78 *vs.* 0,[9a] **14ca**: 100 *vs.* 0;[10] formally, these fragments are ketenes whose terminal carbon atoms correspond to C(5) / (7) and C(6) of the respective 5*H*- / 7*H*-pyrrolotetrazole and 6*H*-imidazo[1,2-*d*]tetrazole framework (in the case of the type C' isomers, loss of molecular nitrogen from the tetrazolic half-ring predominates).[9a]



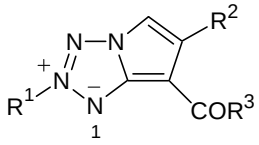
1aa: R^1= Ph, R^2 = Et
ab: R^1= [py], R^2 = CH_2Ph
(for [py], see Scheme 9)



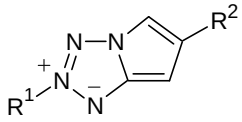
3aa: R^1= H, R^2 = Ph, R^3 = Me
ab: R^1= Me, R^2 = Ph, R^3 = OEt
ac: R^1= R^3 = Me, R^2 = Ph
ad: R^1= R^2 = R^3 = Me



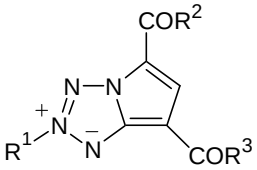
3ca: R^1= Me, R^2 = Ph, R^3 = H
dd: R^1= H, R^2 = Me, R^3 = Ph



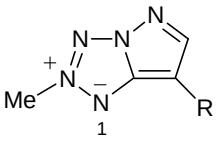
4aa: R^1= Ph, R^2 = R^3 = Me
ab: R^1= Me, R^2 = Ph, R^3 = OMe
ac: R^1= R^2 = Ph, R^3 = Me



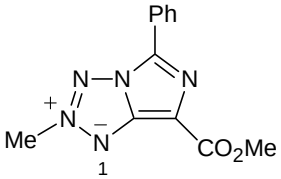
4ba: R^1= Me, R^2 = H
bb: R^1= R^2 = Me
bc: R^1= Ph, R^2 = Me
bd: R^1= Me, R^2 = Ph



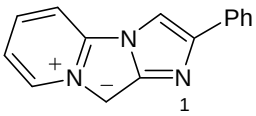
4ca: R^1= R^2 = Ph, R^3 = Me
cb: R^1= R^2 = R^3 = Me
cc: R^1= R^2 = Me, R^3 = OMe



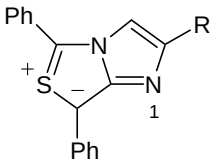
7aa: R = H
ab: R = Ph



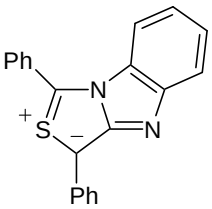
8aa



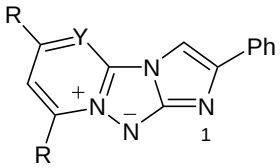
9a



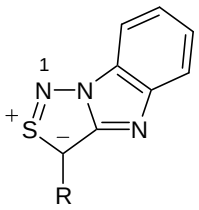
10aa: R = Ph
ab: R = 4-MeC_6H_4



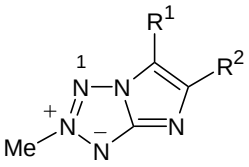
10b



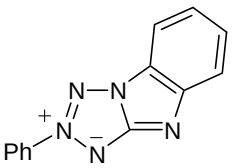
11aa: Y = N, R = Ph
b: Y = CH, R = H



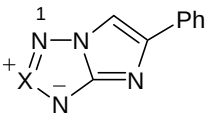
13aa: R = Cl
ab: R = Ph



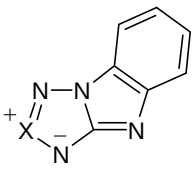
14a : R^1= H, R^2 = Ph
cb: R^1= COMe, R^2 = Me



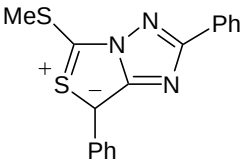
14b



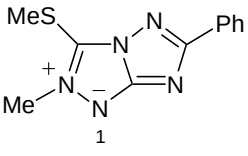
15a: X = S
16a: X = Se



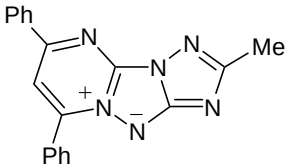
15b: X = S
16b: X = Se



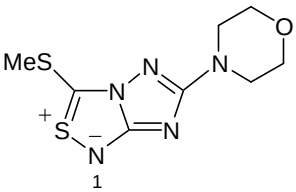
17aa



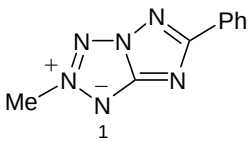
18aa



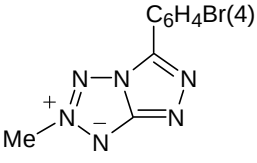
18b



19b



20a



22aa

Figure 3. Structures to Tables 2 and 3

Table 3. Selected Spectral Data [a]

^{1}H NMR: Ring Hydrogens (δ, ppm)

Compd	1-H	3-H	5-H	6-H	7-H	10-H
1aa [b]	6.72					
3aa [c]		10.43	7.13			
3ac [c]			6.58			
3ca [d]				7.80		
4aa [e]			7.07			
4ac [e]			7.24			
4ba [e]			7.14	6.94	5.88	
4bb [e]			6.96		5.69	
4ca [e]				7.99		
7aa [f]				7.86	6.05	
7ab [f]				8.22		
9a [g]		7.47				8.12
10ab [h]		8.05				
11b [i]		7.58				
14a [j]				7.80		
15a [k]				8.27		

^{13}H NMR: Ring Carbons (δ, ppm)

Compd	C(3)	C(3a)	C(4a)	C(5)	C(6)	C(7)	C(7a)
3aa [c]	123.3			100.9	138.5	93.1	154.4
3ab [c]	129.8			96.4	140.5	82.7	152.7
3dd [c]	124.6			115.5	145.4	103.4	152.6
4ab [e]				100.2	139.7	84.8	148.9
4ba [e]				96.9	120.6	78.2	146.6
4bb [e]				96.1	133.0	78.9	146.4
4cb [e]				117.5	127.4	102.1	149.6
7ab [l]					143.3	98.9	147.8
8aa [m]				127.0		105.4	150.4
13aa [n]	129.3	160.8	155.1				
14a [j]		156.3		151.4	99.2		
14b [o]		159.5	151.7				
14cb [j]		159.4		156.3	118.4		
18aa [p]	159.4				168.9		161.9
19b [q]	176.0				166.4		156.7
20a [r]					169.0		156.2

UV/VIS: Longest Wavelength Maxima

Compd	nm	Compd	nm	Compd	nm
1aa [b]	360	**4bd** [e]	377	**14cb** [j]	279
1ab [b]	358	**7ab** [f]	346	**15a** [k]	401
3aa [c]	360	**10aa** [t]	487	**15b** [k]	438
3ad [d]	335	**10b** [u]	512	**16a** [k]	442
4aa [s]	394	**11aa** [v]	456	**16b** [k]	505
4ab [e]	356	**14a** [j]	328	**17aa** [w]	416
4bc [s]	422	**14b** [o]	393	**18b** [x]	398

MS: Relative Intensities of Parent Ions

Compd	%	Compd	%	Compd	%
1aa [b]	100	**4cc** [e]	100	**15a** [k]	95
1ab [b]	50	**7ab** [f]	43	**15b** [k]	57
3aa [c]	85	**10b** [u]	100	**16a** [k]	43
3ab [c]	48	**13aa** [n]	17/50	**16b** [k]	45
3dd [c]	60	**14a** [j]	100	**17aa** [y]	100
4ab [e]	100	**14b** [o]	73	**18aa** [p]	38
4bd [e]	66	**14cb** [j]	76	**20a** [r]	26

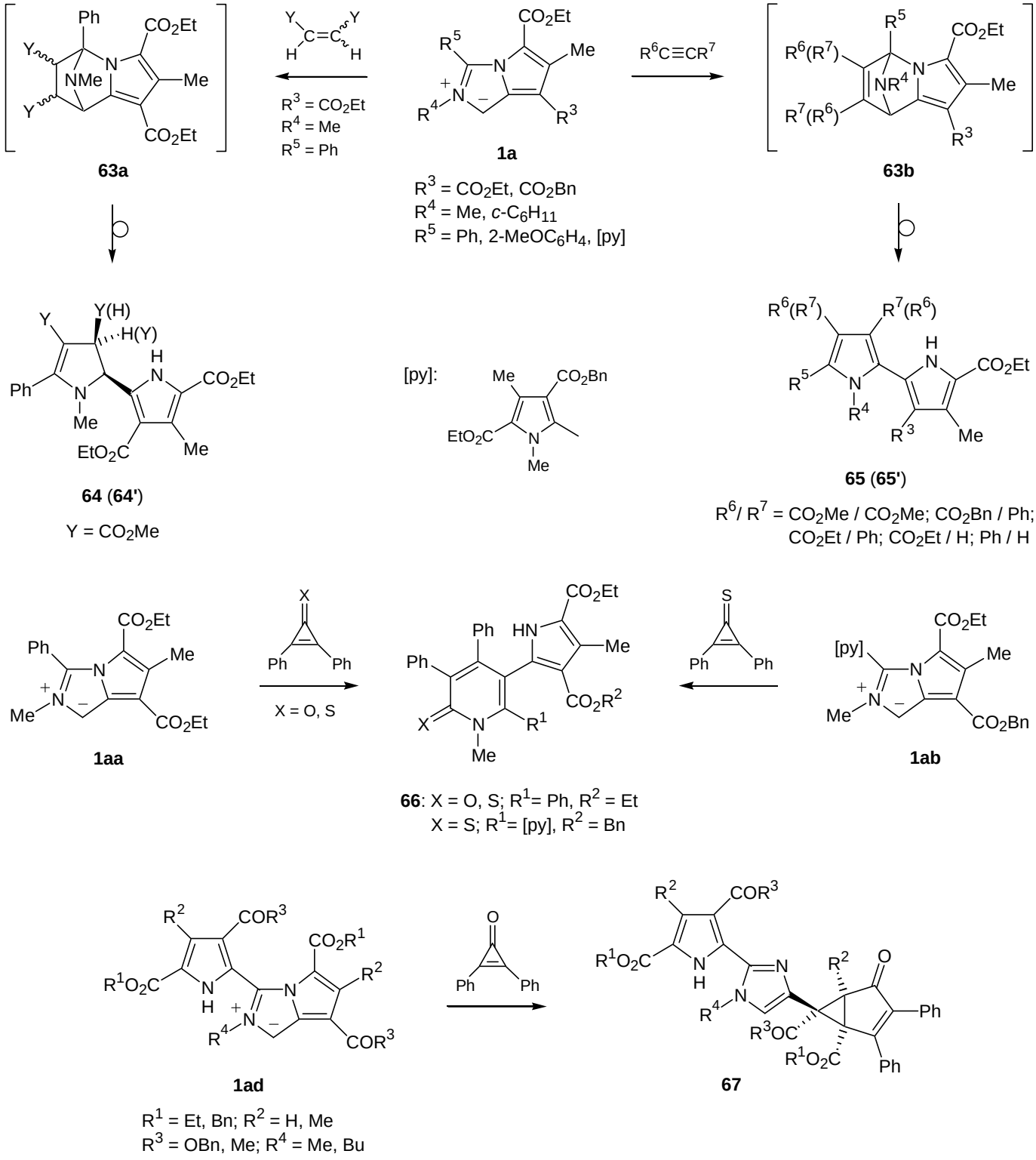
[a] ^{1}H NMR: $CDCl_3$ [except for **1aa** (C_6D_6), **9a** (DMSO-d_6), and **11b** (TFA)]; ^{13}C NMR: $CDCl_3$ [except for **13aa**, **14a**, **18aa**, and **19aa** (DMSO-d_6)]; UV/VIS: MeOH [except for **7ab**, **10aa**, and **10b** (EtOH), **11aa** (hexane), and **14b** and **17aa** (MeCN)]; MS: EI [except for **1ab** (FAB)]. [b] Ref.[31a] [c] Ref.[8a] (regarding ^{1}H NMR of **3aa**, shift value of 3-H missing; complete data in ref.[8b]). [d] Ref.[8b] [e] Ref.[9a] [f] Ref.[34] [g] Ref.[46] [h] Ref.[19] [i] Ref.[47] [j] Ref.[10] [k] Ref.[48] [l] Ref.[22] [m] Ref.[26] [see also ^{15}N NMR (δ, ppm; from liquid NH_3): N(1) 280.8, N(2) 276.4, N(3) 311.3, N(4) 242.5, N(6) 277.3]. [n] Ref.[30a] (regarding ^{13}C NMR, shift value of C-4a open; regarding MS, intensity refers to **13aa** ·HCl). [o] Ref.[14a] (regarding ^{13}C NMR, shift value of C-8a: 122.1). [p] Ref.[24] [q] Ref.[28] [r] Ref.[35] [s] Ref.[9c] [t] Ref.[18] [u] Ref.[49] [v] Ref.[7b] [w] Ref.[13] [x] Ref.[50] [y] Ref.[52]

REACTIONS

Because of the dipolar character and the considerable π-electron density resident in the β half-ring, reactivity of the title systems is mainly concerned with cycloaddition (mixed type A and type B behaviour[1a-c]) and electrophilic substitution; this is illustrated by reactions of **1**, **2**, **6**, **10** and **3**, **4**, **9**, **10**, **11**, **14**, respectively. Yields of products are reasonable throughout; individual figures will be cited only occasionally.

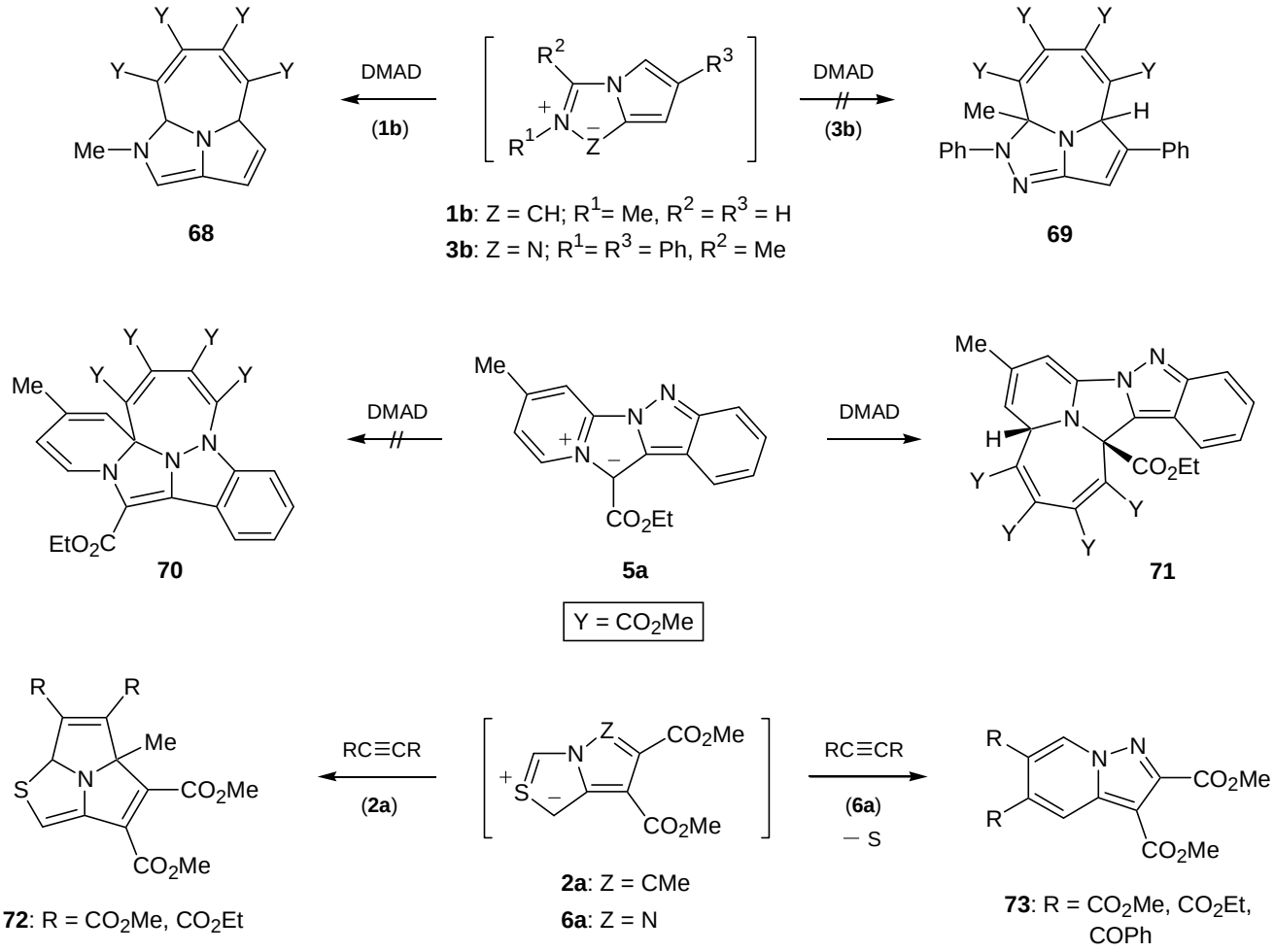
1) 1,3-Dipoar Cycloaddition

The pyrrolo[1,2-*c*]imidazoles (**1a**), by virtue of their C(1)–N(2)–C(3) azomethine ylide, easily combine with olefinic and acetylenic dipolarophiles to form the stereo- and regioisomeric cycloadducts (**63a**,**b**); the latter readily ring-open to the bipyrrole derivatives (**64**/**64'**) and (**65**/**65'**), respectively (Scheme 9).[31a]



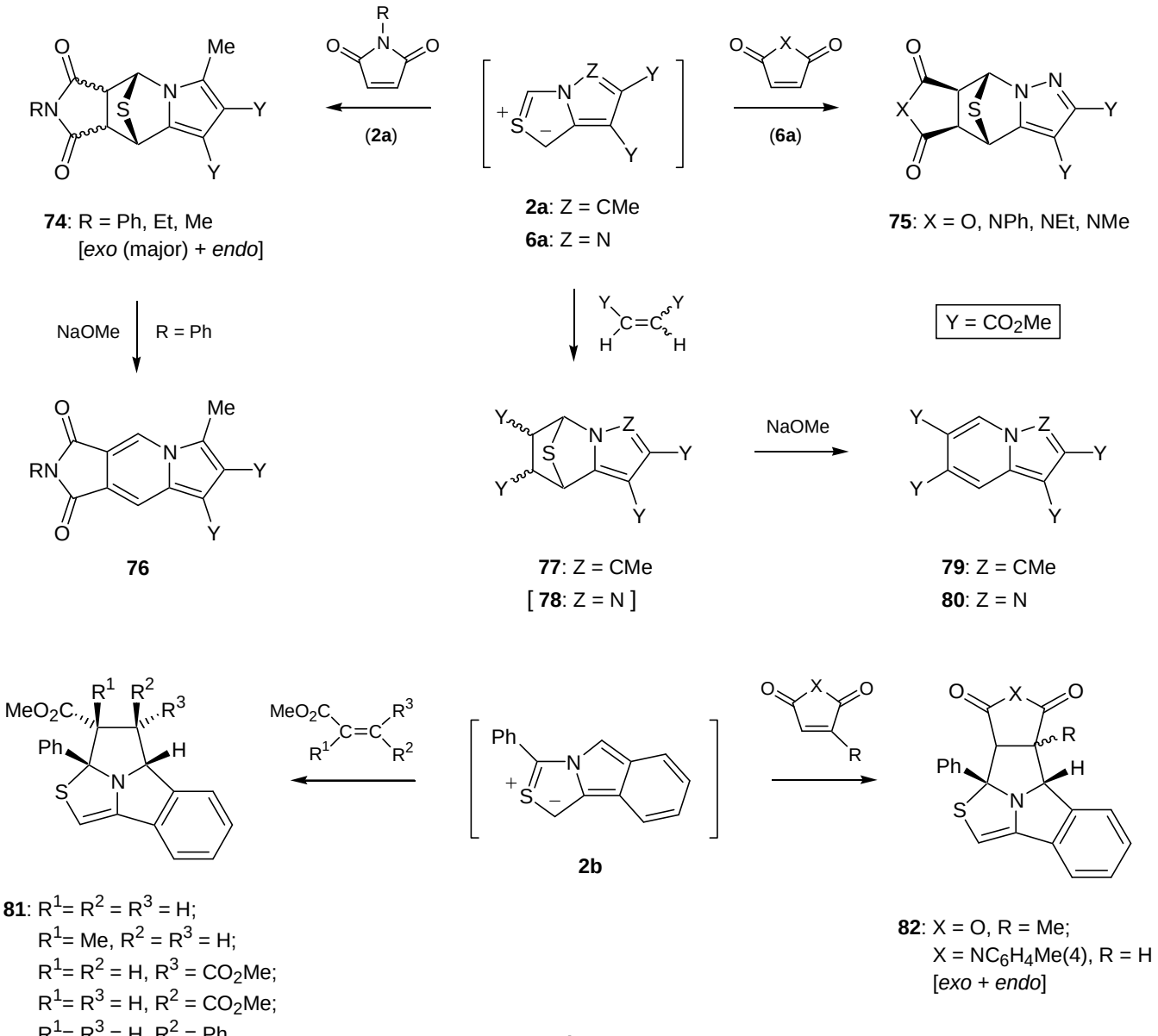
Scheme 9

Towards diphenylcyclopropenone and its thio congener a different behaviour is observed since these reagents act as 1,3-dipoles too: Thus, **1aa** and **1ab** form transient 3 + 3 cycloadducts (in stereoselective manner) which rapidly rearrange to the pyridine derivatives (**66**); in the case of **1ad**, however, a more complex structure like **67** results the formation of which does not originate from cycloaddition but is believed to commence with nucleophilic attack on the ketone by C(5) of the heteropentalene followed by a multi-step rearrangement.[31b]



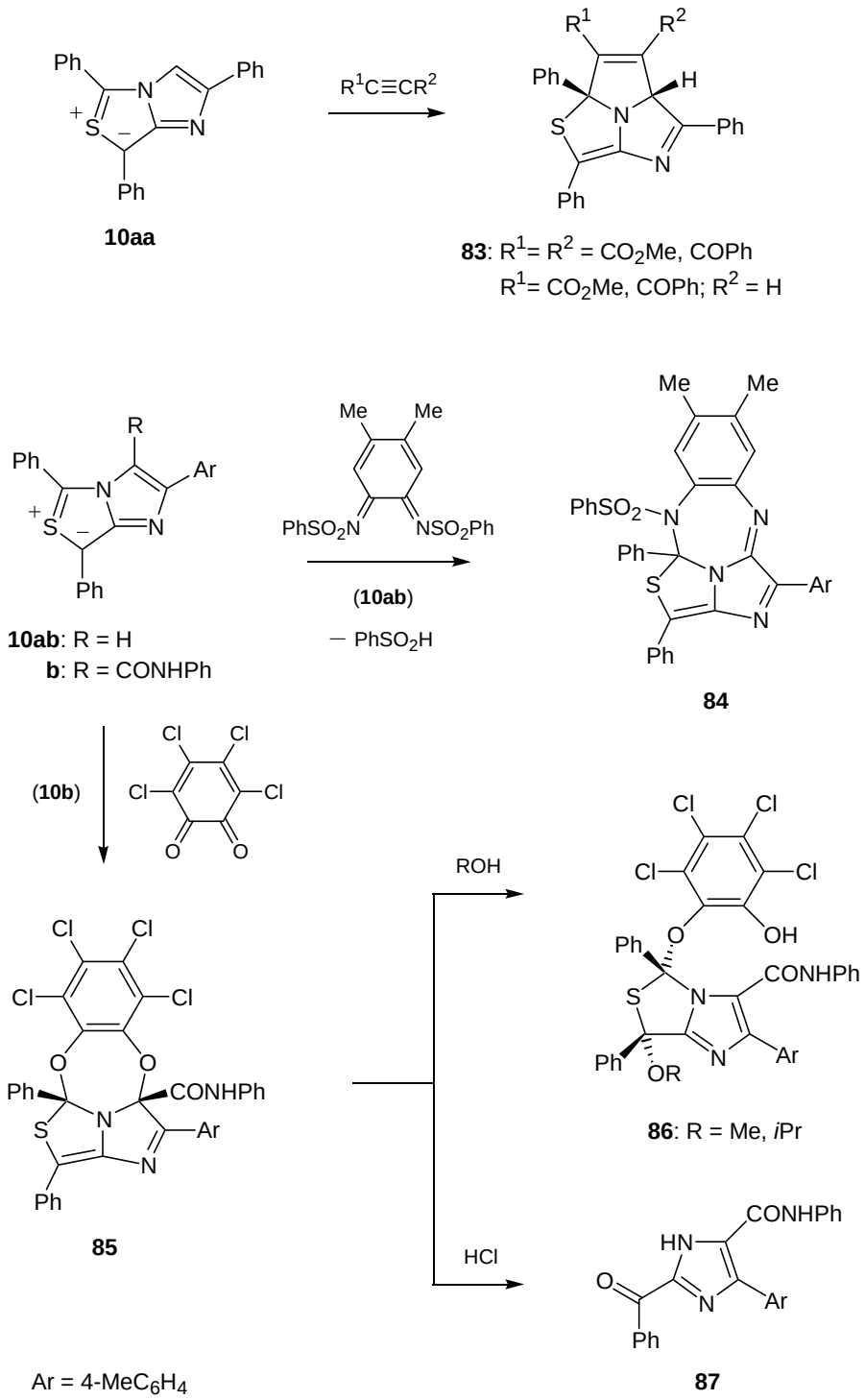
Scheme 10

Contrasting with the foregoing derivatives of system (**1**), the active dipole of **1b** pertains to C(3)–N(4)–C(5): Thus, applying DMAD the 2 : 1 adduct (**68**) is produced (Scheme 10).[32] Surprisingly this kind of reaction does not occur with the pyrrolo[2,1-*c*][1,2,4]triazole (**3b**), instead of **69** a double Michael adduct is formed here (see below Scheme 15).[8a] Treating the tetracyclic derivative (**5a**) with DMAD, again two molecules of the reagent participate. The resultant cycloadduct (**71**), however, is 'atypical' since a fraction of the dipole involved lies outside the heteropentalene core; the 'regular' product would be the azomethine imine cycloadduct (**70**).[15] As already experienced with the congeners (**1b**) and (**3b**), also educts such as **2a** and **6a** that are closely related each other exhibit different behaviour towards the same class of reagent:



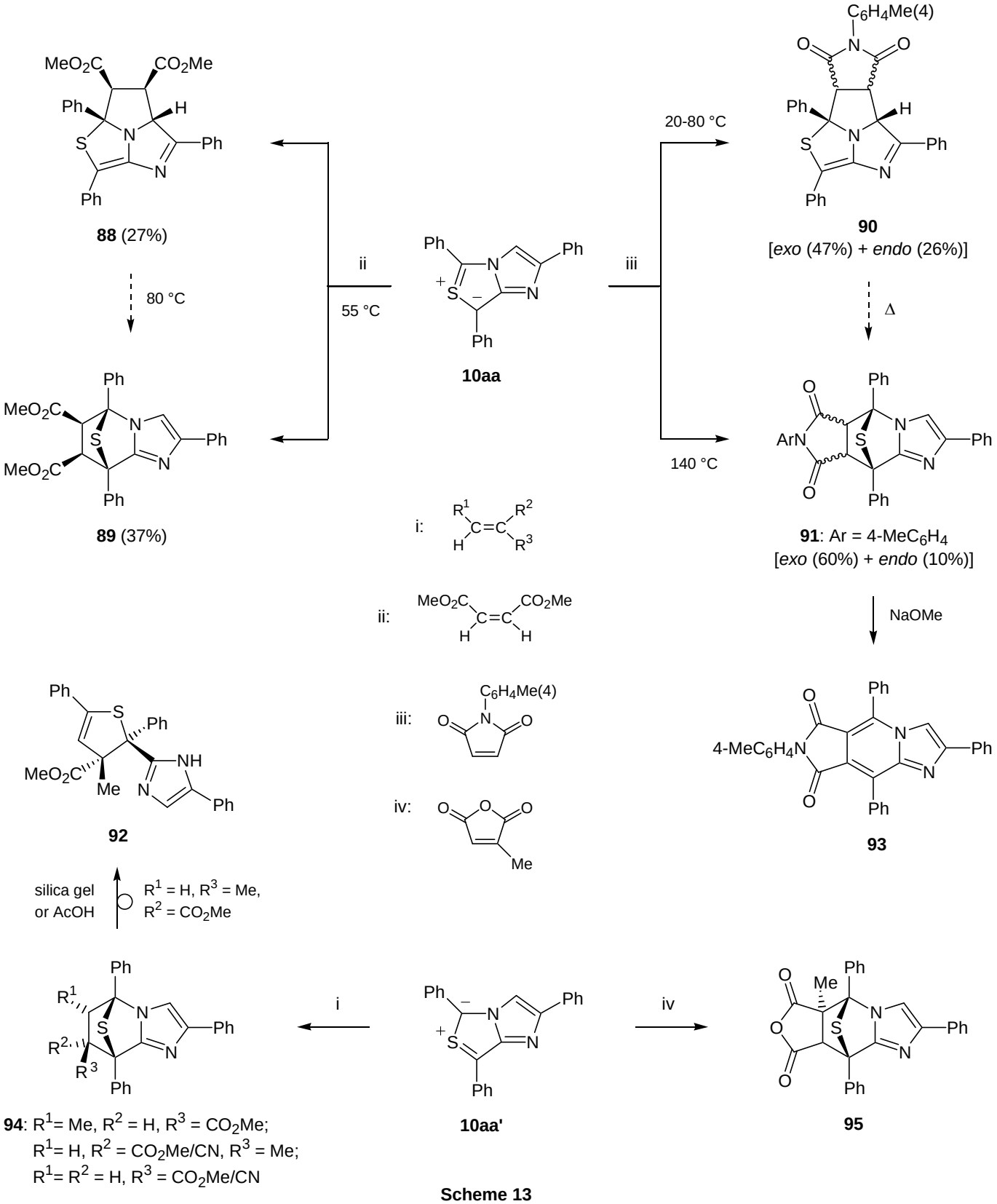
Scheme 11

Whereas **2a** reacts as an azomethine ylide to provide the cyclazine derivatives (**72**), in **6a** the active dipole is the thiocarbonyl ylide[55] which affords, *via* primary epithio adducts, the pyrazolo[1,5-*a*]pyridines (**73**).[37a] Electron-deficient alkenes, however, attack both **2a** and **6a** at the same region, *viz.* the thiocarbonyl ylide unit (Scheme 11): Applying *N*-substituted maleimides – in the case of **6a** also maleic anhydride (which failed to react with **2a**) – , the adducts (**74**) and (**75**) are formed; using dimethyl fumarate or maleate, the analogous adducts (**77**) and (**78**) result (the latter not isolated) which on treatment with base are converted into the azolopyridines (**79**) and (**80**); the same kind of desulfuration affords the pyrrolo[*f*]indolizine (**76**). The above findings with **2a** and **6a** were partially explained by Frontier MO theory.[37a] In contrast to **2a**, the benzo congener (**2b**) adds electron-deficient alkenes across the azomethine ylide dipole giving the cyclazine derivatives (**81**) and (**82**).[17b] Quite a number of experiments have disclosed that also the imidazo-[1,2-*c*]thiazole system (**10**) reacts as a 'bi-perifunctional' class[56] (Schemes 12 and 13). Whereas electron-



Scheme 12

deficient alkynes and also *o*-quinonoid compounds add exclusively across the azomethine ylide portion as illustrated by the conversions (**10aa** → **83**)[57] and (**10ab** / **10b** → **84** / **85**),[19,58] electron-deficient alkenes affect both dipolar regions: Thus, reaction of **10aa** with dimethyl maleate at 55 °C affords a 3 : 4 mixture of the cycloadducts (**88**) and (**89**); the former species, on being heated in boiling benzene, isomerizes into the latter *via* 1,3-dipolar cycloreversion and -addition.[59] Application of *N*-(*p*-tolyl)maleimide gives a simi-

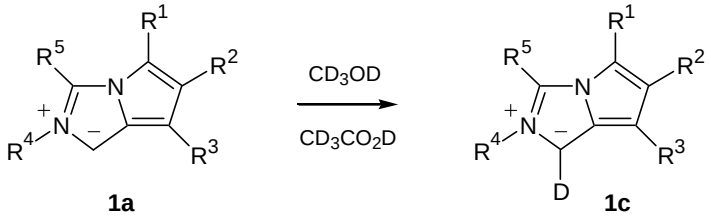


Scheme 13

lar result because at elevated temperature formation of the epithio compound (**91**) is favoured over the cyclazine derivative (**90**).[18,60] Finally, unsymmetrical alkenes (employed in boiling benzene) were found to react not only periselectively but also highly regioselectivly giving products such as **94** and **95**; the latter phenomenon assumedly points to an enhanced contribution of the canonical form (**10aa'**).[61,62,63]

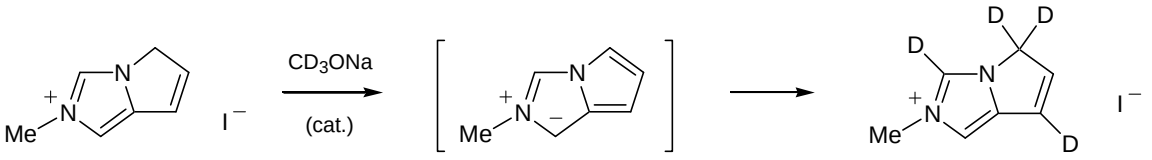
2) Reaction with electrophiles

While electrophilic substitution reactions are certainly of primary interest, reference should first be made to deuteration, protonation, and quaternization. The exchange of ring hydrogen for deuterium has been investigated with the pyrrolo[1,2-*c*]imidazole system (**1**): The proton at C(1) of the derivatives (**1a**) is easily exchanged in acidic media (→ **1c**), showing a considerable delocalization of the negative charge to

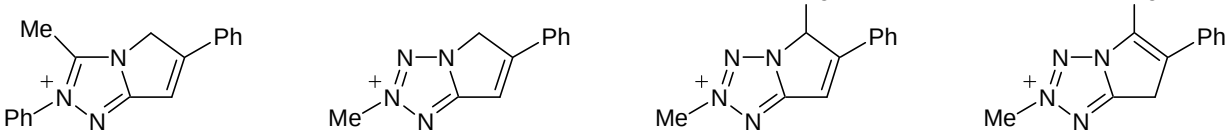


1a **1c**

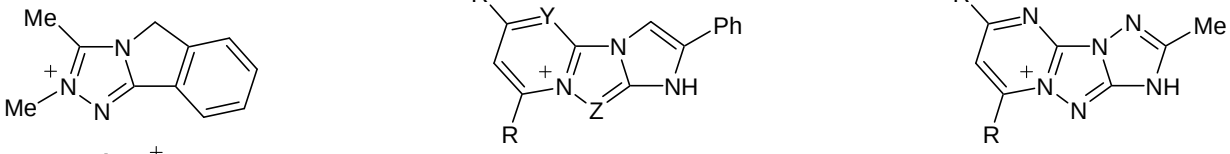
(for R^1–R^5, see Scheme 6)



48 **1b** **1d**



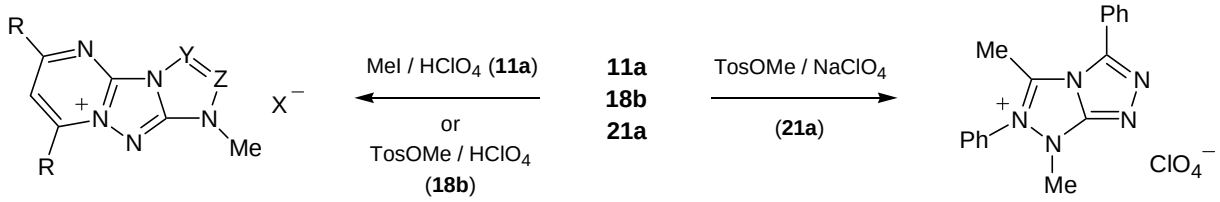
3b • H^+ **4ba** • H^+ **4bc** • $H^+(\alpha)$ **4bc** • $H^+(\beta)$



3d • H^+

9a • H^+: Y = Z = CH; R = H
11a • H^+: Y = Z = N; R = Me, Ph

18b • H^+: R = Me, Ph



11c: Y = CH; Z = CPh;
R / X = Me / ClO_4, Ph / I

18c: Y = N; Z = CMe;
R = Me, Ph; X = ClO_4

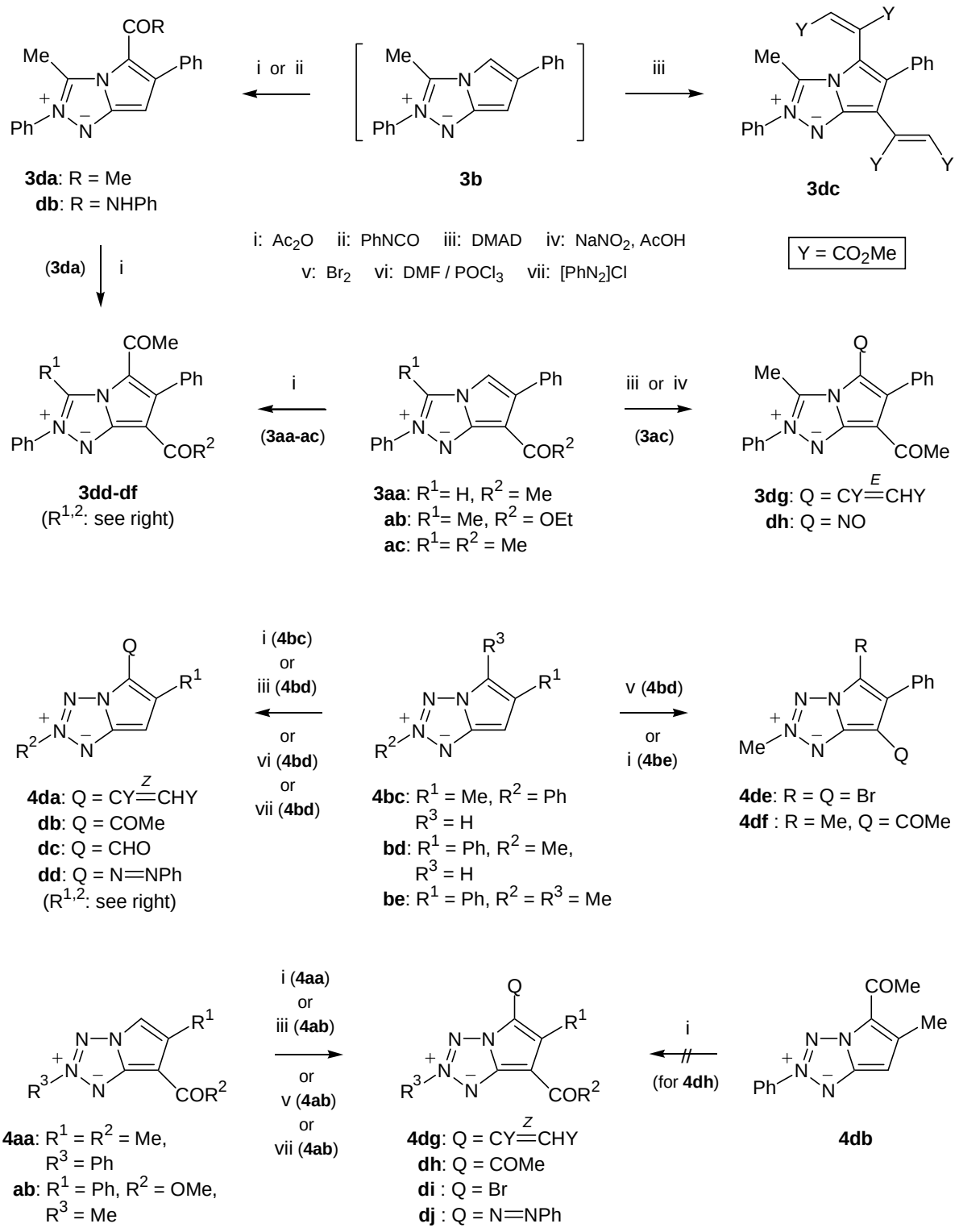
21b

Scheme 14

this position (Scheme 14).[31a] In the case of **1b**, hoewever, C(1) remains unaffected, as observed during the base-catalyzed deuteration of the salt (**48**), which led to the species (**1d**).[32] Regarding the effect of Brønsted acids, pyrroloazoles being unsubstituted at both C(5) and C(7) are protonated exclusively at C(5) as found, for example, with **3b**[8a] and **4ba**;[9b] substitution at C(5), however, gives rise to two cations (α and β, ratio 1 : 4) as observed with **4bc**.[9b] Structures of the type (**3b** · H^+) and (**4ba** · H^+) correspond to those obtained by alkylation of 5*H*-pyrroloazoles (*cf.* Scheme 7); it is from this reverse approach that the cation (**3d** · H^+) results (isolated as the perchlorate salt).[64] Protonation of compounds (**9a**)[46] and (**11a**)[7b] which have as β half-ring an imidazole moiety occurs at N(1); an analogous position, *i.e.* N(3), apparently holds for the triazole containing derivatives (**18b**).[50] Quaternization reactions have been performed with the representatives (**11a**, **18b**, **21a**); while products such as **11c**[7b] and **18c**[50] have constitutions one would expect, the claimed structure (**21b**)[29] appears unusual as the new methyl group did not enter the β half-ring (a confirmation of this finding would be desirable).

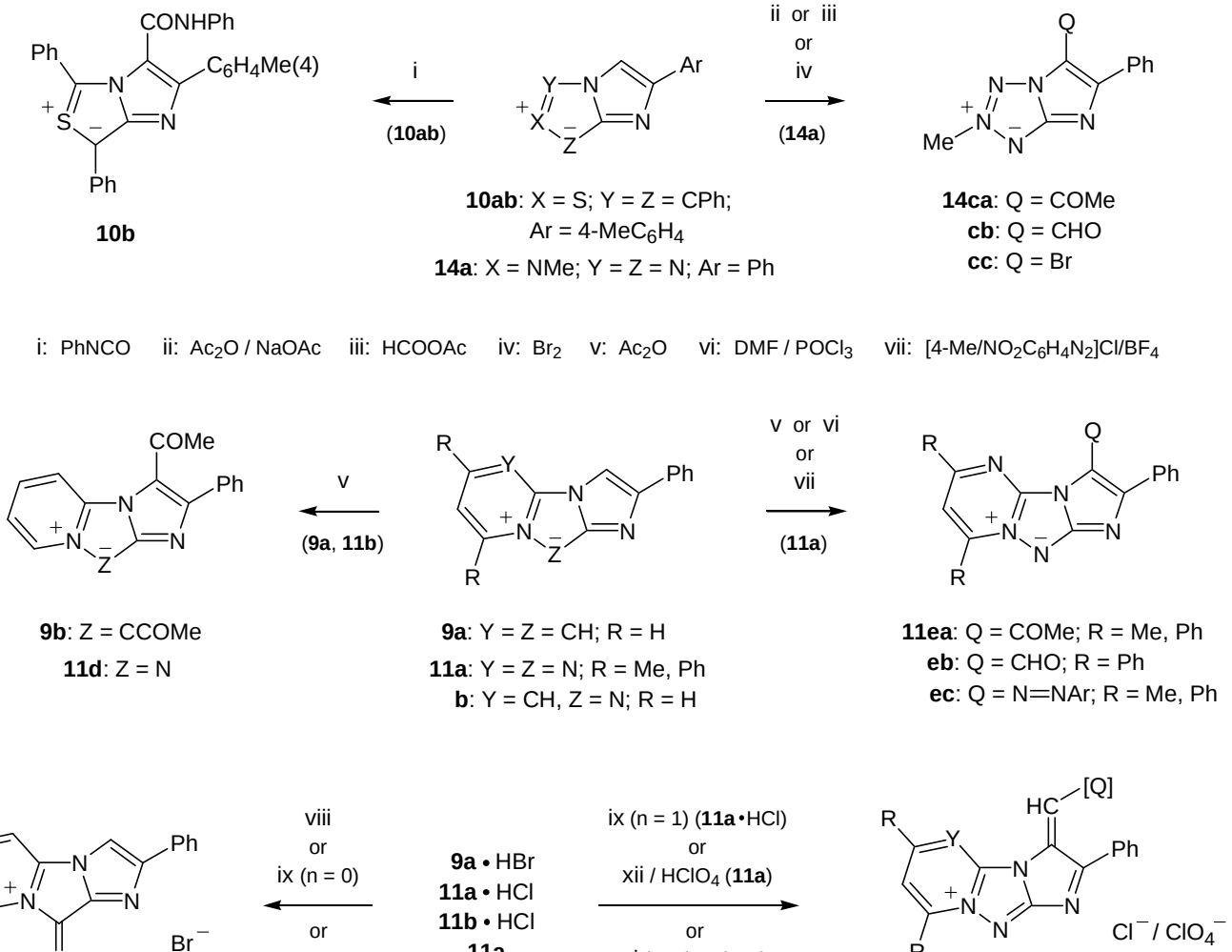
Ample material has been accumulated on S_E reactions; typically, the β half-ring is affected (Schemes 15-17). In the case of the pyrrolo[2,1-*c*][1,2,4]triazole (**3b**) and the pyrrolotetrazoles (**4bc**,**bd**) – *i.e.* educts with free ring positions at C(5) and C(7), preferential attack occurs at C(5) as illustrated by products such as **3da**,**db**[8a] and **4da-dd**,**dk**.[9b] This finding is consistent with quantum-chemical calculations.[8a, 9b,c] Also bicycles with a deactivating group at C(7) like **3aa-ac** and **4aa**,**ab** are sufficiently reactive to give derivatives like **3dd-df**[8a] and **4dg-dj**,**dl**.[9b] Certain experiments disclosed that class (**3**) is more prone towards electrophiles than (**4**): Conspicuous comparisons include the reactions with DMAD [**3b** → **3dc** (twofold attack) / **4bd** → **4da** (single attack)] or acetic anhydride [**3da** → **3dd** (successful) / **4db** → **4dh** (failed)].[9c] Moreover, with series (**4**) an acetylation process like **4aa** → **4dh** is feasible only if C(6) bears an activating methyl group, whereas with class (**3**) no such limitation exists [as evidenced by the conversion (**3aa** → **3dd**)]. When comparing S_E reactions of the corresponding type C' isomers, it was observed that these systems, in agreement with theoretical studies, are partially less reactive.[8a, 9b,c]

Heteropentalenes having as β half-ring an *a*-fused imidazole moiety (like **10ab** and **14a**) react at the position adjacent to the bridgehead nitrogen. This is demonstrated by products such as **10b**[19] and **14ca-cc**.[10] Tricyclic systems with the said structural unit behave accordingly (**11a** → **11ea-ec**[7a,b] and **11b** → **11d**[47]). The substrate (**9a**), however, has a second reactive site at C(10) giving rise to a diacetyl derivative (**9b**); the latter ring carbon is also engaged in the formation of polymethine dyes (→ **9ca-cc**).[46] As expected, dyes of this nature are available too from the tricyclic substrates (**11a**) and (**11b**), which is exemplified by the derivatives (**11fa-fc**)[65] and (**11fd**),[47] respectively.



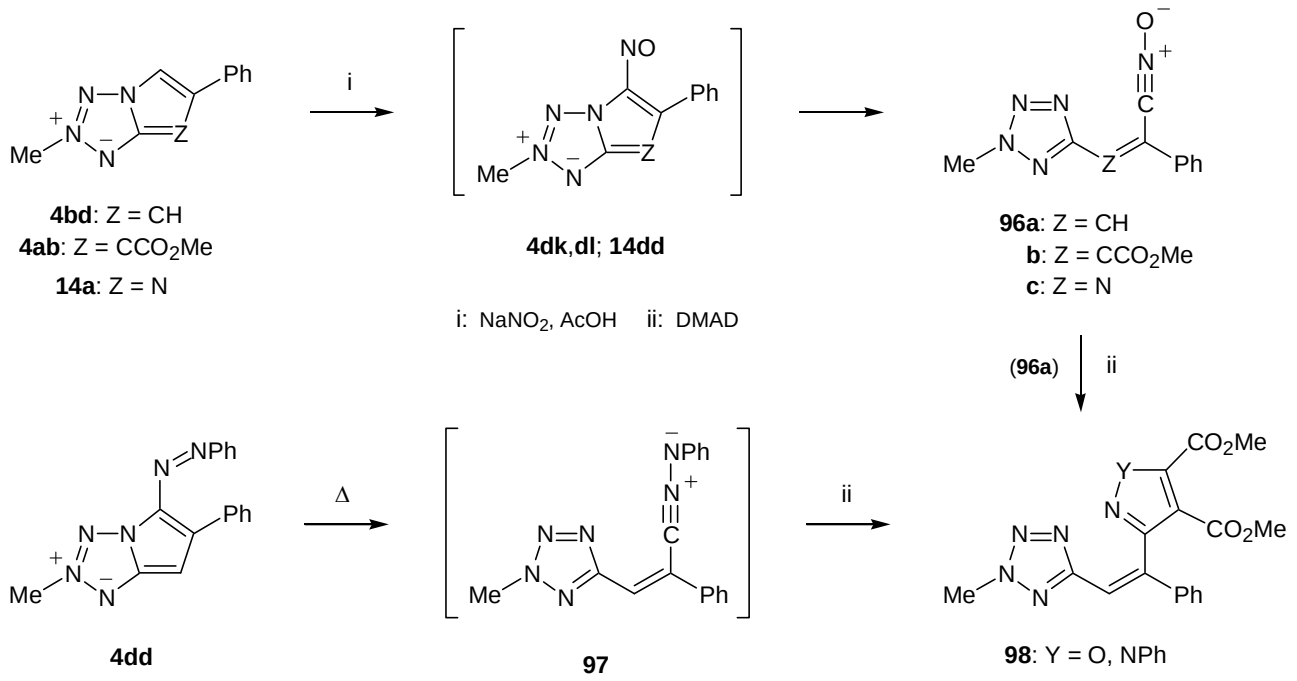
Scheme 15

While all of the above substitution products are isolable materials, certain nitroso derivatives once formed undergo ring opening to the valence-isomeric nitrile oxides: **4bd** → [**4dk**] → **96a**,[9b] **4ab** → [**4dl**] → **96b**,[9b] and **14a** → [**14dd**] → **96c**[10] (Scheme 17).[66] Studying the two equilibria (**4dl** ⇄ **96b**) and (**14a** ⇄ **96c**) in CD_2Cl_2 at various temperatures, *K* values of 17.5 / 9.6 (at 26 / -30 °C) and 25.3 / 13.9 (at 25 / -40 °C) were



Scheme 16

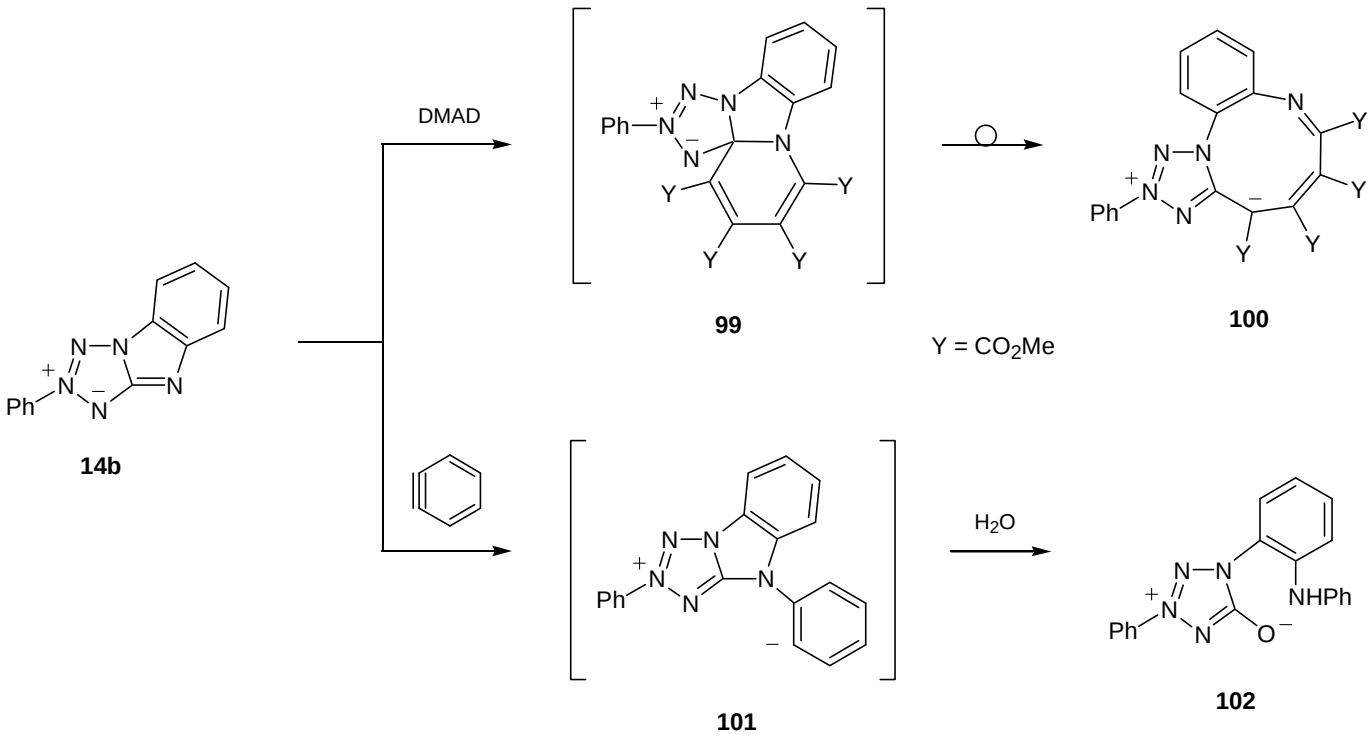
found, respectively.[9c, 10] The nitrile oxides do not tend to dimerize; they readily cycloadd to DMAD [see **96a** → **98** (Y = O)]. An analogous ring opening is possible with the azo derivative (**4dd**); this cleavage, however, requires forcing conditions [the resultant nitrile imine (**97**) has been intercepted with DMAD].[9b]



Scheme 17

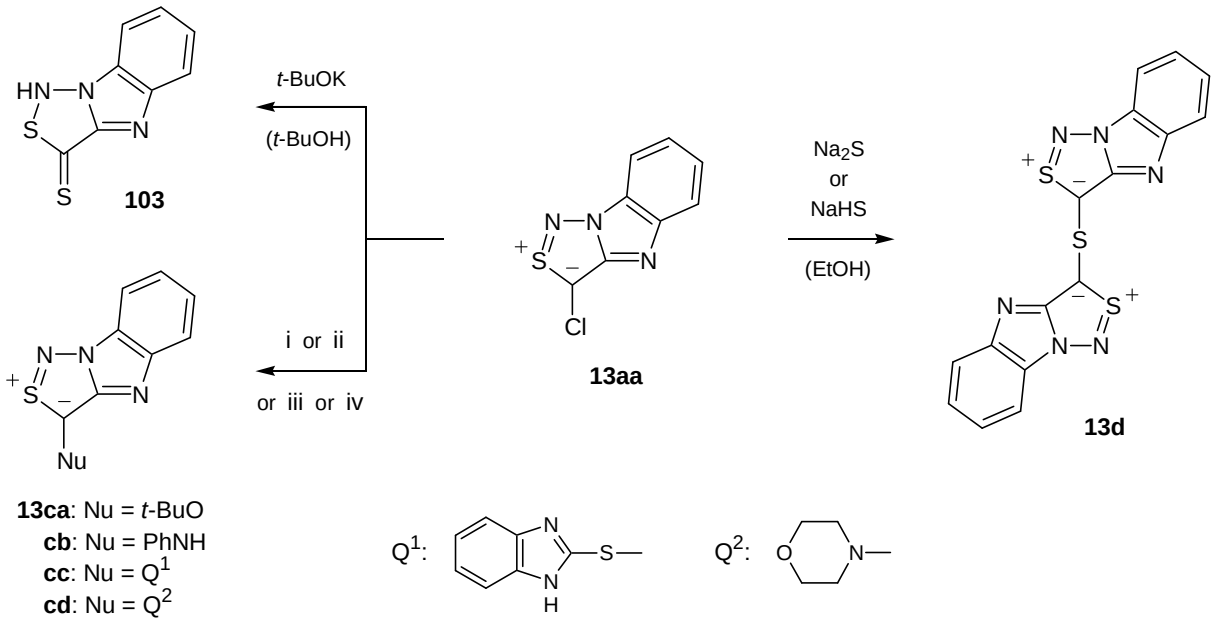
3) Miscellaneous

A product of unusual constitution, the mesomeric betaine (**100**), has been obtained in 78% yield from the benzo-fused imidazo[1,2-*d*]tetrazole (**14b**) and DMAD; its formation is considered to proceed *via* acyclic



Scheme 18

intermediate like **99** which stabilizes by ring expansion (Scheme 18).[67] When treated with benzyne, **14b** affords the tetrazolium-5-olate (**102**) (42% yield); this material obviously arises from electrophilic attack at N(4) giving the adduct (**101**) which, after protonation of the phenyl group, undergoes nucleophilic ring opening by hydroxide ion.[67] Regarding nucleophilic displacement reactions, this mode is still rare; it has been reported for the chloro compound (**13aa**)[30a] (Scheme 19). Here quite remarkable might appear the behaviour towards the *tert*-butoxide and sulfide ions: Depending on the solvent, the first of these nucleophiles affords either the (regular) *tert*-butyl ether (**13ca**) or the thioxo compound (**103**); the latter product should have originated from attack of the sulfide ion, but this nucleophile gives rise to the symmetrical ether (**13d**) – a compound that was also obtained from the other reagents shown (save morpholine) when applied in alcohol as solvent.



Scheme 19

CONCLUSION

The foregoing chapters illustrate the considerable increase of knowledge of non-classical type C heteropentalenes since the years when only studies on type A and B systems were well advanced (type D continues to be rare). However, further efforts are required to fill the gaps of Figure 2, particularly those in the third vertical and horizontal lines showing systems with either a *c*-fused imidazole or a 1,2,3-triazole (1,2,3-thiadiazole) as the leading half-ring. Also systems that are only known as polycyclic derivatives (*i.e.* **5**, **9**, **11**, and **13**) await materialization. Likewise, comparative studies on reactivity – with a view to the 'neutral' type C' systems – should be a concern of future research.

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54. In refs.[9c, 10] it is assumed that C(3a) of the type C' isomer resonates at δ 150.4.
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58. The cycloadduct (**85**) has been found to undergo stereoselective solvolysis with methanol or propan-2-ol to afford the respective ether (**86**); hydrochloric acid causes degradation to the ketone (**87**) which on more stringent conditions is defunctionalized at C(5).[19]
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