

I Structures and spectroscopic properties of aromatic heterocycles

This chapter describes the structures of aromatic heterocycles and gives a brief summary of some physical properties.¹ The treatment we use is the valence-bond description, which we believe is sufficient for the understanding of all heterocyclic reactivity, perhaps save some very subtle effects, and is certainly sufficient for a general text-book on the subject. The more fundamental, molecular-orbital description of aromatic systems, is still not so relevant to the day-to-day interpretation of heterocyclic reactivity, though it is necessary in some cases to utilise frontier orbital considerations,² however such situations do not fall within the scope of this book.

I.1 Carbocyclic aromatic systems

I.1.1 Structures of benzene and naphthalene

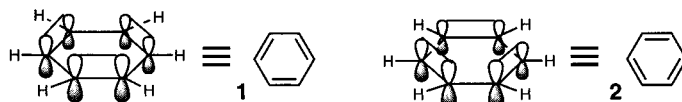
The concept of aromaticity as represented by benzene is a familiar and relatively simple one. The difference between benzene on the one hand and alkenes on the other is well known: the latter react by addition with electrophiles, such as bromine, whereas benzene reacts only under much more forcing conditions and then nearly always by substitution. The difference is due to the cyclic arrangement of six π -electrons in benzene: this forms a conjugated molecular orbital system which is thermodynamically much more stable than a corresponding non-cyclically conjugated system. The additional stabilisation results in a diminished tendency to react by addition and a greater tendency to react by substitution for, in the latter manner, survival of the original cyclic conjugated system of electrons is ensured in the product. A general rule proposed by Hückel in 1931 states that aromaticity is observed in cyclically conjugated systems of $4n + 2$ electrons, that is with 2, 6, 10, 14, etc., π -electrons; by far the majority of monocyclic aromatic, and heteroaromatic systems are those with 6 π electrons.

In this book we use the pictorial valence-bond resonance description of structure and reactivity. Even though this treatment is not rigorous it is still the standard means for the understanding and learning of organic chemistry, which can at a more advanced level give way naturally to the much more complex, and mathematical, quantum mechanical approach. We begin by recalling the structure of benzene in these terms.

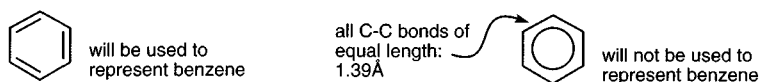
In benzene, the geometry of the ring, with angles of 120° , precisely fits the geometry of a planar trigonally hybridised carbon atom, and allows the assembly of a σ -skeleton of six sp^2 hybridised carbon atoms in a strainless planar ring. Each carbon then has one extra electron which occupies an atomic p orbital orthogonal to the plane of the ring. The p orbitals interact to generate π -molecular orbitals associated with the aromatic system.

Benzene is described as a resonance hybrid of the two extreme forms which correspond, in terms of orbital interactions, to the two possible spin-coupled pairings

of adjacent p electrons – structures **1** and **2**. These are known as canonical structures, have no existence in their own right, but serve to illustrate two extremes which contribute to the ‘real’ structure of benzene.

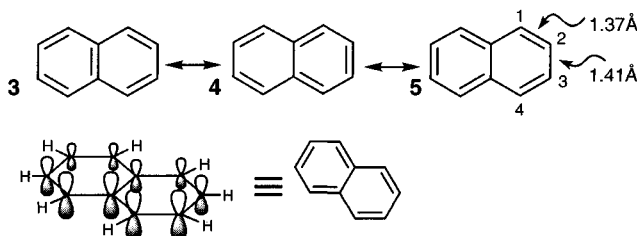


Sometimes, benzenoid compounds are represented using a circle inside a hexagon; although this emphasises their delocalised nature and the close similarity of the ring bond lengths (all exactly identical only in benzene itself), it is not helpful in interpreting reactions, and we do not use this method here.



Treating naphthalene comparably reveals three canonical structures, **3**, **4**, and **5**. Note the standard use of a double-headed arrow to interrelate resonance contributors. This must never be confused with the use of opposing straight ‘fish-hook’ arrows which are used to designate an equilibrium between two species: resonance contributors have no separate existence; they are not in equilibrium one with the other.

This valence bond treatment predicts quite well the non-equivalence of the bond lengths in naphthalene: in two of the three contributing structures, C-1–C-2 is double and in one it is single, whereas C-2–C-3 is single in two and double in one. Statistically, then, the former may be looked on as 0.67 of a double bond and the latter as 0.33 of a double bond: the measured bond lengths confirm that there indeed is this degree of bond fixation, with values closely consistent with statistical prediction.



1.1.2 Aromatic resonance energy³

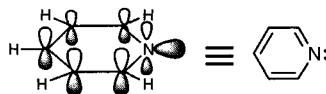
The difference between the ground-state energy of benzene and that of hypothetical, non-aromatic, 1,3,5-cyclohexatriene corresponds to the degree of stabilisation conferred to benzene by the special cyclical interaction of the six π -electrons. This difference is known as aromatic resonance energy. Of course, quantification depends on the assumptions made in estimating the energy of the ‘non-aromatic’ structure, and for this reason and others, a variety of values have been calculated for the various heteroaromatic systems; perhaps their absolute values are less important than their relative values. What one can say with certainty is that the resonance energy of bicyclic aromatics, like naphthalene, is considerably less than twice that of the corresponding monocyclic system, implying a smaller loss of stabilisation energy on conversion to a reaction intermediate which still retains a complete benzene ring,

for example during electrophilic substitution (section 2.2.2). The resonance energy of pyridine is of the same order as that of benzene, that of thiophene is lower, with pyrrole and lastly furan of lower stabilisation energy still. Actual values for the stabilisations of these systems vary according to assumptions made, but are in the same relative order (kJ mol^{-1}): benzene (150), pyridine (117), thiophene (122), pyrrole, (90), and furan (68).

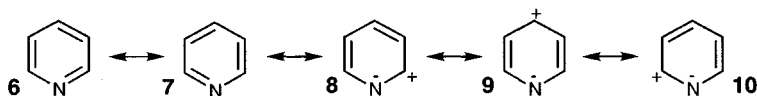
1.2 Structure of six-membered heteroaromatic systems

1.2.1 Structure of pyridine

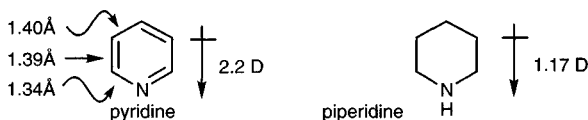
The structure of pyridine is completely analogous to that of benzene, being related by replacement of CH by N. The key differences are: (i) the departure from perfectly regular hexagonal geometry caused by the presence of the hetero atom, in particular the shorter carbon–nitrogen bonds, (ii) the replacement of a hydrogen in the plane of the ring with an unshared electron pair, likewise in the plane of the ring, located in an sp^2 hybrid orbital, and not at all involved in the aromatic π -electron sextet; it is this nitrogen lone pair which is responsible for the basic properties of pyridines, and (iii) a strong permanent dipole, traceable to the greater electronegativity of the nitrogen compared with carbon.



It is important to realise that the electronegative nitrogen causes inductive polarisation, mainly in the σ -bond framework, and additionally, stabilises those polarised canonical structures in which nitrogen is negatively charged – **8**, **9**, and **10** – which, together with contributors **6** and **7**, which are strictly analogous to the Kekulé contributors to benzene, represent pyridine. The polarised contributors imply a permanent polarisation of the π -electron system too (these equate, in the more rigorous molecular orbital treatment, to a consideration of the relative magnitudes of orbital coefficients in the HOMO and LUMO).

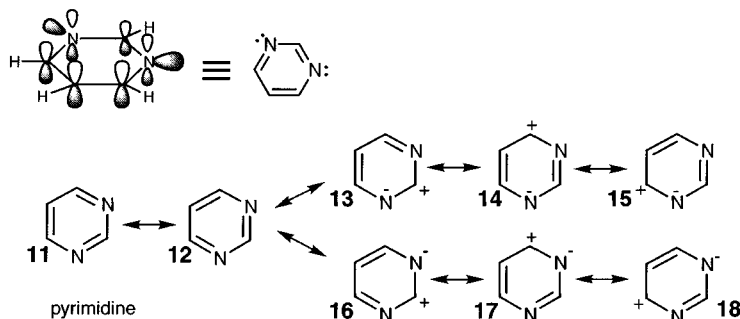


Because inductive and mesomeric effects work in the same sense in pyridine, there results a permanent dipole towards the nitrogen atom. It also means that there are fractional positive charges on the carbons of the ring, located mainly on the α - and γ -positions. It is because of this general electron-deficiency at carbon that pyridine and similar heterocycles are referred to as ‘electron-poor’, or sometimes ‘ π -deficient’. A comparison with the dipole moment of piperidine, which is due wholly to the induced polarisation of the σ -skeleton, gives an idea of the additional polarisation associated with distortion of the π -electron system.



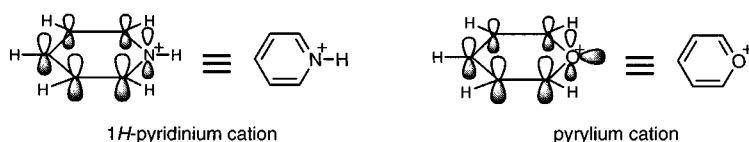
1.2.2 Structure of diazines

The structures of the diazines (six-membered systems with two nitrogen atoms in the ring) are analogous, but now there are two nitrogen atoms and a corresponding two lone pairs; as an illustration, the main canonical contributors (11–18) to pyrimidine are shown below.

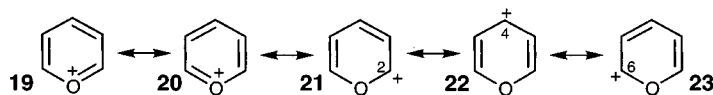


1.2.3 Structures of pyridinium and related cations

Electrophilic addition to the pyridine nitrogen generates pyridinium ions, the simplest being 1*H*-pyridinium formed by addition of a proton. 1*H*-Pyridinium is actually isoelectronic with benzene, the only difference being the nuclear charge of nitrogen, which makes the system, as a whole, positively charged. Thus pyridinium cations are still aromatic, the diagram making clear that the system of six p orbitals required to generate the aromatic molecular orbitals is still present, though the formal positive charge on the nitrogen atom severely distorts the π -system, making the α - and γ -carbons in these cations carry fractional positive charges which are higher than in pyridine, with a consequence for their reactivity towards nucleophiles. Electron density at the pyridinium β -carbons is also reduced relative to these carbons in pyridines.



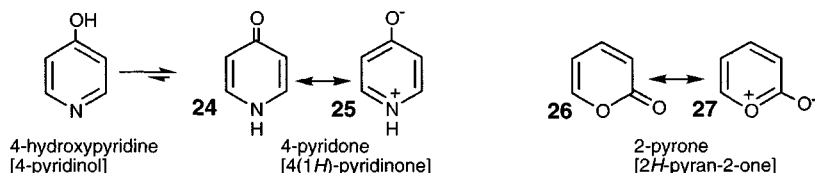
In the pyrylium cation, the positively charged oxygen also has an unshared electron pair, in an sp^2 orbital in the plane of the ring, exactly as in pyridine. Once again, a set of resonance contributors, 19–23, makes clear that this ion is strongly positively charged at the 2-, 4- and 6-positions, in fact, because the more electronegative oxygen tolerates positive charge much less well than nitrogen, the pyrylium cation is certainly a less stabilised system than a pyridinium cation.



1.2.4 Structures of pyridones and pyrones

Pyridines with an oxygen at either the 2- or 4-position exist predominantly as carbonyl tautomers, which are therefore known as pyridones⁴ (see also section 1.5).

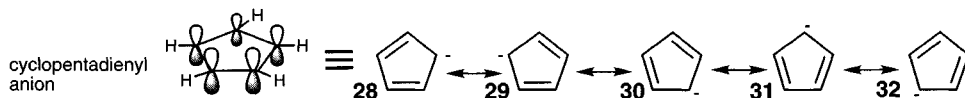
In the analogous oxygen systems, no alternative tautomer is possible; the systems are known as pyrones. The extent to which such molecules are aromatic has been a subject for considerable speculation and experimentation, and estimates have varied considerably. The degree of aromaticity depends on the contribution which dipolar structures, **25** and **27**, with a 'complete' pyridinium (pyrylium) ring make to the overall structure. Pyrones are less aromatic than pyridones, as can be seen from their tendency to undergo addition reactions (section 8.2.2.4), and as would be expected from a consideration of the 'aromatic' contributors, **25** and **27**, which have a positively charged ring hetero atom, oxygen being less easily able to accommodate this requirement.



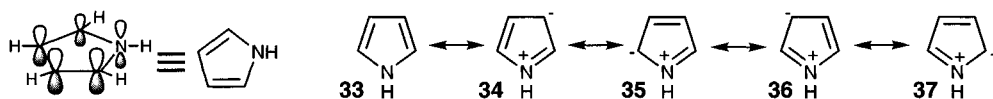
1.3 Structure of five-membered heteroaromatic systems⁵

1.3.1 Structure of pyrrole

Before discussing pyrrole it is necessary to recall the structure of the cyclopentadienyl anion, which is a 6- π -electron aromatic system produced by the removal of a proton from cyclopentadiene. This system serves to illustrate nicely the difference between aromatic stabilisation and reactivity, for it is a very reactive, fully negatively charged entity, and yet is 'resonance stabilised' – everything is relative. Cyclopentadiene, with a pK_a of about 14, is much more acidic than a simple diene, just because the resulting anion is resonance stabilised. Five equivalent contributing structures, **28–32**, show each carbon atom to be equivalent and hence to carry one fifth of the negative charge.

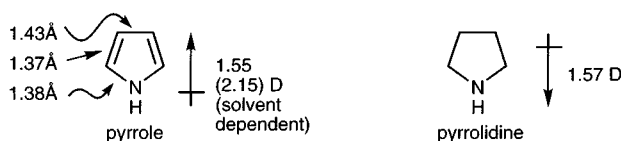


Pyrrole is isoelectronic with the cyclopentadienyl anion, but is electrically neutral because of the higher nuclear charge on nitrogen. The other consequence of the presence of nitrogen in the ring is the loss of radial symmetry, so that pyrrole does not have five equivalent canonical forms: it has one with no charge separation, **33**, and two pairs of equivalent forms in which there is charge separation, indicating electron density drift away from the nitrogen. These forms do not contribute equally; the order of importance is: **33** > **35,37** > **34,36**.



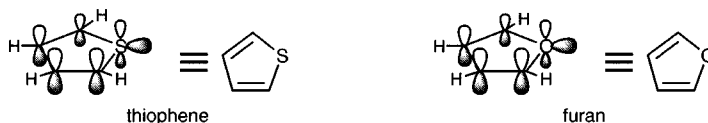
Resonance leads, then, to the establishment of partial negative charges on the carbons and a partial positive charge on the nitrogen. Of course the inductive effect of the nitrogen is, as usual, towards the hetero atom and away from carbon, so that the electronic distribution in pyrrole is a balance of two opposing effects, of which the mesomeric effect is probably the more significant. The lengths of the bonds in

pyrrole are in accord with this exposition, thus the 3,4-bond is very much longer than the 2,3-/4,5-bonds, but appreciably shorter than a normal single bond between sp^2 hybridised carbons, in accord with contributions from the polarised structures **34–37**. It is because of this electronic drift away from nitrogen and towards the ring carbons that five-membered heterocycles of the pyrrole type are referred to as ‘electron-rich’, or sometimes ‘ π -excessive’.



It is most important to recognise that the nitrogen lone pair in pyrrole forms part of the aromatic six-electron system.

1.3.2 Structures of thiophene and furan



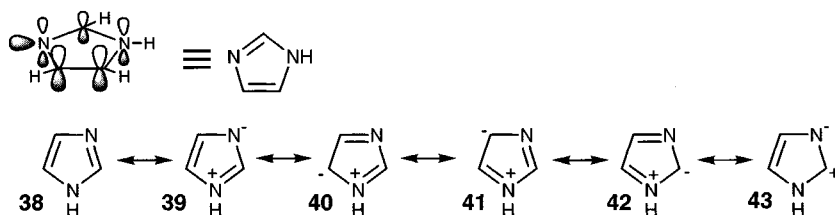
The structures of thiophene and furan are closely analogous to that discussed in detail for pyrrole above, except that the NH is replaced by S and O respectively. A consequence is that the hetero atom in each has one lone pair as part of the aromatic sextet, as in pyrrole, but also has a second lone pair which is not involved, and is located in an sp^2 hybrid orbital in the plane of the ring. Canonical forms exactly analogous to those (above) for pyrrole can be written for each, but the higher electronegativity of both sulfur and oxygen means that the polarised forms, with positive charges on the hetero atoms, make a smaller contribution. The decreased mesomeric electron drift away from the hetero atoms is insufficient, in these two cases, to overcome the inductive polarisation towards the hetero atom (the dipole moments of tetrahydrothiophene and tetrahydrofuran, 1.87D and 1.68D, respectively, both towards the hetero atom, are in any case larger) and the net effect is to give dipoles directed towards the hetero atoms in thiophene and furan.



The larger bonding radius of sulfur is one of the influences making thiophene more stable (more aromatic) than pyrrole or furan – the bonding angles are larger and angle strain is somewhat relieved, but in addition, a contribution to the stabilisation involving sulfur d orbital participation may be significant.

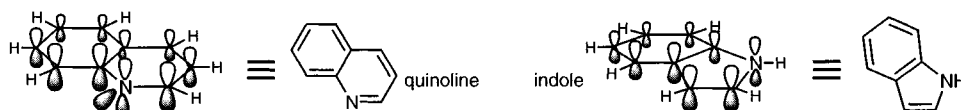
1.3.3 Structures of azoles

The 1,3- and 1,2-azoles, five-membered rings with two hetero atoms, present a fascinating combination of hetero atom types – in all cases, one hetero atom must be of the five-membered heterocycle (pyrrole, thiophene, furan) type and one of the imine type, as in pyridine; imidazole with two nitrogen atoms illustrates this best. Contributor **39** is a particularly favourable one.

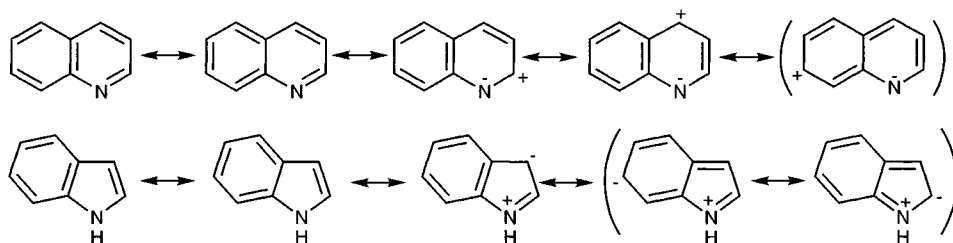


1.4 Structures of bicyclic heteroaromatic compounds

Once the ideas of the structures of benzene, naphthalene, pyridine and pyrrole, as prototypes, have been assimilated it is straightforward to extrapolate to those systems which combine two (or more) of these types, thus quinoline is like naphthalene, only with one of the rings a pyridine, and indole is like pyrrole, but with a benzene ring attached.



Resonance representations must take account of the pattern established for benzene and the relevant heterocycle. Contributors in which both aromatic rings are disrupted make a very much smaller contribution and are shown in parentheses.



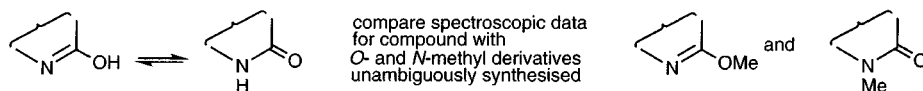
1.5 Tautomerism in heterocyclic systems⁶

A topic which has attracted an inordinately large research effort over the years is the determination of precise structure of heterocyclic molecules which are potentially tautomeric – the pyridinol/pyridone relationship (section 1.2.4) is one such situation. In principle, when an oxygen is located on a carbon α or γ to nitrogen, two tautomeric forms can exist; the same is true of amino groups.



Early attempts to use the results of chemical reactions to assess the form of a particular compound were misguided, since these can give entirely the wrong answer: the minor partner in such a tautomeric equilibrium may be the one which is the more reactive, so a major product may be actually derived from the minor component in the tautomeric equilibrium. Most secure evidence on these questions has come from

comparisons of spectroscopic data for the compound in question with unambiguous models – often *N*- and *O*-methyl derivatives.

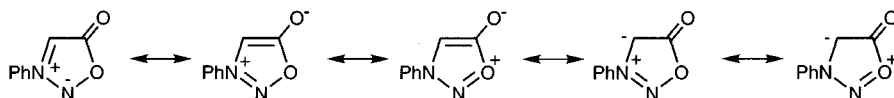


After all the effort that has been expended on this area, the picture which emerges is fairly straightforward: α and γ oxy-heterocycles generally prefer the carbonyl form; amino-heterocycles nearly always exist as amino tautomers. Sulfur analogues – potentially thiol or thione – tend to exist as thione in six-membered situations, but as thiol in five-membered rings.

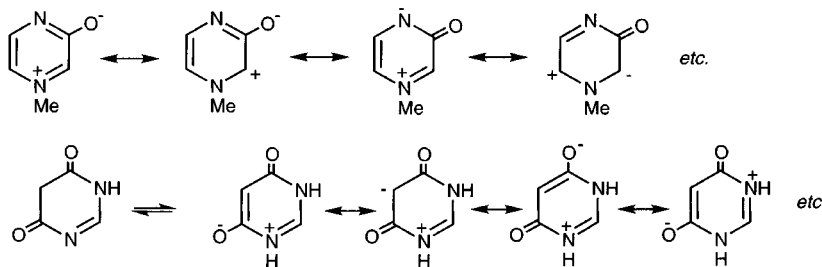
The establishment of tautomeric form is perhaps of most importance in connection with the purine and pyrimidine bases which form part of DNA and RNA, and, through H-bonding involving carbonyl oxygen, provide the mechanism for base pairing (cf. section 24.1).

1.6 Mesoionic systems⁷

There are a substantial number of heterocyclic substances for which no plausible, unpolarised canonical structure can be written: such systems are termed 'mesoionic'. Despite the presence of a nominal positive and negative charge in all resonance contributors to such compounds, they are not salt-like, are of course overall neutral, and behave like 'organic' substances, dissolving in the usual solvents. Examples of mesoionic structures occur throughout the text. Amongst the earliest mesoionic substances to be studied were the sydnones, for which several contributing structures can be drawn.



Mesoionic structures occur amongst six-membered systems too – two are illustrated below:



If there is any one feature which characterises mesoionic compounds it is that their dipolar structures lead to reactions in which they serve as 1,3-dipoles in cycloadditions.

1.7 Some spectroscopic properties of some heteroaromatic systems

The use of spectroscopy is at the heart of chemical research and analysis, but a knowledge of the particular chemical shift of, say a proton on a pyridine, or the

particular UV absorption maximum of, say, an indole, is only of direct relevance to those actually pursuing such research and analysis, and adds nothing to the understanding of heteroaromatic reactivity. Accordingly, we give here only a brief discussion, with relatively little data, of the spectroscopic properties of heterocyclic systems, anticipating that those who may be involved in particular research projects will turn to reviews¹ or the original literature for particular data.

The ultraviolet and infrared spectra of heteroaromatic systems are in accord with their aromatic character. Spectroscopic investigation, particularly ultraviolet/visible (UV/VIS) and nuclear magnetic resonance (NMR) spectroscopies, is particularly useful in the context of assessing the extent of such properties, in determining the position of tautomeric equilibria, and in testing for the existence of non-isolable intermediates.

1.7.1 Ultraviolet/visible (electronic) spectroscopy

The simple unsubstituted heterocyclic systems show a wide range of electronic absorption, from the simple 200 nm band of furan, for example, to the 340 nm maximum shown by pyridazine. As is true for benzenoid compounds, the presence of substituents which can conjugate causes profound changes in electronic absorption, but the many variations possible are outside the scope of this section.

The UV spectra of the monocyclic azines show two bands, each with fine structure: one occurs in the relatively narrow range of 240–260 nm and corresponds to the $\pi \rightarrow \pi^*$ transitions, analogous with the $\pi \rightarrow \pi^*$ transitions in the same region in benzene (see Table 1.1). The other band occurs at longer wavelengths, from 270 nm in pyridine to 340 nm in pyridazine and corresponds to the interaction of the hetero atom lone pair with aromatic π electrons, the $n \rightarrow \pi^*$ transitions, which of course cannot occur in benzene. The absorptions due to $n \rightarrow \pi^*$ transitions are very solvent dependent, as is exemplified in Table 1.1 by the case of pyrimidine. With pyridine, this band is only observed in hexane solution, for in alcoholic solution the shift to shorter wavelengths results in masking by the main $\pi \rightarrow \pi^*$ band. Protonation of the ring nitrogen naturally quenches the $n \rightarrow \pi^*$ band, by removing the hetero atom lone pair; protonation also has the effect of considerably increasing the intensity of the $\pi \rightarrow \pi^*$ band, without changing its position significantly, the observation of which can have considerable diagnostic utility.

The bicyclic azines have much more complex electronic absorption, and the $n \rightarrow \pi^*$ and $\pi \rightarrow \pi^*$ bands overlap; being much more intense, the latter mask the former. Broadly, however, the absorptions of the bicyclic azines resemble that of naphthalene (Table 1.2).

The UV spectra of the simple five-membered heteroaromatic systems all show just one medium-to-strong low-wavelength band with no fine structure. Their absorptions have no obvious similarity to that of benzene, and no detectable $n \rightarrow \pi^*$ absorption, not even in the azoles, which contain a pyridine-like nitrogen (Tables 1.3 and 1.4).

1.7.2 Nuclear magnetic resonance (NMR) spectroscopy⁸

The chemical shifts⁹ of protons attached to, and in particular of the carbons in, heterocyclic systems, can be taken as relating to the electron-density at that position, with lower fields corresponding to electron-deficient carbons. For example, in the ¹H spectrum of pyridine, the lowest field signals are for the α -protons (Table 1.5), the next lowest is that for the γ -proton and the highest field signal corresponds to the β -

Table 1.1 Ultraviolet spectra of monocyclic azines (fine structure not given)

heterocycle (solvent)	$n \rightarrow \pi^*$ $\lambda_{\max.}$ (nm)	ϵ	$\pi \rightarrow \pi^*$ $\lambda_{\max.}$ (nm)	$\pi \rightarrow \pi^*$ $\lambda_{\max.}$ (nm)	ϵ	ϵ
pyridine (hexane)	270	450	195	251	7500	2000
pyridine (ethanol)	-	-	-	257	-	2750
pyridinium (ethanol)	-	-	-	256	-	5300
pyridazine (hexane)	340	315	-	246	-	1400
pyrimidine (hexane)	298	326	-	243	-	2030
pyrazine (hexane)	328	1040	-	260	-	5600
pyrimidine (water)	271	410	-	243	-	3210
pyrimidinium (water)	-	-	-	242	-	5500
pyrylium (90% aq. HClO ₄)	-	-	220	269	1400	8500
benzene (hexane)	-	-	204	254	7400	200

Table 1.2 Ultraviolet spectra of bicyclic azines (fine structure not given)

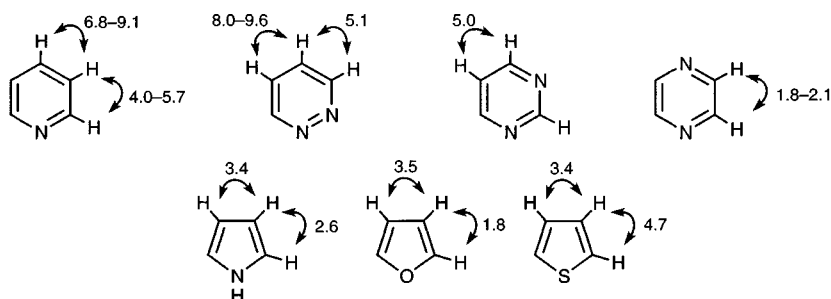
heterocycle	$\lambda_{\max.}$ (nm)	$\lambda_{\max.}$ (nm)	$\lambda_{\max.}$ (nm)	ϵ	ϵ	ϵ
quinoline	313	270	226	2360	3880	35500
quinolinium	313	-	233	6350		34700
isoquinoline	317	266	217	3100	4030	37000
isoquinolinium	331	274	228	4170	1960	37500
quinolizinium	324	284	225	14500	2700	17000
naphthalene	312	275	220	250	5600	100000

protons, and this is echoed in the corresponding ^{13}C shifts (Table 1.6). A second generality relates to the inductive electron withdrawal by the hetero atom – for example it is the hydrogens on the α -carbons of pyridine which are at lower field than that at the γ -carbon, and it is the signals for protons at the α -positions of furan which are at lower field than those at the β -positions. Protons at the α -positions of pyrylium cations present the lowest field ^1H signals. In direct contrast, the chemical shifts for C-protons on electron-rich heterocycles, such as pyrrole, occur at much higher fields.

Coupling constants between 1,2-related (*ortho*) protons on heterocyclic systems vary considerably. Typical values round six-membered systems show smaller values closer to the hetero atom(s). In five-membered heterocycles, altogether smaller values are typically found, but again those involving a hydrogen closer to the hetero atom are smaller, except in thiophenes, where the larger size of the sulfur atom influences the coupling constant. The magnitude of such coupling constants reflects the degree of double bond character (bond fixation) in a particular C–C bond.

Table 1.3 Ultraviolet spectra of monocyclic five-membered heterocycles

heterocycle	$\lambda_{\max.}$ (nm)	$\lambda_{\max.}$ (nm)	ϵ	ϵ
pyrrole	210	-	5100	-
furan	200	-	10000	-
thiophene	235	-	4300	-
imidazole	206	-	3500	-
oxazole	205	-	3900	-
thiazole	235	-	3000	-
cyclopentadiene	200	239	10000	3400



The use of ^{15}N NMR spectroscopy is of obvious relevance to the study of nitrogen-containing heterocycles – it can for example be used to estimate the hybridisation of nitrogen atoms.¹⁰

Table 1.4 Ultraviolet spectra of bicyclic compounds with five-membered heterocyclic rings

heterocycle	$\lambda_{\max.}$ (nm)	$\lambda_{\max.}$ (nm)	$\lambda_{\max.}$ (nm)	ϵ	ϵ	ϵ
indole	288	261	219	4900	6300	25000
benzo[<i>b</i>]thiophene	288	257	227	2000	5500	28000
benzo[<i>b</i>]furan	281		244	2600		11000
2- <i>t</i> -Bu-isoidole	223, 266	270, 277	289, 329	48000, 1800	1650, 1850	1250, 3900
isobenzofuran	215, 244, 249	254, 261, 313	319, 327, 334, 343	14800, 2500, 2350	2250, 1325, 5000	5000, 7400, 4575, 6150
indolizine	347	295	238	1950	3600	32000
benzimidazole	259	275		5620	5010	
benzothiazole	217, 251	285	295	18620, 5500	1700	1350
benzoxazole	231, 263	270	276	7940, 2400	3390	3240
2-methyl-2 <i>H</i> -indazole	275	292	295	6310	6170	6030
2,1-benzisothiazole	203, 221	288sh, 298	315sh	14450, 16220	7590, 2880	3980
purine	263	-	-	7950	-	-

Table 1.5 ^1H chemical shifts (ppm) for heteroaromatic ring protons

heterocycle	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	others
pyridine	-	8.5	7.1	7.5	-	-	-	-	-
2-pyridone	-	-	6.6	7.3	6.2	7.3	-	-	-
quinoline	-	8.8	7.3	8.0	7.7	7.4	7.6	8.1	-
quinoline <i>N</i> -oxide	-	8.6	7.3	7.7	-	-	-	8.8	-
isoquinoline	9.1	-	8.5	7.5	7.7	7.6	7.5	7.9	-
isoquinoline <i>N</i> -oxide	8.8	-	8.1	-	-	-	-	-	-
pyridazine	-	-	9.2	7.7	-	-	-	-	-
pyrimidine	-	9.2	-	8.6	7.1	-	-	-	-
pyrimidine <i>N</i> -oxide	-	9.0	-	8.2	7.3	8.4	-	-	-
pyrazine	-	8.5	-	-	-	-	-	-	-
1,2,4-triazine	-	-	9.6	-	8.5	9.2	-	-	-
1,3,5-triazine	-	9.2	-	-	-	-	-	-	-
cinnoline	-	-	9.15	7.75	-	-	-	-	-
quinazoline	-	9.2	-	9.3	-	-	-	-	-
quinoxaline	-	9.7	-	-	-	-	-	-	-
phthalazine	9.4	-	-	-	-	-	-	-	-
pyrylium	-	9.6	8.5	9.3	-	-	-	-	in SO_2 (liq.)
pyrrole	-	6.6	6.2	-	-	-	-	-	-
thiophene	-	7.2	7.1	-	-	-	-	-	-
furan	-	7.4	6.3	-	-	-	-	-	-
indole	-	6.5	6.3	7.5	7.0	7.1	7.4	-	-
benzo[<i>b</i>]furan	-	7.5	6.7	7.5	7.1	7.2	7.4	-	-
benzo[<i>b</i>]thiophene	-	7.3	7.3	7.7	7.3	7.3	7.8	-	-
indolizine	6.3	6.6	7.1	-	7.8	6.3	6.5	7.2	-
imidazole	-	7.9	-	7.25	-	-	-	-	-
1-methylimidazole	-	7.5	-	7.1	6.9	-	-	-	-
pyrazole	-	-	7.6	6.3	-	-	-	-	-
1-methylpyrazole	-	-	7.5	6.2	7.4	-	-	-	3.8 (CH_3)
thiazole	-	8.9	-	8.0	7.4	-	-	-	-
oxazole	-	7.95	-	7.1	7.7	-	-	-	-
benzimidazole	-	7.4	-	7.0	6.9	-	-	-	-
benzoxazole	-	7.5	-	7.7	7.8	7.8	7.7	-	-
pyrazole	-	-	7.6	7.3	-	-	-	-	-
isothiazole	-	-	8.5	7.3	8.7	-	-	-	-
isoxazole	-	-	8.1	6.3	8.4	-	-	-	-
indazole	-	-	8.1	7.8	7.1	7.35	7.55	-	-
1,2,3-triazole	-	-	-	7.75	-	-	-	-	-
1,2,4-triazole	-	-	7.9	-	8.85	-	-	-	-
tetrazole	-	-	-	-	9.5	-	-	-	-
purine	-	9.0	-	-	-	9.2	-	8.6	-
benzene	7.27	-	-	-	-	-	-	-	-

Table 1.5 (continued)

heterocycle	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	others
anisole	-	6.9	7.2	6.9	-	-	-	-	-
aniline	-	6.5	7.0	6.6	-	-	-	-	-
nitrobenzene	-	8.2	7.4	7.6	-	-	-	-	-
naphthalene	7.8	7.5	-	-	-	-	-	-	-

Table 1.6 ^{13}C chemical shifts (ppm) for heteroaromatic ring carbons

heterocycle	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	$\delta_{\text{ring junction}}$	$\delta_{\text{ring junction}}$	other
pyridine	-	150	124	136	-	-	-	-	-	-	-
1- <i>H</i> -pyridinium	-	143	129	148	-	-	-	-	-	-	-
pyridine <i>N</i> -oxide	-	139	126	126	-	-	-	-	-	-	-
1-Me-pyridinium	-	146	129	146	-	-	-	-	-	-	50 (CH_3)
2-pyridone	-	165	121	142	107	136	-	-	-	-	-
4-pyridone	-	140	116	176	-	-	-	-	-	-	-
quinoline	-	151	122	136	1289	127	130	131	129 (4a)	149 (8a)	-
isoquinoline	153	-	143	120	126	130	127	128	136 (4a)	129 (8a)	-
pyridazine	-	-	153	128	-	-	-	-	-	-	-
1- <i>H</i> -pyridazinium	-	-	152	138	-	-	-	-	-	-	-
pyrimidine	-	158	-	156	121	-	-	-	-	-	-
1- <i>H</i> -pyrimidinium	-	152	-	159	125	-	-	-	-	-	-
pyrazine	-	146	-	-	-	-	-	-	-	-	-
1- <i>H</i> -pyrazinium	-	143	-	-	-	-	-	-	-	-	-
cinnoline	-	-	146	125	128	132	132	130	127 (4a)	151 (8a)	-
quinazoline	-	161	-	156	127	128	134	129	135 (4a)	150 (8a)	-
quinoxaline	-	146	-	-	130	130	-	-	143 (4a)	-	-
phthalazine	152	-	-	-	127	133	-	-	126 (4a)	-	-
1,2,3-triazine	-	-	-	150	118	-	-	-	-	-	-
1,2,4-triazine	-	-	158	-	150	151	-	-	-	-	-
1,3,5-triazine	-	166	-	-	-	-	-	-	-	-	-
pyrylium (BF_4^-)	-	169	128	161	-	-	-	-	-	-	-
2-pyrone	-	162	117	143	106	152	-	-	-	-	-
2,6-Me ₂ -4-pyrone	-	166	114	180	-	-	-	-	-	-	20 (CH_3)
coumarin	-	161	117	144	129	124	132	117	119 (4a)	154 (8a)	-
chromone	-	156	113	177	125	126	134	118	125 (4a)	156 (8a)	-
pyrrole	-	117	108	-	-	-	-	-	-	-	-
thiophene	-	126	127	-	-	-	-	-	-	-	-
furan	-	144	110	-	-	-	-	-	-	-	-
indole	-	124	102	121	122	120	111	-	128 (3a)	136 (7a)	-
oxindole	-	179	36	124	122	128	110	-	125 (3a)	143 (7a)	-
benzo[<i>b</i>]furan	-	145	107	122	123	125	112	-	128 (3a)	155 (7a)	-

Table 1.6 (continued)

heterocycle	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	$\delta_{\text{ring junction}}$	$\delta_{\text{ring junction}}$	other
benzo[b]thiophene	-	126	124	124	124	124	123	-	140 (3a)	140 (7a)	-
indolizine	100	114	113	-	126	111	117	120	133 (8a)	-	-
imidazole	-	135	-	122			-	-	-	-	-
1-methylimidazole	-	138	-	130	120		-	-	-	-	33 (CH ₃)
thiazole	-	154	-	143	120		-	-	-	-	-
oxazole	-	151	-	125	138		-	-	-	-	-
benzimidazole	-	144	-	110	123	122	119	-	-	-	-
benzothiazole	-	155	-	123	126	125	122	-	153 (3a)	134 (7a)	-
benzoxazole	-	153	-	121	125	124	111	-	140 (3a)	150 (7a)	-
pyrazole	-	-	135	106	135		-	-	-	-	-
isothiazole	-	-	157	123	148		-	-	-	-	-
isoxazole	-	-	150	105	159		-	-	-	-	-
indazole	-	-	133	120	120	126	110	-	123 (3a)	140 (7a)	-
3-methyl-1,2-benzisothiazole	-	163	-	-	-	-	-	-	152 (7a)	-	-
purine	-	152	-	155	131	146	-	146	-	-	-
uracil	-	151	-	142	100	164	-	-	-	-	-
benzene	129	-	-	-	-	-	-	-	-	-	-
anisole	160	114	130	121	-	-	-	-	-	-	-
aniline	149	114	129	116	-	-	-	-	-	-	-
nitrobenzene	149	124	130	135	-	-	-	-	-	-	-
naphthalene	128	126	-	-	-	-	-	-	133 (4a)	-	-

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