Metal-assisted reactions. Part 26.[1] Catalytic reactivity and ether bond lengths in aryloxytetrazoles and aryloxypseudosaccharins

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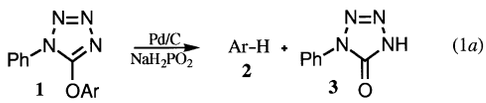
X-Ray structure determinations on a variety of aryloxytetrazoles 1 and aryloxypseudosaccharins 4 have shown that the central C–O–C ether linkage is remarkable in having one very long C–O bond and one very short one. The central C–O–C bond angle is close to 120°. The implications of these effects on the reactivity of compounds 1 and 4 towards catalytic hydrogenolysis or cross-coupling are explored.

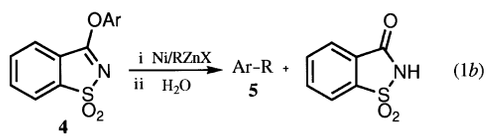
Introduction

The use of X-ray structure determination to aid understanding of reaction mechanism by considering bond lengths and angles in relation to chemical reactivity has been used in both theoretical and experimental contexts.[2] Bond lengths and angles for functional groups may be compared with 'standard' states of the same groups. For example, a simple aliphatic single C–C bond length of *ca.* 1.53 Å is considered normal with bond order, $n = 1$, as is a C=C double bond of 1.34 Å with bond order $n = 2$;[3] any formal single C–C bond length falling between these values suggests a degree of double bond character, with a bond order lying between 1 and 2.[4a,b] Changes in bond lengths and angles for a series of compounds have been used successfully to explain chemical reactivity by relating ground-state structure, as observed by X-ray analysis, to supposed transition state structures.[2–5]

The C–O bond of a phenol can be regarded as having partial double bond character and is generally much more resistant to the sorts of chemical nucleophilic and electrophilic reactions that occur with aliphatic alcohols.[6] A notionally single C–O bond in a phenol of *ca.* 1.37 Å is considerably shorter than a C–O single bond in a simple aliphatic ether (1.43 Å) but is longer than a formal C=O double bond (1.23 Å). From these lengths, a bond order for the C–O bond of a phenol can be calculated to be approximately 1.3, *viz.*, between 1 for a single bond and 2 for a formal double bond.[4a] For similar reasons, a phenolic C–O bond dissociation energy is *ca.* 455 kJ mol^{-1} compared with 347 kJ mol^{-1} for the C–O bond strength in an aliphatic alcohol.[3] As a partial double bond having a greater bond dissociation energy than a formal C–O single bond, it might be expected that nucleophilic displacement of oxygen in a phenol as OH (or as OR in a phenolic ether) should be more difficult than the same sort of reaction involving an aliphatic alcohol or ether. By converting a phenol into a tetrazolyl or pseudosaccharyl ether, it has been found that, as part of such an ether linkage, the original C–O bond undergoes very easy catalytic *ipso* substitution. Aryloxytetrazoles **1**[7] or aryloxypseudosaccharins **4**[8] are rapidly hydrogenolysed to arenes **2** in the presence of palladium and a hydrogen donor [exemplified in eqn. (1*a*) for tetrazoles]. Aryloxytetrazoles **1**[9] and aryloxypseudosaccharins[10] **4** can also be cross-coupled with organometallic reagents in the presence of nickel to give substituted arenes **5** [exemplified in eqn. (1*b*) for pseudosaccharins]. It could be argued that the electron-withdrawing nature of the tetrazolyl or pseudosaccharyl groups weakens the original partially double-bonded C–O of the phenol, making it more



(1*a*)



(1*b*)

like an aliphatic single C–O bond and therefore susceptible to nucleophilic displacement. However, whilst this is undoubtedly true, it is known that hydrogenolysis [eqn. (1*a*)] does not proceed with tetrazolyl ethers of aliphatic alcohols, *viz.*, an aliphatic C–O tetrazolyl ether bond is inert to the same reaction conditions that lead to its easy *ipso* replacement by C–H in phenolic ethers.[11] Other electron-withdrawing groups are known to encourage this *ipso* replacement[12] but there are yet other powerfully electronegative ones that do not.[13] Because of the exceptional effect that the tetrazolyl and pseudosaccharyl groups have on the reactivity of phenolic C–O bonds, it was decided to examine X-ray structures of a series of ethers **1** to explore any C–O bond length changes that might occur on converting the original phenol to its tetrazolyl ether. Initial reports of the X-ray analysis of two aryloxypseudosaccharins have appeared.[14,15]

Results and discussion

Bond lengths ad angles in ethers 1a–f, 4a,b

X-Ray structures for six aryloxytetrazoles **1a**–**f** were determined. The substituent groups in the aryl ring of compounds **1a**–**f** were varied in position and in electron-donating or -withdrawing effects so as to examine any electronic effect there might be in addition to the effect of the tetrazolyl group. Apart from the central C–O–C ether linkage, the bond lengths and angles in the aryl rings and the tetrazolyl or pseudosaccharyl systems in ethers **1a**–**f** were unexceptional and are not discussed further; these lengths and angles are available.[16] Selected bond lengths and angles are listed in the appended X-ray data. The bond lengths and angles for the central C–O–C ether linkage are summarized in Table 1, which for convenience, also contains the corresponding information for the two aryl pseudosaccharyl ethers **4a**,**b** which were reported earlier.

Examination of Table 1 shows that the two C–O bonds in the C–O–C ether linkage in each of the tetrazolyl **1** and pseudosaccharyl ethers **4** are far from equal. After conversion into a tetrazolyl or pseudosaccharyl ether, the original phenolic C–O

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Table 1 Selected bond lengths, bond angles and torsion angles for C–O–C ether bonds[a] in aryloxyphenyltetrazoles **1** and aryloxypseudosaccharins **4**

Ether **1** or **4**	Aryl group in **1** or **4**	C^1–O Bond length/Å	C^2–O Bond length/Å	C^1–O–C^2 Bond angle/°	Torsional angle,[b] α/°	Dihedral angle,[c] β/°
1a	2-Naphthyl	1.437	1.322	119.3	−8.0	134.5
1b	2,6-Dimethylphenyl	1.428	1.333	116.5	21.0	70.2
1c	3,5-Dimethylphenyl	1.423	1.331	117.8	−8.2	17.0
1d	4-Methylphenyl	1.415	1.329	122.2	−2.0	149.5
1e	4-Cyanophenyl	1.414	1.338	117.4	−1.6	124.0, 75.5
1f	4-Methoxyphenyl	1.434	1.335	116.4	−18.0	24.8, 41.0
4a	4-Methoxyphenyl	1.424	1.331	116.8	−1.1	94.7
4b	1-Naphthyl	1.422	1.316	117.6	−3.2	88.4, 85.4

[a] C^1 is the carbon atom of the aryl ring that is joined to the ether oxygen and C_2 is the carbon of the phenyltetrazolyl or pseudosaccharyl ring also joined to the ether oxygen (see structures **1a–f**). [b] The torsional angle α is defined in Fig. 1. [c] The dihedral angle β is that between the planes of the aryl and tetrazolyl rings (Fig. 1). Where two values are reported, these refer one to each of two molecules in a unit cell.

bond length increases from about 1.37 to 1.42–1.44 Å so that it is similar to or even longer than a simple aliphatic ether C–O bond (1.43 Å).[3] In contrast, the ether C–O bond connected to the tetrazolyl ring is much shorter at 1.31–1.34 Å than for many typical alkyl or aryl phenolic ethers, which are normally close to 1.37 Å (alkyl aryl ether) or 1.38 Å (diaryl ether).[3] Table 1 also reveals that the central C–O–C bond angles in the heterocyclic ethers are considerably larger (mean, 118.0 ± 1.9°) than would be expected for sp^3 hybridization and correspond more with sp^2 hybridization at oxygen.

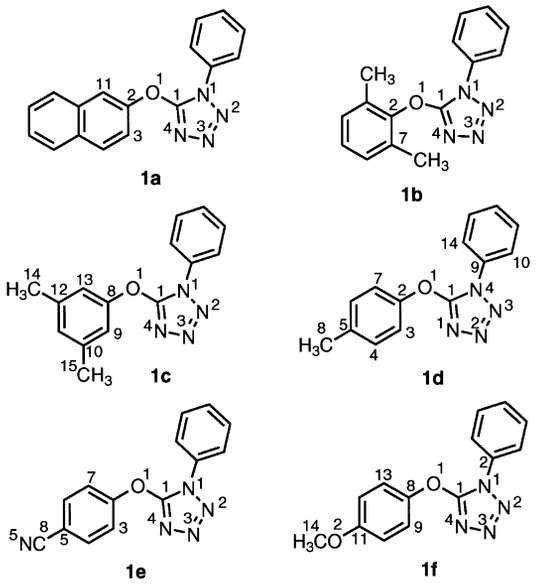
Fractional ionic character and electronegativity

It has been shown[4b] that the percentage ionic character of a bond can be related to the electronegativities of the two atoms or groups that make up its ends. Thus, a simple C–O bond having an electronegativity difference between carbon and oxygen of 1.0 can be considered to be about 22% ionic.[4c] When the oxygen is part of an aryl tetrazolyl ether, the above considerations of bond lengths suggest that the 'group' electronegativity of the oxygen and the tetrazolyl ring system combined must have increased over that for a simple ether because formation of this heterocyclic ether is accompanied by a significant lengthening of the original phenolic C–O bond so that it becomes as long as or longer than an aliphatic single C–O bond. The original phenolic C–O bond (n = 1.3–1.4) is converted into something more like the C–O bond in an aliphatic alcohol (n = 0.96–1.0). The electron density in the original phenol bond, which gave it its partial double bond character, is drawn off into the tetrazolyl system. At the same time, the ether oxygen becomes strongly bonded to the tetrazolyl ring system, with this C–O bond having a bond order n of *ca.* 1.5.

If it be supposed that the C–O bond of the original phenol were to be stretched to become completely ionic, *viz.*, it just separates into C^+ and O^- species, then this stretched length can be estimated in two ways. First, from ionic radii for C^{4+} (0.15 Å) and O^{2-} (1.40 Å),[4d] a fully ionic C–O 'bond' (point of breaking or forming) will be 1.55 Å. Secondly, it is shown below that the overall total length of the two C–O bonds in almost 70 diaryl and aryl tetrazolyl ethers is almost constant at 2.777 Å, even though the difference in electronegativities of any of the aromatic groups attached to the ether oxygen increases or decreases. Thus, as an extreme case when one C–O bond is breaking ionically, the C–O bond attached to the tetrazolyl ether becomes a C=O double bond (1.23 Å) in the tetrazolone **3** [eqn. (1*b*)]. Thus, for a constant C–O–C length of 2.777 Å, this leaves 2.78–1.23 = 1.55 Å as the length of the other 'ionic' C–O bond just as cleavage occurs. This value is the same as that deduced simply from a consideration of ionic radii. Therefore, at the point of breaking (100% ionicity), the original phenolic C–O bond will be *ca.* 1.55 Å long. From this value and the 22% ionicity calculated for a 'simple' C–O covalent bond,[4c] it can be argued that the change in length from a partially double C–O bond in a phenol (1.37 Å) to a single bond in its tetrazolyl ether (1.43 Å) will lead to an increase in ionicity of ([1.43 − 1.37]/[1.55 − 1.37]) × (100 − 22)%, *i.e.* 25%, giving an overall ionicity of 47% for the stretched aryl–oxygen bond in a tetrazolyl or pseudosaccharyl ether. This allows an estimation to be made of the effective electronegativity difference between a tetrazolyloxy group and the aryl carbon. From earlier work,[4c] this difference in ionic bond character of 47% is ascribed to an electronegativity difference of 1.5, giving a 'group' electronegativity for the tetrazolyloxy system of 4.0 (with respect to carbon = 2.5). This value makes the electronic effect of a tetrazolyloxy group about the same as that of a fluorine atom (electronegativity = 4.0). The effective electronegativity of the tetrazolyloxy system deduced from X-ray analysis refers to the solid state, in which the close packing of molecules in a crystal might be expected to exert constraining forces that could cause the central oxygen of the aryl tetrazolyl ethers to be fully conjugated with the tetrazole ring but not at all to an orthogonal aryl ring. It seems unlikely that this situation would be exactly the same for all of the six ethers **1** (and for the two pseudosaccharyl ethers **4**). Nevertheless, it was decided to compare this 'solid state electronegativity' with that existing in the liquid phase, in which constraints to rotation of the aryl and tetrazolyl rings are minimized. NMR spectra for the ethers **1**, **4** provided a value of nearly 4 for the electronegativity of the tetrazolyloxy system in solution (see below). Therefore, the liquid and solid state electronegativities are very similar and it is clear that the effective group electronegativity of the tetrazolyloxy system in the solid state persists into the liquid (dilute solution) state. The effective group electronegativity of the pseudosaccharyl system was slightly less.

Torsional and dihedral angles in ethers 1a–f

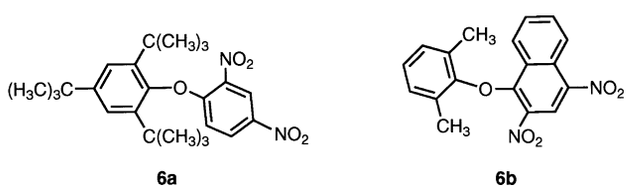
Reference to Table 1 shows that the dihedral angle between the planes of the aryl and tetrazolyl (or pseudosaccharyl) rings in ethers **1a–f** vary considerably from crystal to crystal. Even where there are two molecules in the unit cell, the two dihedral angles are different when there is no internal symmetry in the cell. Since, for two molecules in the unit cell, the corresponding C–O bond lengths are identical within the errors of measurement, it must be concluded that steric constraints within the crystal itself are responsible for the various observed dihedral angles. However, the torsional angle (α) between the plane of the tetrazole ring and O–C_b bond linking it to the aryl ring system is generally close to 0° (Fig. 1). A small angle for α (or one near 180°) would be expected for strong conjugation between an sp^2 hybridized oxygen of the ether and the tetrazolyl ring, as revealed by the very short C_a–O bonds. Because the aryl ring is no longer conjugated with the ether oxygen (long C_b–O bond) then, unlike the tetrazolyl ring, there is no electronic reason for the aryl ring to orientate itself in a specific way with the oxygen. This explains the variety of dihedral angles (β) observed between the planes of the aryl and tetrazolyl rings. The aryl ring must position itself according to crystal con-



straints but not conjugative ones to oxygen. These same solid state restraints appear to have little effect on the electronic need for the ether oxygen and the tetrazolyl ring (C_a–O bond) to align themselves so that the torsional angle α remains near 0 or 180°, as required for pure sp^2 hybridization at oxygen. The C_a–O–C_b angle is not exactly 120° and must possess some sp^3 character. For this reason, angle α would not be expected to be exactly 0 or 180°, even in the absence of effects from solid state steric restraints.

Bond lengths in other diaryl ethers

To discover how exceptional the C–O ether bond lengths in aryloxytetrazoles and pseudosaccharins might be, a search of the Cambridge Crystallographic Database[17] was made for diaryl ethers, in which the aryl rings contained varied electron-withdrawing and electron-donating substituents. Sixty-four such ethers were extracted at random. A histogram of their ether C–O bond lengths is shown in Fig. 2. Almost all of the ethers were found to have one C–O ether bond shorter than the other. Statistically, the shorter C–O bonds are 1.378 ± 0.012 Å whilst the longer ones are 1.399 ± 0.020 Å, giving a mean value for both types of 1.388 Å. A value of about 1.37 Å would be considered normal for aromatic C–O ether bonds.[3] Amongst the 64 entries, there are a few compounds that have particularly long and short C–O bond pairs, especially for compounds **6a**,**b**.



However, these C–O bonds are neither as long nor as short as the corresponding C–O bonds in the tetrazolyl and pseudosaccharyl ethers **1** and **4**. For comparison, the short and long C–O bonds for aryl tetrazolyl and aryl pseudosaccharyl ethers are shown on the same histogram (Fig. 2). These C–O bond lengths lie well outside the normal range for diaryl ethers. Fig. 3 illustrates the point. For Fig. 3, pairs of C–O bond lengths from the C–O–C linkages in the 64 ethers are plotted along two axes. Most pairs of bonds fall within a relatively small region, *viz.*, there is not much variation in C–O bond length from one side of the C–O–C ether linkages to the other. In fact, the sum of the C–O bond lengths for each ether (C–O–C bond length) is 2.777 ± 0.025 Å. Significantly, there are exceptional bond lengths for those diaryl ethers, in which one aryl ring is strongly

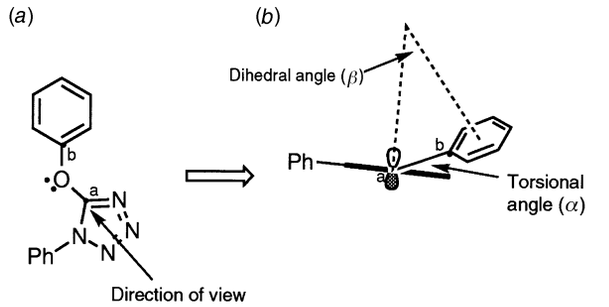


Fig. 1 An aryloxytetrazole system **1** showing, (*a*) a general view and, (*b*) the torsional angle (α) defined by the plane of the tetrazole ring and the C_b–O ether bond furthest from the tetrazole and the dihedral angle (β) between the normals to the planes of the tetrazolyl and aryl rings

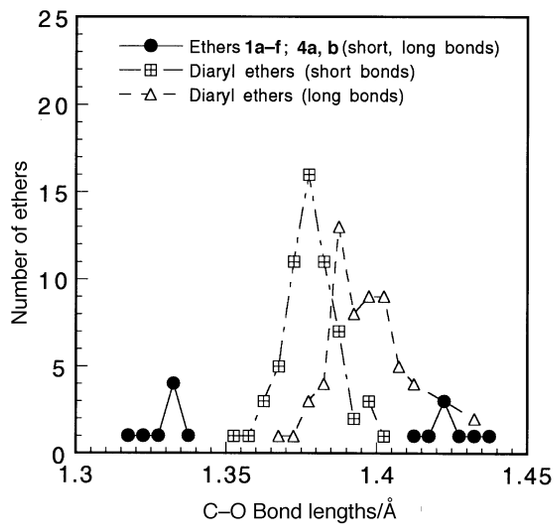


Fig. 2 A histogram showing the frequency of occurrence of C–O bonds of various lengths. The ethers **1a–f**, **4a**,**b** are detailed in Table 1. The 62 diaryl ethers taken randomly from the Cambridge Crystallographic Data Base are detailed in the references. For the ethers **1a–f**, **4a**,**b**, there are clearly two sets of widely different C–O bond lengths, one very short and the other very long when compared with the median for the diaryl ethers. The 62 ethers also show a split (but much smaller) into short and long bonds at about 1.375, 1.395 Å, respectively.

electron-attracting and the other ring strongly electron-donating. For example, in the diaryl ether **6a**, having three *tert*-butyl substituents in one ring and two nitro substituents in the other, one C–O bond on the side of the more electronegative aryl ring is 1.350 Å and the other on the electron-donating (less electronegative) side is 1.430 Å.[18] For the ether **6b** having two nitro groups in a naphthyl ring and two methyl groups in a phenyl ring, the corresponding bond lengths are 1.342 and 1.414 Å.[19] Thus, as the electronegativity difference between the aryl groups in the diarl ethers increases, the C–O bond on the more electronegative side of the C–O–C ether linkage shortens whilst the other C–O bond on the less electronegative side lengthens; this electronic 'push–pull' effect gives one longer C–O ether bond and a corresponding shorter one, with the sum of the C–O bond lengths in each ether remaining almost constant. The tetrazolyl and pseudosaccharyl ethers can be seen to be an extension of this trend, the heterocyclic groups providing an extreme of electronegativity, similar to that for fluorine. The C–O bond lengths for the ethers **1a–f** and **4a**,**b** have been added to Fig. 3. The two types of C–O ether bonds in compounds **1a–f**, **4a**,**b** are respectively longer and shorter than any similar pair from the 64 diaryl ethers taken from the Cambridge Crystallographic Database.

In the ethers **1e**,**f** there is respectively a *para*-cyano and a *para*-methoxy substituent in the aryl ring, the first being

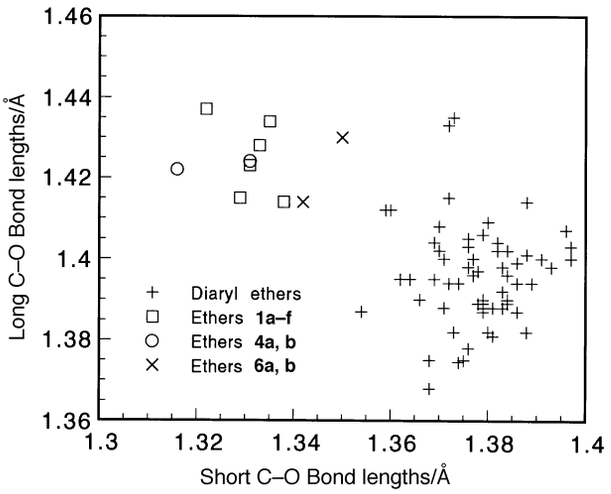


Fig. 3 A scatter diagram showing C–O bond pairs from each ether. For each ether, the shorter bond is plotted on the *x*-axis and the longer bond on the *y*-axis. The points corresponding to each ether clearly fall into two major categories. One set (ethers **1a–f**, **4a**,**b**; Table 1) possess one very short and one very long bond. For most of the 62 ethers from the data base, both bonds are significantly shorter, although a difference in length persists. For the two ethers **6a**,**b** which have very electronegative substituents, their pairs of C–O bonds fall between those of the tetrazolyl and pseudosaccharyl ethers and those of the diaryl ethers from the data base.

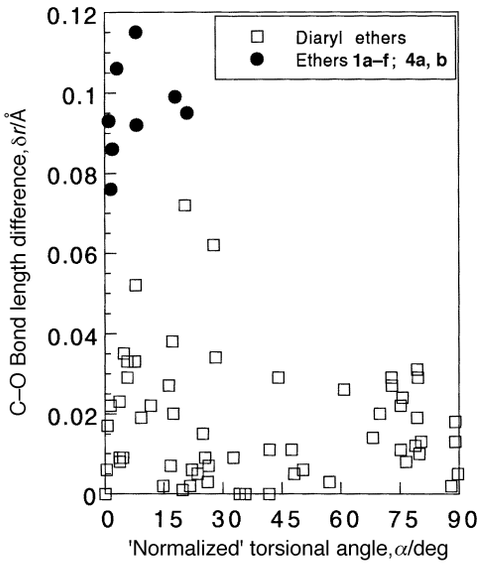


Fig. 4 A plot of the C–O bond length difference (δ*r*) for each ether and the torsion angle (*α*) defined in Fig. 1. The torsion angle has been normalized to a 0–90° scale, as described in the text. Five diaryl ethers (ref. 17: COWTEN, DNPBUB MNPPRB, NPHOPN, TITHYN10), which have particularly large steric constraints about the ether bond, have been omitted for the sake of clarity.

strongly electron-attracting and the other strongly electron-donating. In these cases, the short C–O bonds are both very similar to those in the ethers **1b–d**, in which there are only mildly electron-donating substituents. The long C–O bond in the cyano compound **1e** is about the same as that in the electron-donating methyl compound **1d**. The effects are not large and do not appear to be simply related to the electronegativity of the aryl ring. This suggests that the effect of the tetrazolyl ring overrides any effect of single substituents in the aryl group.

Ether bonds and angles in aryl ethers

In the 64 diaryl ethers in the database, the mean C–O–C bond angle is 118.5 ± 2.2°. This small range also covers the same angles in the ethers **1a–f** and **4a**,**b** (Table 1; mean angle = 117.9 ± 2.02°). Electronegativity effects do not appear to have any simple relationship to these angles, which are about the same as for the C–O–C linkage in methoxyphenyl compounds.[20] The very short C–O bond attached to the tetrazolyl group in the ethers **1a–f** and **4a**,**b** implies strong conjugation from a p-type lone pair with the π-electrons in the tetrazolyl ring system. The long C–O bond is consistent with little or no conjugation from an sp^2 lone pair and the aryl ring. This hybridization is important in considerations of the adsorption of aryloxytetrazoles onto the surface of a catalyst. Further discussion of this aspect will be reported elsewhere in conjunction with measurement of adsorption isotherms.

Torsional angles in other diaryl ethers

The torsional angle (*α*; Fig. 1) and the dihedral angle (*β*) between the planes of the two aryl rings in each of the 64 ethers from the crystallographic database were examined. In the tetrazolyl ethers, the angle *α* is approximately 0–15° and the difference in the two C–O bond lengths is *ca.* 0.1 Å. For the 64 ethers, the same angle *α* was plotted against δ*r*, the difference in the two C–O bond lengths in each ether. Because the angle *α* is complementary with an angle of 180 − *α* for these planar ring compounds and because the sense of rotation is not important in this context, the modulus of each angle (*α*) between 0 and −180° was used; to bring these angles into the same quadrant, all angles, for which $90 \leqslant \alpha \leqslant 180°$ were subtracted from 180° to give 'normalized' torsional angles. The resulting scatter is shown in Fig. 4. This scatter of points shows that, for bond length differences of less than *ca.* 0.03–0.04 Å, the torsional angle appears to be almost randomly distributed from 0 to 90°. In other words, when the bonding from the ether oxygen to each of the aryl rings is similar, the torsion angle *α* appears to have no preferred orientation and steric or crystal constraints must override any conjugative electronic effects that would require the torsional angle to be zero. In contrast, as the difference in electronegativity of the two aryl rings in each ether increases, the conjugative effect begins to override steric and crystal constraints. Four ethers in particular have δ*r* values greater than about 0.04 Å and have torsion angles between *ca.* 10 and 30°. For the tetrazolyl and pseudosaccharyl ethers, the values of δ*r* lie between 0.085 and 0.105 Å and the torsional angle *α* moves much closer to 0°.

In contrast to this behaviour of the angle *α*, the dihedral angle *β* for the diaryl, the aryl tetrazolyl and the aryl pseudosaccharyl ethers has no preferred orientation between 0 and 90°. This is consistent with aryl groups in the tetrazolyl and pseudosaccharyl ethers having no π-conjugation to the ether oxygen and so there is no electronic opposition to steric or crystal constraints; the angle *β* is a resultant only of these constraints. Thus, increasingly greater conjugation from the ether oxygen to one of the aryl (or heterocyclic) rings, with concomitant decreasing conjugation to the other, provides a reason for an increasingly small torsion angle *α* but has no effect on the dihedral angle *β*.

Bond order in C–O bonds for ethers 1a–f,4a,b and their reactivity towards hydrogen transfer

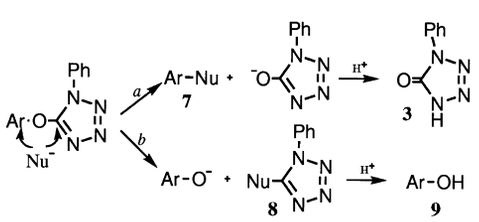
Although there are several approaches to the estimation of bond order, for the tetrazolyl **1** and pseudosaccharyl ethers **4**, a bond order can be estimated from their long and short C–O bonds by using a simple formula.[4a,b] The long single C–O bonds are actually slightly longer than the 'normal' limit given by the formula, suggesting that they are stretched and significantly ionic. At 1.32–1.33 Å, the short C–O bonds have almost 50% of double bond character (bond order = 1.5), as compared with an estimated 30% for a simple phenolic C–O bond (bond order = 1.3) and 100% for a full C=O double bond in a ketone or aldehyde. Thus, the short C–O linkage tends substantially towards being a carbon–oxygen double bond. The variation in bond strength for C–O bonds with bond order (*n*) varying from 1 to 3 has been discussed and has been shown to follow a

relation, $D_{(n)} = D_{(1)}n^{p}$, in which $D_{(n)}$ is the bond strength for bond order n, $D_{(1)}$ is the bond strength for a typical C–O single bond and p is a scaling factor which in this case is approximately equal to 1.[21] Thus, for a phenolic C–O bond with estimated bond order of $n = 1.3$, its bond strength can be estimated to be 462 kJ mol^{-1}. This is comparable to the measured C–O bond dissociation energy for phenol[3a,b] of 460 kJ mol^{-1}. For a phenol that becomes part of a tetrazolyl ether as in compounds **1a**–**f**, **4a**,**b**, its bond length changes from 1.37 Å to *ca.* 1.44 Å and, therefore, its bond order is estimated to change from $n = 1.3$ to 0.96. For this bond order change, the strength of the original C–O phenolic bond on preparation of its tetrazolyl ether must decrease from 462 to 341 kJ mol^{-1}, *i.e.* the phenolic bond dissociation energy falls slightly below even that of a C–O single bond in an aliphatic alcohol or ether. For the shorter C–O bond in aryl tetrazolyl ethers **1a**–**f**, the bond order is $n = 1.44$, implying a bond strength from the oxygen to the tetrazolyl ring of 512 kJ mol^{-1}, some 50 kJ mol^{-1} greater than that for a simple phenol. Therefore, on preparation of a tetrazolyl (or pseudosaccharyl) ether of a phenol, two new C–O bonds are created, one attached to the original phenolic ring and some 121 kJ mol^{-1} weaker than the original phenol and the other attached to the heterocyclic system which is *ca.* 50 kJ mol^{-1} stronger. There is a total change of *ca.* 170 kJ mol^{-1} in favour of a C–O–C cleavage, in which the aryl group separates from the oxygen atom to which it was originally bound as a phenol [eqns. (1*a*) and (1*b*)]. These considerations show that only one direction of bond breaking is favourable towards catalytic *ipso* replacement, in which a C–O bond must be cleaved by oxidative addition before or concurrently with *ipso* replacement.‡ However, there is no information on activation energy and therefore the rate of the reaction.

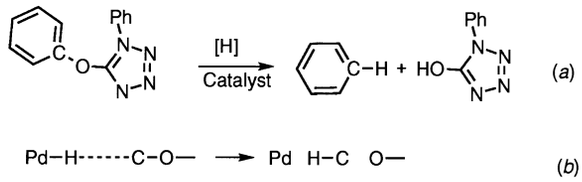
Estimation of relative activation energies

The activation energy for transfer of hydrogen from a catalyst surface to the carbon of a phenolic C–O bond with concomitant breaking of the C–O bond can be investigated using a bond order approach developed for general hydrogen transfer.[21] Thus, in Scheme 2, hydrogen is considered to be transferred from palladium to carbon of a phenolic ether. Part *a* of Scheme 2 illustrates the transfer of hydrogen in a formal chemical sense; part *b* depicts the same process in a more simplified form, in which hydrogen is shown bonding to the phenolic ether carbon whilst, at the same time, the C–O linkage is breaking. For these simplified purposes, the energy of the breaking Pd–H bond is not considered specifically because it is common to all reactions; further, on formation of the tetrazolone structure in (Scheme 2, part *a*), there is a gain of *ca.* 209 kJ mol^{-1}, which offsets much of the energy expenditure required for Pd–H bond cleavage. The combined enthalpies for Pd–H bond cleavage and formation of tetrazolone are thermochemically exothermic. Employing an approach developed earlier and simplifications developed later,[21] the potential energy change (activation energy) for H transfer from palladium to carbon, with concomitant C–O bond cleavage (Scheme 2, part *b*) was calculated for an initial C–O bond strength of 334 kJ mol^{-1}. The estimated activation enthalpy is *ca.* 15–20 kJ mol^{-1}, lying between those of typical diffusion controlled and solvolytic reactions. The estimated activation energy is not expected to be accurate because of the assumptions in the model chosen but its order is expected to be significant. The small activation energy is expected for a strongly exothermic process such as the C–O bond cleavage described here. These results indicate that the easy catalytic hydrogenolysis of aryl tetrazolyl ethers as against the total lack of hydrogenolysis for simpler aryl ethers can be traced back to the strong electronegativity of the tetrazolyl group, which changes the initial phenolic C–O bond strength from being moderately high (*ca.* 460 kJ mol^{-1}) to low (*ca.* 350 kJ mol^{-1}), at the same time making H-transfer from the catalyst to the phenolic C–O bond easy because of the low activation energy.

Because a tetrazolyl or pseudosaccharyl group causes the C–O bond of a phenol to change from a partial double bond to a single bond in the ether, characteristic of a simple aliphatic alkoxy compound, it might be expected that hydrogenolysis of aliphatic ethers would be as easy as is the cleavage of the aryl tetrazolyl ethers. However, as already mentioned,[14] heterogeneous hydrogenolysis of benzyl and alkyl tetrazolyl ethers is not observed. As described above, the hydrogenolysis of aliphatic ethers is not favoured thermochemically. Also, it may be concluded that p-orbitals in the aryl ring receiving the transferred hydrogen are also a necessary requirement. Indeed, simple molecular models suggest that S_N2 type hydrogen attack at a saturated aliphatic carbon attached to an ether linkage is not feasible on the surface of a heterogeneous catalyst since the tetrazolyl ring would be expected to be strongly adsorbed rather than an alkyl group. Experiments to be reported separately§ reveal physical evidence for a need for specific alignment of the tetrazolyl and pseudosaccharyl ethers on the catalyst surface as a second major requirement for cleavage of the ether to occur.



Scheme 1



Scheme 2

‡ It might be noted in passing that non-catalysed nucleophilic displacement at the C–O–C ether linkage does not necessarily have the same energy requirements. Nucleophilic attack may proceed along two pathways (Scheme 1; paths *a*,*b*; Nu^- = nucleophile) to give either a substituted arene (**7**; Scheme 1; path *a*) and phenyltetrazolone **3** or a substituted phenyltetrazole (**8**; Scheme 1; path *b*) and the original phenol **9**. The carbon of the tetrazole, to which the ether oxygen is attached, carries a much greater positive charge than does the carbon of the aryl ring to which the ether oxygen is attached (Scheme 1); this makes the tetrazolyl carbon more susceptible to a nucleophilic attack, which transforms the partially double-bonded C–O back into a single bond, thereby weakening it and requiring energy. At the same time, energy is gained from the newly formed Nu–C linkage and from the reversion of the aryl C–O bond from being single in the tetrazole to partially double in the free phenol. On balance, it becomes much more difficult to predict the direction (path *a* or *b*) of this sort of nucleophilic displacement at the ether linkage. Where there is initial oxidative addition to a metal, a catalytic process that involves cleavage of the weakest C–O ether bond as in the catalytic reactions described here, the energetic effect of the nucleophile becomes of secondary importance and only path *a* is followed.

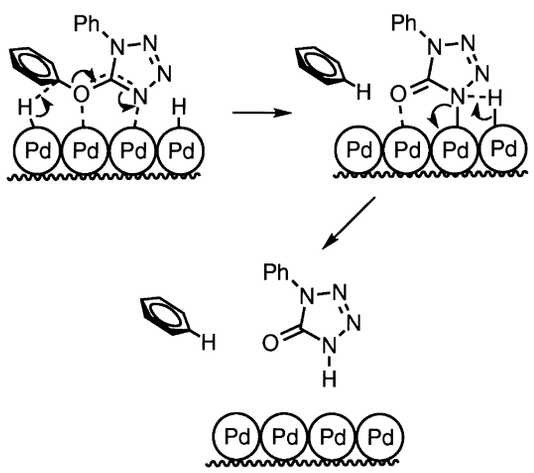
§ Adsorption isotherms for a range of aryloxytetrazoles on a commercial Pd catalyst have been determined in the liquid phase. From these results, an area for each molecule adsorbing onto the metal can be extracted. This area is much less than would be expected for a molecular system, in which the aryloxytetrazole adsorbs fully planar with the surface. From these results and earlier kinetic work (ref. 7), it appears that adsorption takes place with the plane of the tetrazole ring at right angles to the metal surface. Because the plane of the aryl ring attached as an ether to the tetrazole is itself at right angles to the tetrazole, it must lie almost parallel with the metal surface. Detailed results will be published elsewhere.

Table 2 Crystal data for tetrazoles **1a–f**[a]

Compound	**1a**	**1b**	**1c**	**1d**	**1e**	**1f**
Formula	$C_{17}H_{12}N_4O$	$C_{15}H_{14}N_4O$	$C_{15}H_{14}N_4O$	$C_{14}H_{12}N_4O$	$C_{14}H_9N_5O$	$C_{14}H_{12}N_4O_2$
M_r	288.31	266.30	266.30	252.27	263.26	268.27
System	Orthorhombic	Triclinic	Orthorhombic	Orthorhombic	Triclinic	Orthorhombic
Space group	*Pca* 2_1	$P\bar{1}$	$P2_12_12_1$	$Pca2_1$	$P\bar{1}$	$Pca2_1$
a/Å	12.608(8)	8.924(4)	9.526(7)	11.944(7)	12.220(1)	18.018(8)
b/Å	14.956(7)	10.574(3)	17.520(7)	15.093(8)	14.663(2)	21.397(10)
c/Å	7.294(6)	8.261(4)	8.08(2)	6.94(1)	7.429(4)	6.63(1)
α/°	90	105.24(3)	90	90	96.90(3)	90
β/°	90	117.08(3)	90	90	97.76(2)	90
γ/°	90	78.51(3)	90	90	68.31(1)	90
V/Å^3	1376(1)	666.9(5)	1349(3)	1252(2)	1220.0(7)	2555(5)
Z	4	2	4	4	4	8
D_c/mg m^{-3}	1.392	1.326	1.311	1.339	1.431	1.395
Parameters[b]	18	25	8	19	22	20
θ/°	3.49–6.47	19.69–23.76	11.69–16.01	3.64–6.39	18.3–20.7	3.53–5.35
μ/cm^{-1}	0.851	0.818	0.808	0.833	0.910	0.912
Form	Plate	Prism	Prism	Prism	Prism	Prism
Size/mm^3	0.25 × 0.25 × 0.05	0.50 × 0.40 × 0.20	0.40 × 0.40 × 0.15	0.4 × 0.2 × 0.1	0.35 × 0.20 × 0.20	0.40 × 0.35 × 0.20
Colour	Colourless	Colourless	Colourless	Colourless	Colourless	Colourless

[a] For all determinations, Mo-Kα radiation at $\lambda = 0.7107$ Å was used. The crystal density was not determined by actual measurement. The temperature of all measurements was 153 K. [b] Parameters = the number of reflections used to determine the cell parameters.

The *ipso* replacement of C–O in reactions (1*a*,*b*) requires both a weakening of the phenolic C–O bond strength through tetrazolyl or pseudosaccharyl ether formation and a correct orientation of the ether on the catalyst surface; the tetrazolyl or pseudosaccharyl rings provide the required alignment on the surface. Scheme 3 illustrates the adsorption of phenyloxy-1-



Scheme 3

phenyl-1*H*-tetrazole onto palladium surface atoms, with the plane of the tetrazolyl ring vertically orientated and the plane of the phenyl ring that is to undergo *ipso* replacement lying parallel to the surface. Transfer of hydrgen to this phenyl with concomitant C–O bond cleavage is followed by desorption of phenyltetrazolone, after a second transfer of hydrogen. Such a scheme is in keeping with adsorption isotherm measurements§ and with the 'burst' kinetics reported earlier.[22]

Nuclear magnetic resonance effects

The above discussion of bonding about the C–O–C ether linkage in compounds **1** and **4** refers to the solid (crystalline) state from which the X-ray structure determinations were made. To extrapolate any deductions from the solid state to the solution phase for discussion of reactivity requires that there should be some evidence that the behaviour of ethers **1** and **4** in solution is similar to that in the solid state. ^{1}H and ^{13}C NMR spectroscopy have been used to effect such a comparison of the two states. As shown above from the bond length data, it is possible to estimate a group electronegativity for the tetrazolyloxy system, which was found to be very close to that of fluorine.[4b] It has been reported that, for a series of compounds, CH_3CH_2R, the relative shifts of the methyl and methylene protons can be linearly related to the electronegativity of the substituent, R.[23] In experiments to be reported elsewhere, 1-ethoxy-5-phenyl-1*H*-tetrazole **1g** was found to have a group electronegativity of *ca.* 3.81, somewhat greater than that for fluorine on this scale (3.76). Similarly, 3-ethoxy-1,2-benzisothiazole 1,1-dioxide **4c** was estimated to have an electronegativity of 3.76, about the same as that of fluorine. Thus, from both bond length measurements in the solid state and ^{1}H NMR information in the liquid state, the effective or group electronegativity of both the tetrazolyloxy and pseudosaccharyloxy systems is about the same as that of fluorine. The NMR results indicate that, in solution, the tetrazolyl or pseudosaccharyl system have very similar electronic effects to those observed in the solid state.

Chemical reactivity

From the point of view of reactivity, it appears that, in the tetrazolyl and pseudosaccharyl ethers, the following major changes occur. (*a*) The original phenolic C–O bond loses its partial double bond character and becomes a stretched single bond. (*b*) The original phenolic oxygen atom is no longer conjugated with the aryl ring but is π-conjugated strongly with the tetrazolyl group; this tetrazolyl C–O bond now possesses considerable double bond character. (*c*) The ether C–O–C bond angle is close to 120°, indicating sp^2 hybridization at the oxygen atom. For such hybridization, the residual p-electron pair must conjugate with the π-electrons of the tetrazolyl ring. The remaining lone pair must reside in a strongly directional sp^2 hydrid orbital orthogonal to the p-pair.

For catalytic reactions on metals, oxidative addition is frequently a first step.[11] These considerations suggest that oxidative addition with H-transfer might be expected to proceed along one or other of the two routes shown in Scheme 1, to give either an arene **7** plus the tetrazolone **3** (pathway *a*) or to give back the original phenol **9** plus a tetrazole **8** (pathway *b*). However, the stretched 'phenolic' single bond and the 50% partial double bond character of the tetrazolyl ethers suggest that the ether structures have already developed to being close to the early transition state expected for formation of an aryl derivative (pathway *a*, Scheme 1). This finding is consistent with postulates on the relation between exo- and endo-thermicity of a reaction and its activation energy.[24,25] Earlier experiments[22] have shown that substituents in the aryl ring have no linear free energy effect (a lack of any Hammett correlation) on the rate of reaction. This observation is in keeping with the lack of any observed consistent effect on the C–O bond lengths in the tetra-

Table 3 Details of data collection and refinement for tetrazoles **1a–f**

Compound	**1a**	**1b**	**1c**	**1d**	**1e**	**1f**
Data collection[a]						
Measured reflections	1467	2569	1435	1342	4503	2671
Independent reflections	1428	2512	1399	1306	4286	2608
Observed reflections $I > 3\sigma(I)$	763	2022	1112	831	3096	1867
θ_{max}/°	24.89	24.95	24.96	24.89	24.96	24.92
h	0 ⟶ 15	0 ⟶ 11	0 ⟶ 11	0 ⟶ 14	0 ⟶ 15	0 ⟶ 21
k	0 ⟶ 18	−13 ⟶ 13	0 ⟶ 21	0 ⟶ 18	−17 ⟶ 17	0 ⟶ 25
l	0 ⟶ 9	−10 ⟶ 10	0 ⟶ 10	0 ⟶ 8	−9 ⟶ 9	0 ⟶ 8
Intensity decay (%)	0.00	−0.30	0.07	−1.10	−0.10	0.73
Data refinement[b]						
R	0.0531	0.0401	0.0485	0.0585	0.0383	0.0570
wR	0.0531	0.0529	0.0557	0.0619	0.0457	0.0648
S	1.537	2.300	2.070	2.050	1.75	2.344
Reflections	757	1884	1112	829	3096	1867
Parameters	118	181	146	135	361	230
$(\Delta/\sigma)_{max}$	0.0218	0.0101	0.0154	0.0101	0.0079	0.0520
$\Delta\rho_{max}$/e Å^{-3}	0.24	0.30	0.26	0.30	0.17	0.397 76
$\Delta\rho_{min}$/e Å^{-3}	−0.19	−0.29	−0.26	−0.30	−0.25	−0.355 60

[a] Rigaku AFC-6S diffractometer; $\omega/2\theta$ scans; no absorption correction; 3 standard reflections monitored every 150 reflections. [b] Refinement on F; H-atom positions were found from ΔF synthesis and included with $U_{iso}(H) = 1.2U_{eq}(C)$; $\omega = 4F_o^2/\sigma^2(F_o^2)$; no correction for extinction; atomic scattering factors from *International Tables for X-ray Crystallography* (1974, Vol. IV); absolute configuration not established.

zolyl ethers from substituent changes in the aryl ring (Table 1). Pathway *a* indicates that the tetrazolone **3** would be formed in its thermodynamically more stable keto form and not in the slightly less favourable hydroxy form. Reaction along pathway *b* would require an unfavourable electronic structural (endothermic) reversal in going towards a late transition state. For catalytic hydrogenolysis[7,8] or cross-coupling[9,10] of these ethers with initial oxidative addition of the ether to the catalytic metal, attack at the aryl ring by respectively hydrogen or an organic group would be expected to proceed in terms of pathway *a* products (Scheme 1) and is observed to do so.

Conclusions

X-Ray structure determinations on a series of tetrazolyl and pseudosaccharyl ethers of phenols have revealed remarkable differences in length for the C–O bonds of the central C–O–C ether linkages. The central ether oxygen appears to be sp^2 hybridized. The structural significance of these solid state results with regard to electronegativity appears to correlate well with ^{1}H and ^{13}C NMR chemical shift data obtained in solution, confirming the powerful electronegative nature of a tetrazolyloxy or pseudosaccharyloxy ring system. The effects observed by X-ray analysis are not due simply to the 'freezing' of a particular structure in the solid state. The electronic effects resulting from the bonding about the central C–O–C ether linkage provide part of the explanation for the ease and direction of heterogeneously or homogeneously catalysed *ipso* displacement of the tetrazolyl or pseudosaccharyl group to form either arenes by hydrogenolysis or substituted arenes by cross-coupling.

Experimental

General experimental procedures

Melting points are uncorrected. Mass spectra were recorded on a VG Trio 1000 quadrupole mass spectrometer, using electron ionization at 70 eV. ^{1}H and ^{13}C NMR spectra were measured on either a Bruker ACE 200 at 200 MHz or a Bruker WM 250 at 250 MHz or a Varian Gemini 2000 at 300 MHz, using tetramethylsilane as internal standard. Microanalyses for C, H, N were obtained on a Carlo Erba 1106 elemental analyser. X-Ray analyses were carried out on a Rigaku AFC6S four circle diffractometer.

X-Ray structure analysis

Data collection and cell refinement used MSC/AFC Diffractomer Control Software (Molecular Structure Corporation, 1988). Data reduction was effected with TEXSAN Process. The programs used for structure refinement were TEXSAN LS and material for publication was produced by TEXSAN FINISH. Particular selected geometric details appear in Table 1. Details of the structure determination factors for tetrazoles **1a–f** are given in Tables 2 and 3. Other selected geometric parameters are given in Table 4. Where there were two molecules in the unit cell (**1e**,**f**), refinement of the structure of opposite polarity gave no significant differences either in residuals or in molecular geometry parameters. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited with the Cambridge Crystallographic Data Centre (CCDC).[16] Full details of the structures of the pseudosaccharins **4a**,**b** have been reported elsewhere.[12]

Preparation of substituted 1-phenyl-1*H*-tetrazoles

5-(2-*Naphthyloxy*)-1-*phenyl*-1H-*tetrazole* 1a. In a typical reaction, potassium *tert*-butoxide (4.0 g, 35.6 mmol) was added to a stirred solution of 2-naphthol (5.0 g, 34.7 mmol) in dry dimethylformamide (120 ml). After the butoxide had dissolved, 5-chloro-1-phenyl-1*H*-tetrazole (6.4 g, 34.7 mmol) was added and stirring was continued at room temp. for 1 h. The mixture was poured into an excess of ice–water and the solid that separated was filtered off, washed with water, dried in air at room temp. and then was recrystallized from methanol to give the required compound **1a** as colourless plates (8.4 g, 84% yield), mp 137–138 °C (Found: C, 70.6; H, 4.2; N, 19.4. $C_{17}H_{12}N_4O$ requires C, 70.8; H, 4.2; N, 19.4%); *m/z* 288 (M^+); δ_H 7.46–7.65 (5 H, m), 7.83–7.95 (7 H, m). 5-(2,6-*Dimethylphenoxy*)-1-*phenyl*-1H-*tetrazole* **1b**, was prepared similarly, colourless crystals (from ethanol, 85% yield), mp 122–125 °C (Found: C, 67.4; H, 5.3; N, 21.2. Calc. for $C_{15}H_{14}N_4O$: C, 67.7; H, 5.3; N, 21.0%); *m/z* 266 (M^+); δ_H 2.21 (6 H, s), 7.14 (3 H, m), 7.59 (3 H, m), 7.90 (2 H, m); 5-(3,5-*dimethylphenoxy*)-1-*phenyl*-1-1H-*tetrazole* **1c**, colourless crystals (from ethanol, 80% yield), mp 106–107 °C (Found: C, 67.3; H, 5.3; N, 21.2. Calc. for $C_{15}H_{14}N_4O$: C, 67.7; H, 5.3; N, 21.0%); *m/z* 266 (M^+); δ_H 2.35 (6 H, s), 6.95 (2 H, m), 7.01 (1 H, s), 7.57–7.81 (5 H, m); 5-(4-*methylphenoxy*)-1-*phenyl*-1H-*tetrazole* **1d**, colourless crystals (from ethanol, 90% yield), mp 85–87 °C (Found: C, 66.5; H, 4.8; N, 22.4. Calc. for $C_{14}H_{12}N_4O$: C, 66.7; H, 4.8; N, 22.2%); *m/z* 252 (M^+); δ_H 2.36

Table 4 Selected geometric parameters for tetrazoles **1a**–**f** (Å, °)[a]

Compound **1a**					
O1–C1	1.322(8)	C1–O1–C2	119.3(5)	N1–C1–O1–C2	174.8(6)
O1–C2	1.437(7)	O1–C1–N1	121.0(6)	N4–Cl–O1–C2	−7(1)
N1–N2	1.366(7)	O1–C1–N4	128.7(6)	C1–O1–C2–C3	−44(1)
N1–C1	1.347(7)	O1–C2–C3	121.0(6)		
N2–N3	1.289(7)				
N3–N4	1.368(1)				
N4–C1	1.320(8)				
C2–C3	1.375(9)				
C2–C11	1.355(8)				
Compound **1b**					
O1–C1	1.333(2)	C1–O1–C2	116.5(1)	N1–C1–O1–C2	−159.7(2)
O1–C2	1.428(2)	N2–N1–C1	106.7(1)	N4–C1–O1–C2	21.0(3)
N1–N2	1.365(2(	N1–N2–N3	106.5(1)	C1–O1–C2–C3	101.6(2)
N1–C1	1.344(2)	N2–N3–N4	111.5(2)		
N2–N3	1.290(2)	N3–N4–C1	104.7(2)		
N3–N4	1.367(2)	O1–C1–N1	120.6(2)		
N4–C1	1.307(3)	O1–C1–N4	128.9(2)		
C2–C3	1.383(3)	O1–C2–C3	116.1(2)		
C2–C7	1.387(3)	O1–C2–C7	118.9(2)		
Compound **1c**					
O1–C1	1.331(5)	C1–O1–C8	117.8(3)	N1–C1–O1–C8	174.4(4)
O1–C8	1.423(4)	N2–N1–C1	106.7(3)	N4–C1–O1–C8	−8.2(6)
N1–N2	1.368(5)	N1–N2–N3	106.1(4)	C1–O1–C8–C9	−54.9(5)
N1–C1	1.352(5)	N2–N3–N4	111.9(4)	C1–O1–C8–C13	129.9(4)
N2–N3	1.295(5)	N3–N4–C1	104.7(3)		
N3–N4	1.368(5)	O1–C1–N1	120.7(4)		
N4–C1	1.304(5)	O1–C1–N4	128.7(4)		
C8–C9	1.371(6)	N1–C1–N4	110.6(3)		
C8–C13	1.373(6)	O1–C8–C9	120.7(4)		
C10–C15	1.495(6)	O1–C8–C13	116.3(3)		
C12–C14	1.507(7)	C11–C12–C14	121.7(4)		
		C13–C12–C14	120.1(4)		
Compound **1d**					
O1–C1	1.329(6)	C1–O1–C2	122.2(5)	N1–C1–O1–C2	−2(1)
O1–C2	1.415(7)	N2–N1–C1	103.5(5)	N4–C1–O1–C2	174.4(6)
N1–N2	1.366(7)	N1–N2–N3	113.5(5)	C1–O1–C2–C3	−151.2(5)
N1–C1	1.313(7)	N2–N3–N4	104.8(4)	C1–O1–C2–C7	33.2(9)
N2–N3	1.285(7)	N3–N4–C1	107.4(5)		
N3–N4	1.374(7)	O1–C1–N1	130.1(6)		
N4–C1	1.340(7)	O1–C1–N4	119.1(5)		
C2–C3	1.372(8)	O1–C2–C3	114.1(5)		
C5–C8	1.494(9)	O1–C2–C7	123.4(5)		
C9–C10	1.392(9)	C4–C5–C8	121.8(6)		
C9–C14	1.365(9)				
Compound **1e**					
O1–C1	1.337(3)	C1–O1–C2	117.4(2)	O1–C1–N1–N2	179.3(2)
O1–C2	1.414(2)	N2–N1–C1	106.3(2)	N1–C1–O1–C2	−178.4(2)
N1–N2	1.363(3)	N1–N2–N3	106.7(2)	N4–C1–O1–C2	0.1(3)
N1–C1	1.344(2)	N2–N3–N4	111.6(2)	C1–O1–C2–C3	−58.1(3)
N2–N3	1.289(3)	N3–N4–C1	104.4(2)		
N3–N4	1.368(3)	O1–C1–N1	120.3(2)		
N4–C1	1.303(3)	O1–C1–N4	128.6(2)		
N5–C8	1.143(3)	O1–C2–C3	121.7(2)		
C2–C3	1.373(3)	O1–C2–C7	115.0(2)		
C2–C7	1.382(3)	C3–C2–C7	123.1(2)		
C5–C8	1.446(3)	N5–C8–C5	178.2(3)		
Compound **1f**					
O1–C1	1.335(7)	C1–O1–C8	116.4(4)	N1–C1–O1–C8	−163.1(5)
O1–C8	1.434(6)	C11–O2–C14	117.3(4)	N3–N2–N1–C2	178.3(6)
O2–C11	1.379(6)	N2–N1–C1	105.6(4)	N4–C1–O1–C8	18(1)
O2–C14	1.444(7)	N1–N2–N3	106.8(4)	C1–O1–C8–C9	102.2(6)
N1–N2	1.367(7)	N2–N3–N4	111.5(5)		
N1–C1	1.354(7)	N3–N4–C1	104.5(5)		
N2–N3	1.286(6)	O1–C1–N1	118.7(5)		
N3–N4	1.371(6)	O1–C1–N4	129.7(5)		
N4–C1	1.289(7)				
C8–C9	1.380(9)				
C8–C13	1.358(9)				

[a] Atom numbering is given on the structures shown **1a**–**f**. There were two molecules to the unit cell in structures **1e**,**f**; atom numbering is given for only one of these, full data being available from the Cambridge Crystallographic Data Centre.[16]

(3 H, s), 7.21 (2 H, m), 7.27 (2 H, m), 7.48–7.82 (5 H, m); 5-(4-*cyanophenoxy*)-1-*phenyl*-1H-*tetrazole* **1e**, colourless crystals (from ethanol, 74% yield), mp 118–119 °C (Found: C, 63.9; H, 3.4; N, 26.9. Calc. for $C_{14}H_9N_5O$: C, 63.9; H, 3.4; N, 26.6%); *m/z* 263 (M^+); δ_H 7.58–7.81 (9 H, m); 5-(4-*methoxyphenoxy*)-1-*phenyl*-1H-*tetrazole* **1f**, colourless crystals (from ethanol, 93% yield), mp 82–84 °C (Found: C, 62.4; H, 4.5; N, 21.2. Calc. for $C_{14}H_{12}N_4O_2$: C, 62.7; H, 4.5; N, 20.9%); *m/z* 268 (M^+); δ_H 3.81 (3 H, s), 6.94 (2 H, d, *J* 10.0), 7.54–7.80 (5 H, m); 5-*ethoxy*-1-*phenyl*-1H-*tetrazole* **1g**, colourless crystals (from ethanol, 71% yield), mp 62–64 °C (Found: C, 57.1; H, 5.0; N, 29.5. Calc. for $C_9H_{10}N_4O$: C, 56.8; H, H, 5.3; N, 29.5%); *m/z* 190 (M^+); δ_H 1.51 (3 H, t, *J* 8.8), 4.72 (2 H, q, *J* 8.8), 7.40–7.60 (5 H, m), 7.73 (2 H, d, *J* 8.0).[28]

Preparation of substituted pseudosaccharins

The formation of 3-(4-methoxyphenoxy)-1,2-benzoisothiazole 1,1-dioxide **4a**[14] and 3-(1-naphthyloxy)-1,2-benzoisothiazole 1,1-dioxide **4b**[15] have been described elsewhere. 3-Ethoxy-1,2-benzisothiazole 1,1-dioxide **4c** was prepared by heating a chloroform solution of pseudosaccharyl chloride (1.0 g; 5 mmol), containing a slight excess of ethanol, until it refluxed. The mixture was filtered off and allowed to cool to give the required compound as colourless crystals, mp 221 °C (lit.,[27] 219 °C) (Found: C, 51.2; H, 4.3; N, 6.6. Calc. for $C_9H_9NO_3S$: C, 51.2; H, 4.3; N, 6.6%); *m/z* 211 (M^+); δ_H 1.54 (3 H, t, *J* 5.5), 4.67 (2 H, q, *J* 5.5), 7.66–7.81 (3 H, m), 7.87–7.91 (1 H).

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