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Revisit of the leaving group (LG)/halogen exchange in 1,2-dimesityl-2-phenylvinyl–LG systems: a caveat about 'mistaken identity' by X-ray diffraction†

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epoc ABSTRACT: The unusual report that *Z*-1,2-dimesityl-2-phenylethenol (***Z*-4-OH**) affords with $POBr_3$ the crystallographically identified *E*-1,2-dimesityl-2-phenylvinyl bromide (***E*-4-Br**) was reinvestigated together with related reactions. Reaction of ***Z*-4-OH** with tosyl chloride gave ***Z*-4-OT**s, ***Z*-4-Cl** with $SOCl_2$ and ***Z*-4-Br** with $Me_3SiCl/LiBr$, PBr_3 or PPh_3/Br_2. Reaction of ***Z*-4-OT**s with Br^- or I^- in MeCN gave ***Z*-4-Br** or ***Z*-4-I** respectively. The reaction of ***Z*-4-OH** with $POBr_3$ was repeated under several conditions and gave ***Z*-4-Br**, which was identified by X-ray diffraction. The discrepancy with the previous experiment was ascribed to the formation of a minute percentage of ***E*-4-Br** within the bulk of ***Z*-4-Br** and to analysis of a crystal of ***E*-4-Br** by X-ray diffraction. The generalization that MesC(Ph) = C*-Mes (* = $^\bullet$ or +) species capture reagents (e.g. Br^-, I^- for 2 when * = +) from the face carrying the β-mesityl ring is corroborated and extended. It is suggested that the reactions of ***Z*-4-OH** with $SOCl_2$, PBr_3 or $POBr_3$ proceed *via* initial formation of chlorosulfite or phosphorus-containing ester leaving groups that solvolyze to 2 or its ion pair, which react with halide ions formed from the anionic leaving group to give ***Z*-4-X** (X = Cl, Br). From the X-ray data of MesC(Ph) = C(X)Mes, (X = Br, OAc, *E* and *Z* isomers; X = OTs, Cl, I, *Z* isomer; X = H, *E* isomer) the effect of X on bond lengths, angles and dihedral angles, as well as on the difference between the *E/Z* isomers (X = OAc, Br), is determined and discussed. Although steric crowding is important, its effect is significant mainly on the Ar—C═C dihedral angles. ^1H δ values for the nine systems show free rotation of all rings around the Ar—C═C bonds on the NMR time scale. Higher field *o*-Mes-Me, *m*-Mes-H signals and lower field Ph-H signals for the *Z*- than for the *E*-isomers for X = OAc, Br were observed. Copyright © 2001 John Wiley & Sons, Ltd.
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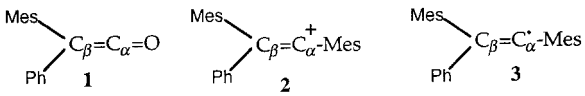
INTRODUCTION

In two previous studies we had investigated both experimentally and theoretically the stereochemistry of reaction at C_α of the double bond of geminal β-mesityl β-phenyl-substituted systems. Nucleophilic addition to C_α of the ketene **1**,[1] the vinyl cation **2**,[1] and capture of the radical **3**[2] was found to be subject to stereoelectronic effects, capture being always from the side of the β-mesityl ring. It was concluded that in the ground state configuration of **1**–**3** the phenyl is nearly coplanar (and conjugate) with the C═C double bond, whereas the mesityl ring is significantly twisted from it and is sometimes close to being perpendicular to the C═C plane. Approach of the reagent to C_α then becomes less hindered and the product forms with two mesityl groups *trans* to one another.



Mes = Mesityl = 2,4,6-$Me_3C_6H_2$

However, the reaction of *Z*-1,2-dimesityl-2-phenylethenol (***Z*-4-OH**) with $POBr_3$ in the presence of $PhNEt_2$ in CCl_4 gave, according to X-ray crystallography, the *E*-1,2-dimesityl-2-phenylvinyl bromide (***E*-4-Br**) and this synthesis was reported.[2] This observation was inconsistent with our generalization, since the entering bromide came from the side of the phenyl rather than

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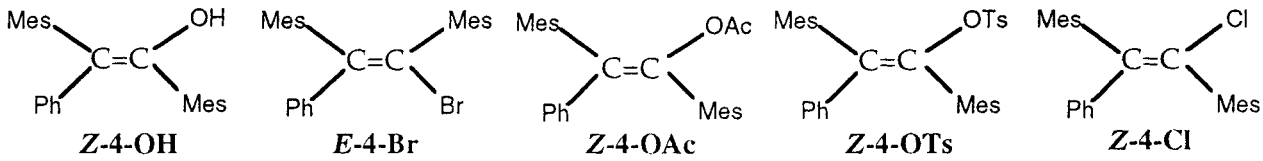
from the mesityl side.



The mechanism of this reaction is unknown, but since it is a substitution process it is expected to be either an S_N1, S_N2 or S_Ni-type reaction or an ion pair variant. However, an S_N1 reaction gave the *Z*-acetate ***Z*-4-OAc** from solvolysis of the *Z*-tosylate (***Z*-4-OTs**) as expected. An in-plane S_N2 substitution of an external Br^- from the medium on a system carrying a phosphorus-containing leaving group (e.g. $OPOBr_2$) should give ***E*-4-Br** but is expected to be very difficult in such a system (for activation of vinylic systems to bimolecular S_NV reactions see Refs 3a,b; for nucleophilicity towards vinylic carbon see Ref. 3c), whereas the S_Ni reaction or its ion pair equivalent is expected to give ***Z*-4-Br**. The formation of ***E*-4-Br** is more astonishing, since the reaction of the enol ***Z*-4-OH** with $SOCl_2$ was briefly reported to give the 'expected' ***Z*-4-Cl**.[2]

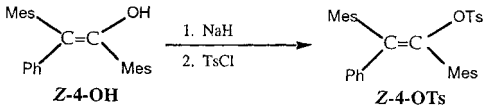
Since this apparently unusual reaction can be due to the nature of the bromine-containing reagent that replaces the OH, to the difference between chlorine and bromine (e.g. in their bulk), or to a preferred *E*-structure for vinyl halide carrying the larger halogen, the replacement of the OH by bromine with various bromine-introducing reagents, and the structures of the corresponding vinyl chloride and iodide were investigated. As described below, we found that related reactions of Mes(Ph)C═C systems conform with our stereoelectronic generalization. This had suggested that the reported unusual stereochemistry is due to a mistake that is based on the X-ray diffraction analysis of the stereochemistry of the main product in the reaction.

The experiments that led to this conclusion are described below.

RESULTS AND DISCUSSION

Reaction of *Z*-1,2-dimesityl-2-phenylvinyl tosylate with Br^- and I^- ions

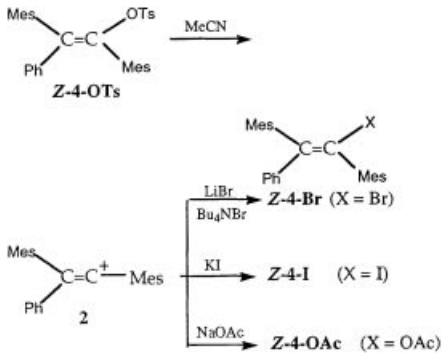
Preparation and stereochemistry of the tosylate. A reaction whose mechanism should not be controversial in the present context is the solvolysis of *Z*-1,2-dimesityl-2-phenylvinyl tosylate (***Z*-4-OTs**). This compound is prepared by tosylation of the enolate formed from the *Z*-enol, ***Z*-4-OH**, the geometry of which was determined by X-ray diffraction,[4] (Eqn. (1)).



(1)

This reaction, which formally does not involve the double bond, is not expected to change the configuration, and hence it should give the *Z*-tosylate. We confirmed the ***Z*-4-OTs** configuration by X-ray diffraction. The ORTEP drawing is given in Fig. 1, and important bond lengths and angles are given in Table 1.

Reaction with Br^-. *Z*-4-OTs was reacted with LiBr/Bu_4NBr in acetonitrile. The progress of the reaction was followed by thin-layer chromatography (TLC) and only one new spot was detected. The bromide isolated at the end of the reaction has a melting point (m.p.) of 180–181 °C and an ^1H NMR spectrum identical with that of the bromide obtained by all other methods and which is presently identified (see below) as ***Z*-4-Br**. Hence the Br^- captures the vinyl cation from the mesityl side (Eqn. (2)), as expected, and as found for the capture by AcO^- ion.[1]



(2)

Reaction with I^-. *Z*-4-OTs was reacted with KI in refluxing acetonitrile. Again, only one TLC spot was observed during and at the end of the reaction. The product obtained was an iodide (**4-I**), which displayed a 2:1 ratio of Me to aromatic protons in the ^1H NMR spectrum. The configuration was determined by X-ray diffraction as that of the *Z*-isomer, ***Z*-4-I**. There are two crystallographically independent molecules in the unit cell. The ORTEP drawing of one of them is given in Fig. 2, and selected bond lengths and angles are given in Table 1.

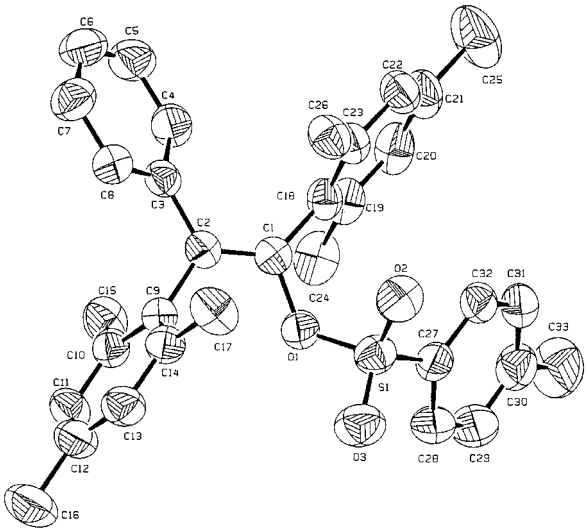
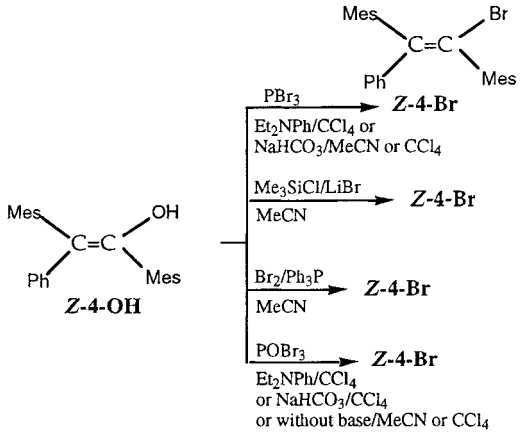


Figure 1. ORTEP drawing of ***Z*-4-OTs**

Reactions of *Z*-4-OH with several OH → Br, OH → Cl reagents

The possibility that different reagents which convert a C—OH to a C—Br bond give different configurations (***E*-4-Br** or ***Z*-4-Br**) of the product was investigated. ***Z*-4-OH** was reacted with PBr_3 under several conditions, with bromine and triphenylphosphine in acetonitrile[5] or with $Me_3SiCl/LiBr$,[6] and always gave the same single product (Eqn. (3)) having a m.p. of 180–181 °C and a typical ^1H NMR spectrum that was very similar to that of the previously prepared **4-Cl**.[7] These data were identical to those reported previously for the ***E*-4-Br**.[2]



(3)

The configuration of **4-Cl** was determined by X-ray crystallography as that of the *Z*-isomer, ***Z*-4-Cl**. Important crystallographic parameters are given in Table 1.

Revisit of the reaction of *Z*-4-OH with $POBr_3$

The formation of ***E*-4-Br** as the only exception to the general behavior, the similarity of the NMR spectra of ***Z*-**

Table 1. X-ray parameters for MesC(Ph)=C(X)Mes systems with *trans* and *cis* mesityl groups

	trans-Mes/Mes							*cis*-Mes/Mes	
	X = H ***Z*-4-H**	Cl ***Z*-4-Cl**	Br ***Z*-4-Br**	I ***Z*-4-I**	OH ***Z*-4-OH**	OAc ***Z*-4-OAc**	OTs ***Z*-4-OTs**	X = Br ***E*-4-Br**	OAc ***E*-4-OAc**
Bond length (Å)									
C1=C2	1.337(3)	1.332(3) 1.340(3)	1.302(6) 1.34(2)	1.340(9) 1.340(2)	1.26(1)	1.34	1.331(2)	1.330(7)	1.338(2)
β-Mes—C=	1.501(3)	1.507(3) 1.495(3)	1.512(7) 1.59(2)	1.500(9) 1.60(2)	1.546(7)	1.51	1.502(2)	1.520(8)	1.506(9)
Bond angle (°)									
α-Mes—C1—C2	129.1(4)	129.3(2) 128.2(2)	129.8(5) 124(1)	131.0(6) 126(2)	126.8(9)	130.4(7)	129.8(1)	128.6(5)	128.0(7)
β-Ph—C2—C1	123.4(2)	122.9(2) 121.2(2)	121.1(5) 117(1)	120.9(6) 119(2)	119.3(8)	121.9(7)	122.9(1)	124.4(5)	121.2(7)
Ph—C_β—β-Mes	117.6(2)	115.0(2) 115.4(2)	117.1(4) 126.8(8)	117.3(5) 122(1)	114.4(8)	115.7(6)	116.2(1)	115.4(5)	116.3(7)
β-Mes—C2—C1	118.1(2)	122.1(2) 123.4(2)	121.8(5) 116(1)	121.7(6) 118(2)	126.3(7)	122.3(7)	120.9(1)	120.3(5)	122.4(7)
X—C1—C2		119.0(2) 118.5(2)	118.5(4) 118(1)	118.0(5) 115(2)	120(1)	116.9(6)	114.5(1)	120.1(4)	116.3(7)
X—C1—α-Mes		111.7(2) 113.2(2)	111.7(3) 118.1(7)	110.9(4) 114.3(7)	113.2(7)	112.1(6)	115.4(1)	111.3(4)	115.2(7)
Dihedral angle (°)									
α-Mes—C=C	64.0(8)	97.9(4)	97.0(9)	96.4(1.2)	79.0(1.6)	67.0(1.4)	116.9(2)	74.8(9)	62.0(1.4)
β-Mes—C=C	64.4(4)	80.1(4)	94.6(9)	93.2(1.2)	74.1(1.4)	77.0(1.4)	78.9(2)	109.6(9)	65.0(1.4)
β-Ph—C=C	38.2(4)	30.7(4)	26.2(9)	25.1(1.2)	38.3(1.6)	43.0(1.4)	39.6(2)	60.3(9)	57.0(1.4)
α-MesC_αX—PhC_β Mes	0.5(4)	1.3(4)	2.5(9)	3.4(1.2)	1.1(1.6)		6.9(2)	5.9(9)	

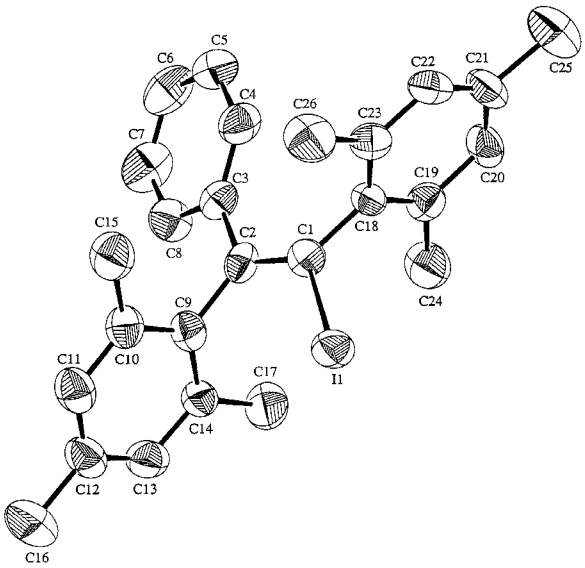


Figure 2. ORTEP drawing of one form of ***Z*-4-I**

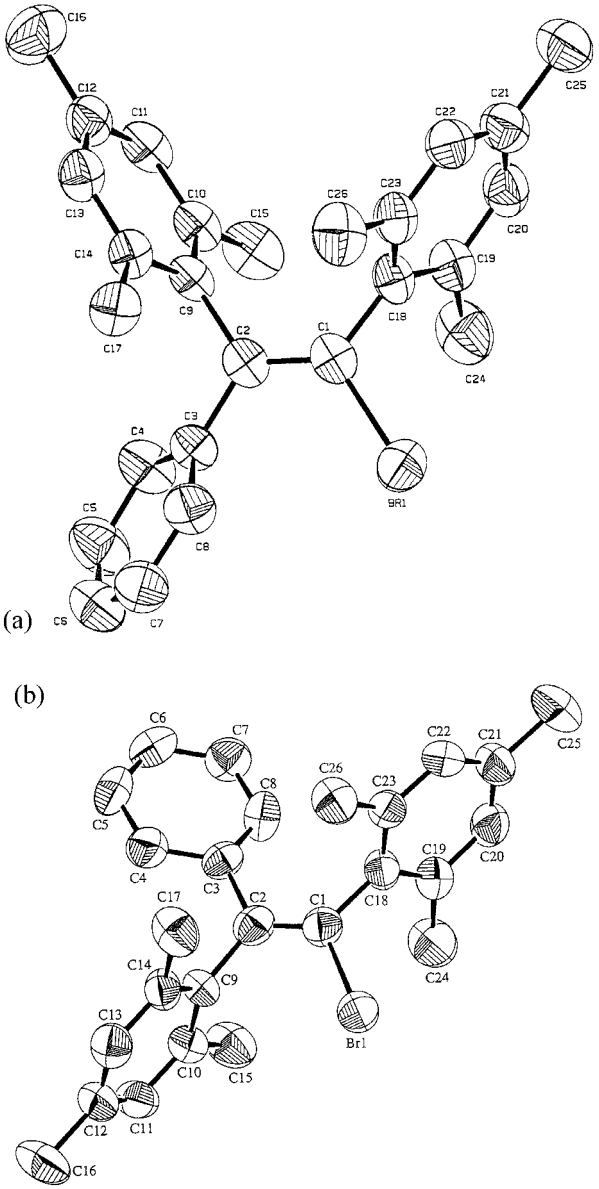


Figure 3. ORTEP drawings of (a) ***E*-4-Br**, and (b) one form of ***Z*-4-Br**

4-Cl and ***E*-4-Br** whereas the spectra of ***E*-** and ***Z*-4-OAc** differ significantly, the formation of the same bromide under a variety of conditions, the lack of ***E*-4-Br** → ***Z*-4-Br** isomerization and the calculation that indicates that ***Z*-4-Br** is thermodynamically more stable (see below) led to the suspicion of an error in the deduced stereochemical outcome, in spite of the unequivocal X-ray structure of ***E*-4-Br**. The most conceivable source for such an error is that traces of ***E*-4-Br** were formed in the original experiment and that a single crystal of this isomer was picked up for the X-ray crystallography from the bulk containing nearly exclusively ***Z*-4-Br**. Consequently, the reported reaction leading to ***E*-4-Br** was repeated under exactly the same conditions, as well as in the absence of added base. The m.p. of the crystals was again 180–181 °C and the ^{1}H NMR spectrum was identical with that obtained in all the other experiments, but which were ascribed previously to ***E*-4-Br**. X-ray crystallography of the newly prepared sample showed a *Z*-bromide configuration, ***Z*-4-Br**. The ORTEP drawings of the ***E*-4-Br** and of one of the two crystallographically independent molecules in the unit cell of ***Z*-4-Br** are given in Fig. 3. ***Z*-4-Br** and ***Z*-4-I**, which belong to the same space group, have very similar crystallographic data. Selected bond lengths and angles of ***E*-4-Br** and ***Z*-4-Br** are given in Table 1. The second crystallographically independent molecule of ***Z*-4-Br** shows an approximate two fold disorder (C1′*:C1′ = 43:57) for the C1′—C2′ bond. Hence, the data for this molecule are not discussed below.

We conclude that by a rare occurrence of formation and X-ray analysis of a very minor component, which was formed irreproducibly and only once in many repeated experiments, a wrong stereochemical outcome of the main reaction was observed and reported, although this point was noted when reported and mechanistic speculations were avoided.

Two points still remain unclear, viz. what is the mechanism of formation of ***E*-4-Br** in the first experiment and why were both isomers not distinguished by TLC of the original reaction mixture.

We were able to retrieve the crystal of ***E*-4-Br** used previously for the X-ray analysis and found that its m.p., its ^{1}H NMR data in solution (see below) and its R_f on a TLC plate differ from those of ***Z*-4-Br**. We believe that since the original product was mostly ***Z*-4-Br** the sample chosen for the m.p., TLC and ^{1}H NMR determinations

was also the ***Z*-4-Br** isomer, whereas the X-ray analysis was done on ***E*-4-Br**. The formation of a minute amount of ***E*-4-Br** should not be too surprising. Not all the reactions of the 1,2-dimesityl-2-phenylvinyl systems[1,2] are necessarily 100% stereoselective. Indeed, in a few of the reactions described previously (e.g. in the capture of radical **3** by hydrogen) both *E*- and *Z*-isomers were formed. However, the irreproducible formation of ***E*-4-Br** suggests the possibility that some catalytic impurity was responsible for its formation.

Z-4-X/*E*-4-X relative stabilities

The relative stabilities of a few of our *E/Z* isomeric pairs were calculated by Yamataka.[8] The isomer having two *trans*-Mes groups was always more stable than that with *cis*-Mes rings. At B3LYP/3-21G the differences are 0.7 (X = H) and 6.3 kcal mol^{-1} (X = Br) and at HF/3-21G the values are 7.5 (X = OH), 9.7 (X = Cl) and 7.1 kcal mol^{-1} (X = Br), so that the numbers are not directly proportional to the bulk of X. The differences are sufficiently large at this level and we do not believe that they will be changed at a higher computation level. Consequently, the products of thermodynamic and kinetic control are identical.

X-ray structures in the 1,2-dimesityl-2-phenylvinyl–X system

Our new crystallographic data, together with earlier data, accumulates to nine 1,2-dimesityl-2-phenylvinyl–X structures, including seven derivatives with *trans*-Mes groups (X = H, Cl, Br, I, OH, OAc, OTs; all *Z* except when X = H) and two (X = OAc, Br) with *cis*-Mes groups (*E* structures). This enables comparison of the effect of X of increasing size, from H to I and OTs and of differing electronic effects on the bond lengths, bond angles and dihedral angles. Parameters of interest are assembled in Table 1.

Notwithstanding that the structures were determined at room temperature, that their degree of disorder is variable, that crystallographically independent molecules in the unit cell have slightly different structures (e.g. for the two structures of ***Z*-4-I** almost all bond lengths differ by $\leq$0.03 Å and bond angles differ mostly by $\leq$4°) and that the data were collected for structure determination rather than for comparative reasons, the important conclusion is that the effect of the group X on all parameters is relatively small. The only exception is when X = OH where we deduce from the 'too long' sp^2–sp^2 β-Mes—C= bond length of 1.546 Å[4] that the discrepancy is probably due to the use of a crystal of relatively low quality. Thus, the C=C bond lengths for X = H, Cl, Br (one form), I, OTs and OAc are all 1.33–1.34 Å and the β-Mes—C= bond lengths (excluding X = OH) are 1.50–1.51 Å for seven of the compounds and 1.52 Å for another one. The six bond angles around the double bond should be more sensitive than the bond lengths to crowding imposed by both geminal and vicinal-*cis* X groups. Nevertheless, the α-Mes—C1—C2 angle, which differs most from the ideal 120° angle than all other bond angles, covers only the range of 128.0–131.0° (or 126–131° if data for crystallographically different molecules in the unit cell are considered). The range of other angles is also not large, being 5.1° (β-Ph—C2—C1), 3.2° (Ph—C_β—β-Mes), 4.3° (β-Mes—C2—C1, OH excluded), 5.5° (X—C1—C2), and 7.2° (X—C1—α-Mes).

E- versus *Z*-isomer geometry

The only *E/Z*-isomeric pair **4** whose structure was previously known was for X = OAc.[1] The new pair of bromides (X = Br) enable one to evaluate the effect of increased formal crowding on several crystallographic parameters.

The most pronounced effect is on the dihedral angles. In the *E*-isomer the α-Mes—C=C angle is 8° lower than in the *Z*-isomer, but both rings are not too far from being perpendicular to the C=C plane. The situation is reversed with the β-Mes rings, which are 94.6° (*Z*) and 109.6° (*E*), but the difference is more significant for the β-Ph—C=C angle [26.2° (*Z*) and 60.3° (*E*)]. Consequently, the steric crowding is larger for the *E*-isomer where the rings *cis*-vicinal and geminal to the bromine are *ca* 34° and 15° more twisted from the double bond plane than the other β-ring. The lower twist angle of the α-Mes ring vicinal to bromine in the *E*- than in the *Z*-isomer is due to the conformation of the β-ring *cis*-vicinal to this ring. In ***Z*-4-Br** it is Ph that is twisted only by 26° from planarity with the double bond, and hence its *o*-hydrogen atoms can interact sterically with the α-ring, with a consequent decreased interaction when the dihedral α-Mes—C=C angle increases. In the *E*-isomer the vicinal ring is Mes, which is almost perpendicular to the double bond plane, so that inspite of the larger bulk due to the *o*-Me substituents, the effect is smaller. The higher crowding is also relieved by twisting the two parts of the double bond, and the twist angles in ***Z*-4-Br** and ***E*-4-Br** are 2.5° and 5.9° respectively.

These effects are also observed, but to a lower extent, for the corresponding acetates **4-OAc**, where the dihedral angle of the β-Ph is 14° higher and those of the β-Mes and α-Mes rings are lower, by 12° and 5° respectively, in the *E*-than in the Z-isomer.[1]

The six bond angles around the double bond are less sensitive to the structure, five of them differ by <2°, and only the β-Ph—C=C angle is 3.3° higher (as expected) in ***E*-4-Br** than in the *Z*-isomer. The β-Mes—C=C bond lengths are within the experimental error, and although the C1=C2 bond is significantly longer in the *E*-isomer, the whole set of the C=C bond lengths with their

combined experimental errors in Table 1 indicate that a discussion of the difference is unwarranted.

The mechanism of the S_NV reactions

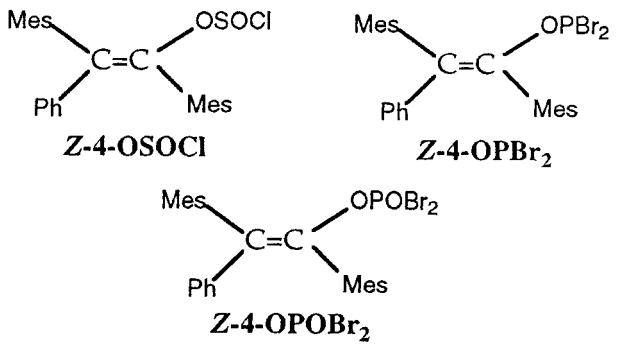
Solvolysis of *Z*-4-OTs. The solvolysis of ***Z*-4-OTs** in MeCN in the presence of added I^- and Br^- ions led exclusively to ***Z*-4-I** and ***Z*-4-Br** (Eqn. (2)). These experiments supplement the earlier reported formation of ***Z*-4-OAc** with AcO^-.[1] The exclusive formation of the *Z*-isomers is consistent with solvolysis *via* the intermediate vinyl cation **2**, which is captured exclusively from the face of the *β*-mesityl group. That mesityl behaves as being smaller than phenyl in such a situation was shown by the reactions of **1–3** and discussed extensively.[1,2] However, the evidence for such reaction of **2** has been limited so far to capture by AcO^-,[1] and the present work extends this conclusion. The solvolysis proceeds formally with exclusive retention, but this outcome in vinylic solvolysis has little mechanistic meaning unless *both* the *E*- and *Z*-isomers lead to retention.

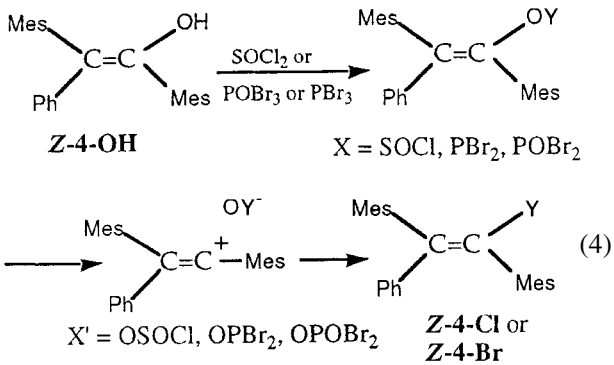
A retained product is also predicted by the common perpendicular bimolecular nucleophilic vinylic substitution (S_NV) route,[3] but the low activation of ***Z*-4-OTs** coupled with the low nucleophilicity of halide ions[3c] in bimolecular S_NV reactions exclude this route.

The OH → Br, Cl substitution. The stereochemical outcomes of the reactions of ***Z*-4-OH** with $SOCl_2$, $POBr_3$ and PBr_3 and other bromine-containing reagents are identical, i.e. formation of ***Z*-4-X**, X=Cl, Br, in an apparent retention. These halogen-carrying reagents are common in affording alkyl halides from alcohols in aliphatic systems (for reviews see Refs 9a,b), and the initially suggested mechanism was an S_Ni reaction.[10] The accepted first step is the conversion of the poor OH leaving group to a much better ester leaving group, a chlorosulfite ester with $SOCl_2$ and phosphorus-containing esters with phosphorus reagents. The following steps depend on the nature of the alkyl halide and the reaction conditions.[11] Primary substrates give inversion by an S_N2 reaction of the halide ion on the alkyl group of the ester. Secondary and tertiary substrates probably react *via* carbocation intermediates, as shown by the observation of a rearrangement (e.g. see Ref. 12). A recent experimental/computational reinvestigation of the reaction of thionyl chloride suggests that ion pairs are playing a key role in the reaction (see Ref. 13a; for a further comment see Ref. 13b).

To our knowledge, the mechanism of the similar reaction in vinylic systems was not investigated, except in a single case.[7] A stereochemical study of the reaction requires the use of both *E* and *Z* stable precursor enols with defined geometry. Several pairs of stable triarylethenols with bulky aryl groups are known, but they undergo rapid mutual *E/Z* isomerization.[14] An attempt to generate ***E*-4-OH** from an *E*-precursor gave only ***Z*-4-OH**, indicating a rapid $E \rightarrow Z$ isomerization.[1,15]

The rapid cyclization reaction of the *in situ* generated trimesitylvinyl tosylate to an indene derivative was interpreted as resulting from formation and further cyclization of an intermediate trimesitylvinyl cation.[7] A labeling experiment had shown an extensive *β*-Mes group rearrangement, corroborating this conclusion. We suggest that ***Z*-4-OH** forms initially the retained ***Z*-4-OSOCl**, ***Z*-4-OPBr$_2$** and ***Z*-4-OPOBr$_2$** analogously to the formation of the retained ***Z*-4-OTs** from tosyl chloride, discussed below. The presence of the carbenium-ion-stabilizing *α*-mesityl group suggests that these are cleaved to carbenium ion species, most likely the ion pairs **2**.OY^-, where OY = OSOCl, $OPBr_2$ or $OPOBr_2$, although formation of MesC(Ph)=C—Mes(Y′)+X^-, Y′ = OSO, OPBr, OPOBr; X = Cl, Br cannot be excluded. The capture of **2** in the ion pair to form ***Z*-4-Cl** or ***Z*-4-Br** (Eqn. (4)) is consistent with this route based on the stereochemistry of the reactions of ***Z*-4-OTs**.

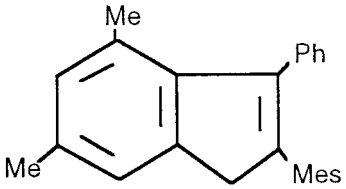




(4)

If **2** is captured faster than diffusion of the anion, the capture will preferentially be from the mesityl than from the phenyl face, thus strengthening the probability of formation of the *Z*-isomers. Again, this point cannot be investigated experimentally when ***E*-4-OH** is unavailable.

We ascribe the lack of observed cyclized product (**5**) from ***Z*-4-Cl** to a higher capture by X^-/cyclization ratio for **2** than for the trimesitylvinyl cation, due to higher steric hindrance to approach of an external anion to the latter cation.



5

An S_Ni route is also excluded by the formation of the *Z*-isomer when the reaction with $POBr_3$ is conducted in the presence and the absence of $PhNEt_2$. A change in the stereochemistry in the presence of an amine was previously ascribed to this route.[9a,10]

The stereochemistry of the tosylation of *Z*-4-OH

The X-ray data of ***Z*-4-OH** and ***Z*-4-OTs** indicate that the vinylic hydroxy to tosylate conversion proceeds with retention of configuration. This is the expected outcome, since the double bond is not directly involved, but since the reaction presumably proceeds *via* the enolate ion, where negative charge delocalization reduces the C_α—C_β bond order, a *Z* to *E* enolate ion isomerization preceding the tosylation cannot be *a priori* excluded. Apparently, the rate constants of the various processes and the barrier for *Z*- to E-enolate interconversion are such that isomerization is not observed in the product. The bulk of the aryl substituents, which increases the kinetic barrier to isomerization and reduces the stability of the *E*-product with two *cis*-Mes rings, seem responsible to a large extent for this result.

NMR spectra of compounds 4-X

Table 2 gives the $^1H(CDCl_3)$ chemical shifts for systems **4**. Several conclusions arise from the data. (i) For each system the Ph group appears as a multiplet, and the additional two 2H singlets in the aromatic region are ascribed to the *m*-Mes-H protons. This indicates a free rotation of the two mesityl rings around the Mes—C═ bonds for all systems at room temperature. (ii) This conclusion is corroborated by the nature of the Me signals. For each compound there are at least two 6H signals for the identical (on the NMR time scale) *o*-Me signals. Sometimes one of these overlaps a *p*-Me signal. (iii) The three *Z*-halides (X = Cl, Br, I) have remarkably similar ^1H NMR spectra, except that for ***Z*-4-I** the two *p*-Me signal appears separately. The *m*-Mes-H signals are 0.08–0.10 ppm apart for the three compounds. (iv) For the oxygen derivatives (X = Ph, OTs, OAc) the aromatic protons are more spaced than for the halo derivatives and the $\Delta\delta$ between the *m*-Mes-H signals of the two rings range from 0.07 ppm for ***Z*-4-OAc** to 0.25 ppm for ***Z*-4-OTs**. (v) For both the tosylate where X is one of the bulkier substituents and for X = H the spacings of the Me signals are the larger ones.

There is a significant difference between the positions of the signals for ***E***- and ***Z*-4-X**, X = OAc, Br, the only systems where both isomers were unequivocally assigned. In both *E*-isomers, with *cis*-Mes groups, the aliphatic signals are four to six times more spread, whereas the *m*-Mes-H signals are closer (0.01 ppm and 0.07 ppm), when X = OAc and Br respectively, compared with the *Z*-isomers (where the differences are 0.09 ppm). The phenyl ring signals are at a higher field in the *E*- than in the *Z*-isomers with *trans*-Mes groups. These differences may be diagnostic in future studies, even if only one isomer is formed.

A priori there should be some qualitative correlation between the Ar—C═C dihedral angles and the δ(Mes-Me), δ(Mes-H) and δ(Ph-H) values, since the δ values in one ring should be affected by the ring current due to the

Table 2. ^1H NMR chemical shifts (in ppm) for MesC(Ph)═C(X)Mes in $CDCl_3$

Compound	δ(Me)[a]	δ(Ar)[b]
***E*-4-H**	2.15 (6H), 2.29 (9H), 2.33 (3H)	6.87–7.11 (9H) including 6.84, 7.00 (2 × 2H)
***Z*-4-Cl**	2.29 (6H), 2.32 (6H), 2.33 (6H)	6.83–7.02 (9H) including 6.87, 6.95 (2 × 2H)
***Z*-4-Br**	2.30 (6H), 2.33 (6H), 2.34 (6H)	6.86–7.09 (9H) including 6.86, 6.95 (2 × 2H)
***Z*-4-I**	2.30 (3H), 2.31 (6H), 2.33 (6H), 2.35 (3H)	6.84–7.09 (9H) including 6.84, 6.94 (2 × 2H)
***Z*-4-OH**[c]	2.31 (6H), 2.33 (9H), 2.36 (3H)	6.69–7.03 (9H) including 6.90, 7.03 (2 × 2H)
***Z*-4-OTs**	2.20 (6H), 2.28 (3H), 2.35 (3H), 2.37 (3H), 2.39 (6H)	6.70–7.11 (13H) including 6.70, 6.95 (2 × 2H)
***Z*-4-OAc**	2.27 (3H), 2.29 (6H), 2.31 (9H)	6.82–7.03 (9H) including 6.82, 6.91 (2 × 2H)[d]
***E*-4-OAc**	1.98 (6H), 2.18 (6H), 2.22 (6H)	6.68–7.28 (9H) including 6.68, 6.69 (2 × 2H)[e]
***E*-4-Br**	2.11 (6H), 2.13 (3H), 2.18 (3H), 2.28 (6H)	6.63–7.32 (9H) including 6.63, 6.70 (2 × 2H)

[a] All the Me signals are singlets.
[b] The 2 × 2H signals are two Mes-H singlets.
[c] In THF, δ 2.28 (6H), 2.297 (6H), 2.30 (3H), 2.33 (3H), 6.70–7.03 (9H).
[d] OAc, δ 1.78.
[e] OAc, δ 2.04.

other two rings and hence by the relative conformations of the three rings.

The fact that for the two *E/Z* pairs all the signals in the two mesityl rings are at a higher field and the Ph-H signals are at lower field when the two rings are *cis* to one another is consistent with this assumption. In the isomer with two *cis* rings, which undergo rapid internal rotation on the NMR time scale, the *m*-H and *o*-Me groups are closer to the center of the other ring and hence are more in the shielding range of this ring than in the other isomer. In contrast, the phenyl ring is more in the plane of the C=C bond in the *trans* isomers, and hence its protons are more shielded than when this ring is more twisted from this plane in the *cis* isomers.

However, superposition of the effects of the various rings is probably responsible for the lack of a clear-cut correlation between the chemical shifts and the dihedral angles for the whole set, as shown by comparison of Tables 1 and 2.

EXPERIMENTAL SECTION

General methods and materials

The equipment used was described earlier.[16] ***Z*-4-OH** was prepared according to Fuson *et al.*[17] The solvents were commercial and were used without further purification.

Reaction of *Z*-4-OH with phosphorus tribromide

(a) To a solution containing ***Z*-4-OH** (90 mg, 0.25 mmol) and *N,N*-diethylaniline (0.2 ml, 1.23 mmol) in CCl_4 (3 ml), PBr_3 (0.32 ml, 3.34 mmol) was added and the mixture was refluxed for 6 h, until the reaction was completed according to TLC. Ice-water (5 ml) was added with stirring, the organic phase was separated, the aqueous phase was extracted with CCl_4 (3×2 ml) and the combined organic phases were washed with water (3×2 ml), dried and the solvent was evaporated. Chromatography of the remaining solid using 19:1 petroleum ether (40–60°)–AcOEt eluent yielded ***Z*-4-Br** (42 mg, 40%), m.p. 180–181 °C. ^{1}H NMR ($CDCl_3$) δ: 2.30, 2.33, 2.34 (18H, 3s, Me), 6.83–7.01 (9H, m, Ar).

(b) A similar result was obtained when $NaHCO_3$ was used as a base. Chromatography in this case was with petroleum ether eluent.

(c) To a mixture containing ***Z*-4-OH** (90 mg, 0.25 mmol) and $NaHCO_3$ (0.34 g, 4.05 mmol) in MeCN (4 ml), PBr_3 (0.32 ml, 3.34 mmol) was added and the mixture was refluxed for 7 h with stirring. Work-up as above gave ***Z*-4-Br** (46 mg, 44%), m.p. 180–181 °C with identical unit cell to that obtained by X-ray crystallography of the product from the reaction with $POBr_3$.

Reaction of *Z*-4-OH with Me_3SiCl/LiBr

To a solution containing trimethylsilyl chloride (0.21 ml, 1.65 mmol) and LiBr (0.12 g, 1.3 mmol) in acetonitrile (3 ml) was added the enol ***Z*-4-OH** (120 mg, 0.34 mmol) under nitrogen atmosphere. The reaction mixture was refluxed for 28 h, when the reaction was complete according to TLC. Water (3 ml) was added to the mixture, and the aqueous phase was extracted with CCl_4 (3×2 ml), dried (Na_2SO_4) and the solvent was evaporated. Chromatography of the remaining gray solid on silica gel, using 19:1 petroleum ether (40–60°)–AcOEt mixture as the eluent, yielded the bromide ***Z*-4-Br**, (73 mg, 52%), m.p. 180–181 °C, with ^{1}H NMR spectrum identical to that reported above.

An attempt to prepare the corresponding iodide by a similar method failed.

Reaction of *Z*-4-OH with bromine and triphenylphosphine

A mixture of triphenylphsophine (0.30 g, 1.1 mmol) and bromine (0.06 ml, 1.13 mmol) in acetonitrile (1 ml) was stirred for 3 min. The solvent was evaporated, enol ***Z*-4-OH** (140 mg, 0.39 mmol) and then acetonitrile (3 ml) were added to the solid residue and the mixture was refluxed for 18 h until the reaction was completed. Water (3 ml) was added and the mixture was extracted with CCl_4 (2×2 ml), dried (Na_2SO_4) and the solvent was evaporated. Chromatography of the residue on a silica gel column using 19:1 petroleum ether (40–60%)–AcOEt eluent yielded 82 mg (50%) of ***Z*-4-Br**, m.p. 180–181 °C, with NMR data as reported above.

Reaction of *Z*-4-OH with $POBr_3$

(a) Reaction of ***Z*-4-OH** and $POBr_3$ and $PhNEt_2$ in CCl_4 was conducted exactly as described in our previous work.[2] The product (32%), which was crystallized now from EtOH, was ***Z*-4-Br** according to X-ray crystallography.

(b) A solution containing ***Z*-4-OH** (180 mg, 0.5 mmol) and $POBr_3$ (2 g, 4 mmol) in CCl_4 was refluxed for 12 h, water (10 ml) was added, the phases were separated and the organic phase was washed with H_2O, dried (Na_2SO_4) and the solvent was evaporated to leave the crude product containing some $POBr_3$. Column chromatography on silica gel using petroleum ether eluent gave 100 mg (47%) of the vinyl bromide, m.p. 180–181 °C, with the ^{1}H NMR spectrum identical to that described previously[2] and that given in Table 2.

(c) A solution containing ***Z*-4-OH** (180 mg, 0.5 mmol) and $POBr_3$ (2 g, 4 mmol) in CH_3CN (10 ml) was refluxed for 10 h (complete reaction by TLC). The solvent was evaporated, the residue was dissolved in CCl_4, washed with water, dried (Na_2SO_4), the solvent was evaporated and the crude product was purified by chromatography

over silica gel using petroleum ether (40–60 °C) as eluent giving 95 mg (45%) of the vinyl bromide as a white solid, m.p. 180–181 °C, mixed m.p. 180 °C, identified as the isomer obtained in the other experiments.

(d) To a solution containing ***Z*-4-OH** (180 mg, 0.5 mmol) and sodium bicarbonate (1.5 g, 18 mmol) in CCl_4 (4 ml), $POBr_3$ (1.32 g, 2.64 mmol) was added and the mixture was refluxed for 5.5 h. Work-up as above gave a solid (55 mg, 26%) with NMR spectra identical to that described in above.

(e) The single crystal obtained previously by the same method, which gave by X-ray crystallography the ***E*-4-Br** structure, was retrieved and analyzed. It has m.p. 174–175 °C (mixed m.p. of a 1:1 mixture with ***Z*-4-Br**, 151–153 °C). ^{1}H NMR ($CDCl_3$) δ: 2.11 (6H, s, *o*-Me), 2.13 (3H, s, *p*-Me), 2.18 (3H, s, *p*-Me), 2.28 (6H, s, *o*-Me), 6.63 (2H, s, Mes-H), 6.70 (2H, s, Mes-H), 7.19–7.32 (5H, m, Ph). Small signals at δ 2.146, 2.196, 2.293, 2.327 and 2.335 were also observed.

Z-1,2-Dimesityl-2-phenylvinyl tosylate (*Z*-4-OTs)

A mixture of ***Z*-4-OH** (0.14 g, 0.39 mmol) and NaH (0.16 g, 6.7 mmol) in dry benzene (10 ml) was stirred at room temperature for 2 h, and tosyl chloride (0.09 g, 0.47 mmol) was then added to the mixture. After stirring for 2 h, TLC showed that **1-OH** was still present. More tosyl chloride (0.05 g, 0.27 mmol) was added and the reaction was complete within 20 min. The solid was filtered, washed with dry ether and the combined solutions were dried ($MgSO_4$). The solvent was removed and the remaining crude product was recrystallized from ether, giving the tosylate (0.18 g, 90%) as a white solid, m.p. 140–141 °C (dec.). ^{1}H NMR ($CDCl_3$) δ: 2.20 (6H, s, Me), 2.28, 2.35, 2.37 (3 × 3H, 3s, Me), 2.39 (6H, s, Me), 6.70 (2H, s, Mes-H), 6.87–6.90 (2H, m, Ar), 6.95 (2H, s, Mes-H), 7.02–7.07 (5H, m, Ph), 7.08–7.11 (2H, m, Ar). ^{13}C NMR ($CDCl_3$) δ: 20.67, 20.84, 21.18, 21.23, 21.65 (5 Me), 127.26, 127.42, 127.97, 128.41, 128.61, 128.80, 129.47, 131.74, 134.79, 134.96, 136.07, 136.40, 136.76, 138.75, 139.31, 143.69, 143.88 (18 Ar-C).

Anal. Found: C, 77.24; H, 6.76; S, 6.17. Calc. for $C_{33}H_{34}O_3S$: C, 77.60; H, 6.71; S, 6.28%.

Z-4-Br from the solvolysis of 1,2-dimesityl-2-phenylvinyl tosylate

A solution of 1,2-dimesityl-2-phenylvinyl tosylate (***Z*-4-OTs**), (150 mg, 0.29 mmol), LiBr (100 mg, 1.15 mmol), and tetrabutylammonium bromide (120 ml, 0.37 mmol) in acetonitrile (5 ml) was refluxed for 18 h, when TLC showed the complete disappearance of the tosylate and only one new spot for ***Z*-4-Br**. Water (3 ml) was added with stirring and the mixture was extracted with CCl_4 (2 × 2 ml). The organic phase was washed with water, dried (Na_2SO_4), the solvent was evaporated and column chromatography of the remaining solid over silica gel using petroleum ether (40–60 °C) eluent yielded 91 mg (74%) of ***Z*-4-Br**, m.p. 180–181 °C, having ^{1}H NMR data as reported above for the reaction with PBr_3.

Z-1,2-Dimesityl-2-phenylvinyl iodide (*Z*-4-I)

To a solution of 1,2-dimesityl-2-phenylvinyl tosylate (***Z*-4-OTs**, 30 mg, 0.177 mmol) in acetonitrile (10 ml), KI (90 mg, 0.54 mmol) was added and the mixture was refluxed for 26 h (when the reaction was complete according to TLC). Water (5 ml) was added with stirring and the mixture was extracted with CCl_4 (5 × 3 ml), dried (Na_2SO_4) and the solvent was evaporated. The residue was purified by chromatography on silica gel using petroleum ether (40–60 °C) as eluent, yielding pure ***Z*-4-I** (62 mg, 76%), m.p. 186–187 °C. ^{1}H NMR ($CDCl_3$) δ: 2.30 (3H, s, Me), 2.31 (6H, s, Me), 2.33 (6H, s, Me), 2.35 (3H, s, Me), 6.84–7.09 (9H, m, Ar).

Anal. Found: C, 66.57; H, 6.01. Calc. for $C_{26}H_{27}I$: C, 66.97; H, 5.79%.

Attempts to prepare the vinyl iodide by reacting ***Z*-4-OH** with iodine/imidazole in tetrahydrofuran or acetonitrile, or with Me_3SiCl/NaI (or KI) in CH_3CN or with Ph_3P/I_2 in CH_3CN failed.

The configuration was shown to be *Z* by X-ray crystallography.

Attempted *Z*-4-Br⇌*E*-4-Br isomerization

A solution of ***Z*-4-Br** (70 mg, 0.17 mmol) in acetonitrile (10 ml) containing anhydrous LiBr (120 mg, 1.38 mmol) was refluxed for 72 h. TLC of the mixture during and at the end of the reaction showed only the starting material.

A similar reaction mixture was refluxed in dimethylsulfoxide for 8 h with a similar conclusion. Only ***Z*-4-Br** was detected by TLC or after work-up of the reaction mixture.

Crystallographic data

***E*-4-Br**: $C_{26}H_{27}Br$; space group: $P2_1/c$; $a = 14.177(3)$ Å, $b = 14.308(3)$ Å, $c = 10.911(2)$ Å, $\beta = 98.18(1)°$; $V = 2191(1)$ Å^3; $Z = 4$; $\rho_{calc} = 1.27$ g cm^{-3}; μ(Mo Kα) = 18.63 cm^{-1}; no. of unique reflections: 4024; number of reflections with $I > 3\sigma_I$: 2121; $R = 0.054$, $R_W = 0.060$.

***Z*-4-Cl**: $C_{28}C_{27}Cl$; space group $P2_1/c$; $a = 8.937(2)$ Å, $b = 61.45(1)$ Å, $c = 8.458(3)$ Å, $\beta = 113.87(2)°$, $V = 4248(2)$ Å^3; $Z = 8$; $\rho_{calc} = 1.17$ g cm^{-3}; μ(Cu Kα) = 16.26 cm^{-1}; no. of unique reflections: 7106; no. of reflections with $I > 3\sigma_I$: 5704; $R = 0.049$, $R_W = 0.075$.

***Z*-4-Br**: $C_{26}H_{27}Br$; space group: $P2_1/n$; $a = 29.86(1)$ Å, $b = 8.560(6)$ Å, $c = 17.358(5)$ Å, $\beta = 104.59(3)°$; $V =$

4295(3) Å^3; $Z = 8$; $\rho_{calc} = 1.30$ g cm^{-3}; μ(Cu Kα) = 2368 cm^{-1}; no. of unique reflections: 6850; no. of unique reflections with $I > 3\sigma_I$: 5073; $R = 0.051$, $R_W = 0.069$.

***Z*-4-I**: $C_{26}H_{27}I$; space group: $P2_1/n$; $a = 30.323(9)$ Å, $b = 8.627(3)$ Å, $c = 17.410(4)$ Å, $\beta = 104.79(2)°$; $V =$ 4404(2) Å^3; $Z = 8$; $\rho_{calc} = 1.41$ g cm^{-3}; μ(Mo Kα) = 114.52 cm^{-1}; no. of unique reflections: 7072; no. of unique reflections with $I > 3\sigma_I$: 5238; $R = 0.048$, $R_W =$ 0.069.

***Z*-4-OTs**: $C_{33}H_{34}O_3S$; space group: $P2_1/n$; $a = 18.542(3)$ Å, $b = 8.769(2)$ Å, $c = 18.501(4)$ Å, $\beta =$ 107.81(2)°; $V = 2864(1)$ Å^3; $Z = 4$; $\rho_{calc} =$ 1.18 g cm^{-3}; μ(Cu Kα) = 12.02 cm^{-1}; no. of unique reflections: 4166; no. of unique reflections with $I > 3\sigma_I$: 4166; $R = 0.039$.

Supplementary material available

Tables S1–S25 of crystal structure analysis, bond lengths, bond angles, position and thermal parameters of all compounds. Stereoviews of five compounds and ORTEP drawings of ***Z*-4-Cl** and the second molecules of ***Z*-4-I** and ***Z*-4-Br** (S1–S8) were deposited in the Cambridge Structural Database.

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