[3+2] Cycloaddition of Phenyliodonium Bis(arylsulfonyl)methylides with α,β-Enones

Waldemar Adam,[a,b] Efstathios P. Gogonas,[a,c] Ioannis A. Nyxas,[c] Lazaros P. Hadjiarapoglou*[c]

[a] Institute of Organic Chemistry, University of Würzburg, Am Hubland, 97074 Würzburg, Germany

[b] Department of Chemistry, Facundo Bueso 110, University of Puerto Rico, Rio Piedras, Puerto Rico 00931, USA

[c] Section of Organic Chemistry and Biochemistry, Department of Chemistry, University of Ioannina, 45110 Ioannina, Greece
Fax +30(26510)98799; E-mail: lxatziar@uoi.gr

Received 11 July 2007; revised 23 July 2007

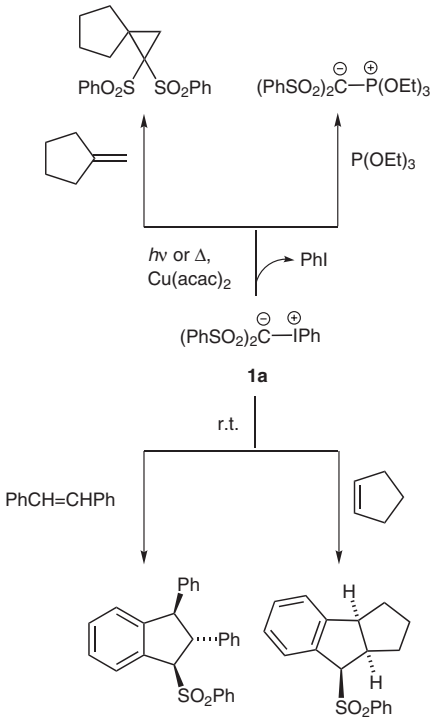
Abstract: The [3+2] cycloaddition of phenyliodonium bis(arylsulfonyl)methylides to α,β-enones affords exclusively *trans*,*trans*-configured 1-(arylsulfonyl)-2-aroyl-3-arylindanes. The initial electrophilic attack of the iodonium ylide on the alkenyl double bond of the chalcone, followed by cyclization of the dipolar species, and subsequent ejection of iodobenzene and sulfur dioxide, stereoselectively affords the indane cycloadduct.

Key words: iodonium ylide, chalcones, diastereoselectivity, regioselectivity, 1,2,3-trisubstituted indanes

Phenyliodonium bis(arylsulfonyl)methylides **1**[1] constitute a class of compounds with unique properties among the iodonium ylides (Scheme 1). Under photochemical or $Cu(acac)_2$-catalyzed thermal activation, an iodonium bis(sulfonyl)methylide reacts with simple alkenes to give the corresponding cyclopropanes,[1] and with various heteroatom nucleophiles to provide new ylides,[1,2] presumably through a carbene (or carbenoid) pathway. At room temperature, however, an unusual [3+2] cycloaddition occurs, in which a 1,2,3-trisubstituted indane is produced. For example, various acyclic 1,2-disubstituted alkenes, either *Z*- or *E*-configured, lead to the *trans*,*trans*-indane cycloadducts,[3] whereas cyclic alkenes yield the *cis*,*cis*-stereoisomers[4] (Scheme 1). This reactivity is explained by postulating an initial electrophilic attack of the ylide on to the alkenyl double bond, followed by cyclization to the [3+2] cycloadduct.

This perplexing chemical behavior poses the mechanistic question, whether an iodonium bis(sulfonyl)methylide reacts initially as a nucleophile in view of its stabilized carbanionic center, as an electrophile through its positively charged iodonium center, and/or as a carbene (or carbenoid) precursor by cleavage of iodobenzene. The incentive of the present study was to distinguish between these mechanistic options by examining the reaction of the iodonium bis(sulfonyl)methylides with α,β-enones.

In α,β-enones, which are widely distributed in nature, the carbonyl group decreases the electron density of the olefinic double bond. Thus, while the carbonyl and the β-ethylenic carbon atoms are activated toward nucleophilic attack, the alkenyl double bond should be less susceptible to electrophilic attack. Nevertheless, it is well known that α,β-enones react with a variety of stable ylides to yield cyclopropanes;[5] adducts are formed as well with rather mild electrophiles[6] and diazo compounds.[7] If the iodonium ylide should react initially as a nucleophile, then attack at the β-ethylenic carbon atom of the α,β-enone would produce an enolate, which on subsequent intramolecular ring closure with ejection of iodobenzene should afford a cyclopropane product. Such a reaction type is known as a Michael-induced ring closure,[5] observed in the reaction of α,β-enones with sulfur and phosphorus ylides. The same cyclopropane cycloadduct would also result if the iodonium bis(sulfonyl)methylide should serve as a carbene (or carbenoid) source. In contrast, if the iodonium bis(sulfonyl)methylide should react initially as an electrophile by attacking the α-ethylenic carbon atom of the α,β-enone, indane derivatives should be formed by [3+2] cycloaddition, as observed for the simple alkenes.[3,4]

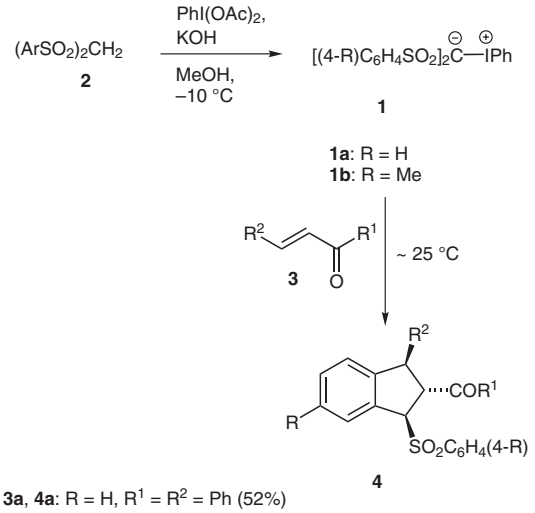


Scheme 1 Cycloaddition modes for a phenyliodonium bis(arylsulfonyl)methylide with alkenes

SYNTHESIS 2007, No. 20, pp 3211–3218
Advanced online publication: 21.09.2007
DOI: 10.1055/s-2007-990801; Art ID: Z16507SS

Indeed, we report here that the reaction of iodonium bis(sulfonyl)methylides **1** with a variety of α,β-enones affords, in moderate yields, 1,2,3-trisubstituted indanes **4** with the *trans*,*trans* configuration. Given that the sulfonyl substituent may be reductively cleaved or appropriately modified through established[8] carbanion methodology, the present cycloaddition constitutes a potentially valuable synthetic method for the construction of 2-aroylindane derivatives.[9]

The iodonium bis(sulfonyl)methylides **1** were prepared,[5] in analytically pure form, by condensation of the corresponding disulfones **2** with iodobenzene diacetate and potassium hydroxide as base at –10 °C (Scheme 2). These ylides were stored at –30 °C for a few weeks without significant decomposition. They are practically insoluble in common organic solvents (except DMSO), so that their reactions were conducted under heterogeneous conditions.



3a, **4a**: R = H, $R^1 = R^2$ = Ph (52%)
3a, **4b**: R = Me, $R^1 = R^2$ = Ph (77%)
3b, **4c**: R = H, R^1 = Me; R^2 = Ph (18%)
3c, **4d**: R = Me, R^1 = MeO; R^2 = Ph (33%)
3d, **4e**: R = H, R^1 = 4-MeC_6H_4; R^2 = Ph (54%)
3d, **4f**: R = Me, R^1 = 4-MeC_6H_4; R^2 = Ph (41%)
3e, **4g**: R = H, R^1 = 4-$MeOC_6H_4$; R^2 = Ph (49%)
3e, **4h**: R = Me, R^1 = 4-$MeOC_6H_4$; R^2 = Ph (33%)
3f, **4i**: R = H, $R^1 = R^2$ = 4-$MeOC_6H_4$ (10%)
3g, **4j**: R = H, $R^1 = R^2$ = 4-MeC_6H_4 (28%)
3h, **4k**: R = H, R^1 = (2-HO)(5-Cl)C_6H_3; R^2 = Ph (22%)

Scheme 2 Preparation of methylides **1** and their cycloaddition with α,β-enones **3**

When a suspension of ylide **1a** in acetonitrile was heated at reflux for two hours, the formation of iodobenzene and the disulfone **2a** was observed. Under similar reaction conditions, but in the presence of a catalytic amount of $Cu(acac)_2$, sulfur dioxide was detected, and the disulfone **2a** and *S*-phenyl benzenesulfonothioate ($PhSO_2SPh$) were obtained in 22% and 54% yield, respectively. In the presence of $Rh_2(OAc)_4$, however, only the disulfone **2a** was produced in 58% yield. Sulfur dioxide and $PhSO_2SPh$ are decomposition products obtained from the labile bis(phenylsulfonyl)methylene.[1,10]

All the reactions of the ylides **1** with the α,β-enones **3** were run with an excess of the α,β-enone until complete consumption of the ylide, as indicated by the dissolution of the heterogeneous mixture to a clear solution (Scheme 2). Furthermore, all the reactions of ylide **1a** with the α,β-enones **3** were carried out in the presence of a catalytic amount of $Rh_2(OAc)_4$ to shorten the reaction time. Without the metal catalyst, longer reaction times are required, but the same product composition is obtained. In contrast, all the reactions of ylide **1b** with the chalcones ran faster and were carried out in the absence of $Rh_2(OAc)_4$. The indanes **4** were isolated in moderate yields after flash chromatography on silica gel (Table 1).

The initial experiments were performed with the ylides **1** and chalcone **3a**. Treatment of ylide **1a** with chalcone **3a** in acetonitrile and a catalytic amount of $Rh_2(OAc)_4$ furnished the indane **4a** in 52% yield (Table 1, entry 1). Similarly, the reaction of ylide **1b** with the same chalcone **3a** in dichloromethane was much faster, even without any catalytic amounts of $Rh_2(OAc)_4$, giving the analogous indane derivative **4b** as a single diastereomer in 77% yield (Table 1, entry 2). The *para*-methyl substituent of the arylsulfonyl moiety in ylide **1b** allowed us to assess which aryl group (the ylide or the chalcone) is the source of the aryl ring in the indane cycloadduct. Also, it was possible to determine the regioselectivity of the cycloaddition process with regard to the location of the methyl group in the benzo ring of the indane product.

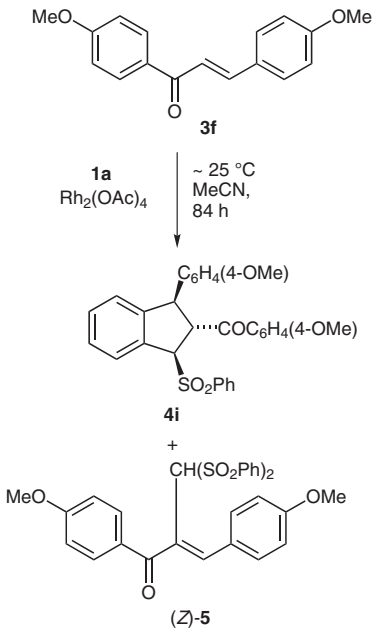
Replacement of the aroyl functionality of the chalcone by an acetyl or an ester group lowered the reactivity of the enone toward the ylides **1**. For example, the reaction of ylide **1a** with (*E*)-4-phenylbut-3-en-2-one (**3b**) gave indane **4c** in 18% yield (Table 1, entry 3), while ylide **1b** with methyl cinnamate (**3c**) afforded indane **4d** in 33% yield (Table 1, entry 4). Introduction of an electron-donating substituent in the aroyl functionality of the chalcone increases the reactivity of the enone toward the ylides **1**. Thus, the reaction of ylide **1a** with chalcones **3d** and **3e** (Table 1, entries 5, 7) gave the indanes **4e** (54% yield) and **4g** (49% yield), whereas ylide **1b** with chalcones **3d** and **3e** (Table 1, entries 6, 8) afforded indanes **4f** (41% yield) and **4h** (33% yield).

It should be noted that a clean process operates, except that a substantial amount of the ylide is diverted to the disulfone **2** through thermal decomposition. Introduction of an electron-donating substituent in the aryl functionality of the chalcone molecule results, however, in alkene byproduct, together with the desired indane **4**. Evidently, reaction of iodonium ylide **1a** with chalcone **3f** furnishes, after the usual workup and silica gel chromatography, the *Z*-alkene (*Z*)-**5** in 34% yield, along with the indane cycloadduct **4i** in 10% yield (Scheme 3; Table 1, entry 9). Although the *Z*-alkene (*Z*)-**5** was isolated in pure form after silica gel chromatography, it readily isomerizes in solution to a 60:40 mixture of the *Z*- and *E*-diastereomers.

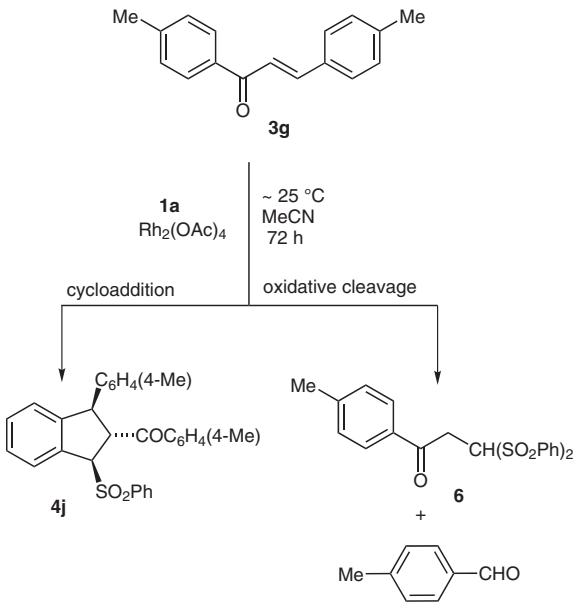
Table 1 Reactions of Iodonium Bis(arylsulfonyl)methylides **1** with α,β-Enones **3**[a]

Entry	Ylide	α,β-Enone	R	R^1	R^2	Time[b] (h)	Product(s) [Yield[c] (%)]
1	**1a**	**3a**	H	Ph	Ph	62	**4a** (52)
2	**1b**	**3a**	Me	Ph	Ph	12	**4b** (77)
3	**1a**	**3b**	H	Me	Ph	84	**4c** (18)
4	**1b**	**3c**	Me	MeO	Ph	48	**4d** (33)
5	**1a**	**3d**	H	4-MeC_6H_4	Ph	18	**4e** (54)
6	**1b**	**3d**	Me	4-MeC_6H_4	Ph	12	**4f** (41)
7	**1a**	**3e**	H	4-$MeOC_6H_4$	Ph	132	**4g** (49)
8	**1b**	**3e**	Me	4-$MeOC_6H_4$	Ph	12	**4h** (33)
9	**1a**	**3f**	H	4-$MeOC_6H_4$	4-$MeOC_6H_4$	84	**4i** (10), (*Z*)-**5** (34)
10	**1a**	**3g**	H	4-MeC_6H_4	4-MeC_6H_4	72	**4j** (28), **6** (36)
11	**1a**	**3h**	H	2-HO-5-ClC_6H_3	Ph	16	**4k** (22), **7** (67)

[a] All reactions were carried out by stirring a suspension of the ylide **1** (0.37–1.00 mmol) and the α,β-enone **3** (0.90–6.20 mmol) in CH_2Cl_2 or MeCN (5–10 mL) in the presence of a catalytic amount of $Rh_2(OAc)_4$ (only for ylide **1a**) at room temperature (ca. 25 °C).
[b] Time required for the complete consumption of the ylide **1**.
[c] Yield of isolated pure product after column chromatography on silica gel.



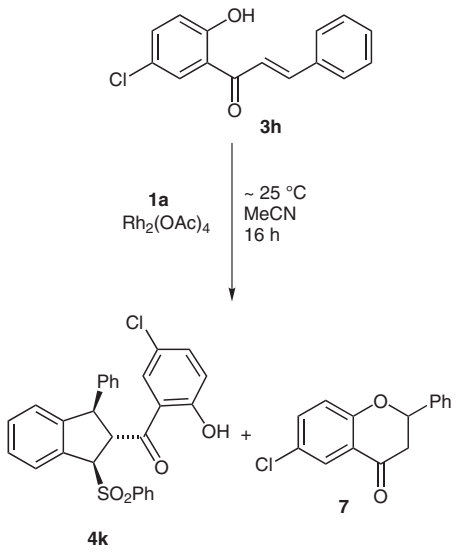
Scheme 3 Cycloadduct **4i** and insertion product (*Z*)-**5** in the reaction of enone **3f** with methylide **1a**



Scheme 4 Cycloadduct **4j** and oxidative cleavage product **6** in the reaction of enone **3g** with methylide **1a**

When ylide **1a** was allowed to react with chalcone **3g**, after the usual workup and silica gel chromatography, indane **4j** was isolated in 28% yield, along with propanone **6** (36%) and significant amounts of 4-methylbenzaldehyde (Scheme 4; Table 1, entry 10). Presumably, propanone **6** and 4-methylbenzaldehyde result from the oxidative cleavage of either the corresponding *Z*-alkene or its labile precursor intermediate.

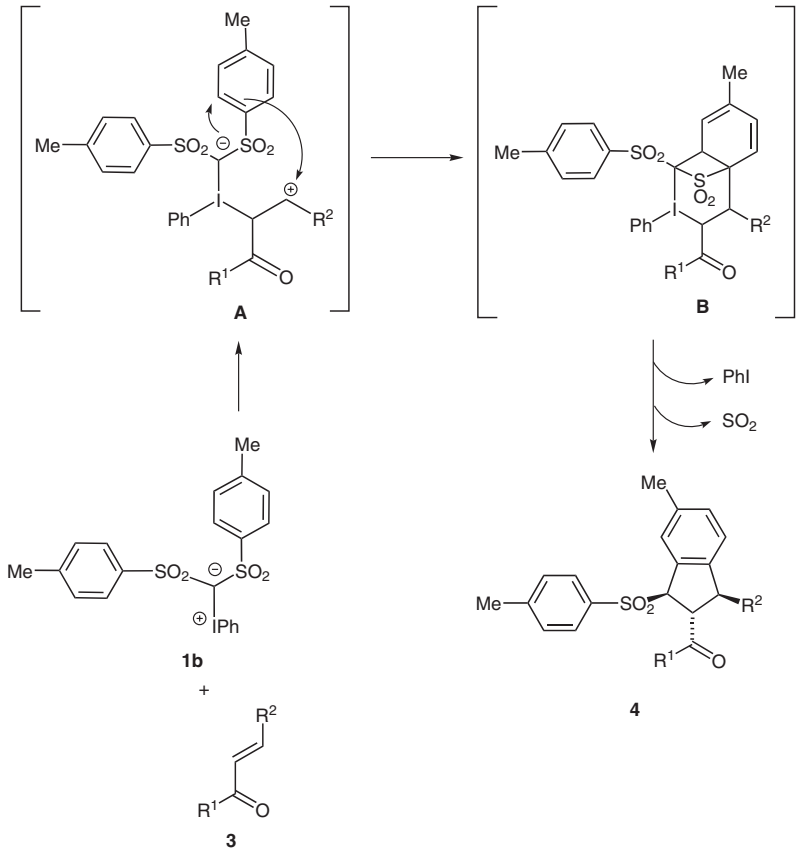
The introduction of a hydroxy substituent in the aroyl group of the chalcone molecule leads to the corresponding flavanone, together with the desired indane cycloadduct, but in a much lower yield. Thus, the reaction of iodonium ylide **1a** with 2-hydroxychalcone **3h** in the presence of a catalytic amount of $Rh_2(OAc)_4$ gave, after the usual workup and silica gel chromatography, the flavanone **7** (67% yield) and the indane derivative **4k** in only 22% yield (Scheme 5; Table 1, entry 11).



Scheme 5 Cycloadduct **4k** and cyclization product **7** in the reaction of enone **3h** with methylide **1a**

The structural assignment of the indanes is exemplified for the **4b** derivative. Its ^{1}H NMR spectrum displays a doublet signal at δ = 4.15 with J = 7.8 Hz for the proton at C-3, a triplet at δ = 4.48 with J = 7.6 Hz for the proton at C-2, and a doublet at δ = 5.65 with J = 7.2 Hz for the proton at the sulfonyl-bearing C-1 position. The lack of a ROESY signal between the protons at the C-1 and C-2 positions and the protons at the C-2 and C-3 positions, as well as the values of the coupling constants,[3,4] indicate the *trans*,*trans* configuration of the three substituents in the five-membered ring. 2-D NMR studies of this cycloadduct reveal that the methyl group of the fused aryl ring and the sulfonyl-bearing C-1 position of the five-membered ring are located *meta* to one another in the indane product, although originally this methyl substituent occupied the *para*-position in the *p*-tolylsulfonyl group of the iodonium ylide.

In regard to the mechanism for this [3+2] cycloaddition, the exact role of the $Rh_2(OAc)_4$ catalyst is unclear; palladium complexes have the same effect of enhancing the rate of the cycloaddition. The formation of bis(phenylsulfonyl)methylene is evidenced[1,10] by the isolation of *S*-phenyl benzenesulfonothioate ($PhSO_2SPh$) and the detection of sulfur dioxide. This is corroborated by the independent $Cu(acac)_2$-catalyzed thermal decomposition of iodonium ylide **1a**, which yields disulfone **2a** and bis(phenylsulfonyl)methylene, the latter again indicated by the *S*-phenyl benzenesulfonothioate and sulfur dioxide products. The analogous $Rh_2(OAc)_4$-catalyzed thermal decomposition affords, however, exclusively the disulfone **2a**. Besides, had a cyclopropane product been generated by carbene (or carbenoid) addition to the α,β-enone, it should have been sufficiently persistent for isolation. Such a cyclopropane cycloadduct, instead of rearranging into the isolated indane derivative, would be expected to undergo dipolar ring opening, reclosure and aromatization to afford a 2-benzoyl-1,1-bis(sulfonyl)indane. The benzo ring would



Scheme 6 Mechanism of formation of the indane cycloadducts **4** in the reaction of enones **3** with methylide **1b**

stem from the alkene partner and not, as observed, from the ylide.

As for a Michael-type nucleophilic addition of the carbanionic carbon atom of the iodonium bis(sulfonyl)methylide to the enone partner, this negatively charged center is only weakly nucleophilic due to the electron-withdrawing sulfonyl and the phenyliodonio groups. Moreover, the severe steric hindrance of this site should render the nucleophilic addition of the iodonium ylide to the chalcone as unlikely. The fact that the reaction of phenyliodonium bis(phenylsulfonyl)methylide (**1a**) with triethyl phosphite gives a persistent triethoxyphosphonium ylide[2a] (Scheme 1) indicates that these ylides are electrophilic rather than nucleophilic in their chemical behavior.

In accord with our previously proposed mechanism for the [3+2] cycloaddition with simple alkenes,[3,4] the current results support the mechanistic scenario displayed in Scheme 6 for the reaction between ylide **1b** and chalcones **3**. The dipolar species **A** may be generated directly by electrophilic attack of the iodonium ylide on the chalcone. This dipolar intermediate is expected[11] to have a T-shaped geometry for the trivalent iodine functionality, which prevents the ring closure to a four-membered cyclic iodinane. Instead, nucleophilic attack by the bis(sulfonyl)-substituted carbanion on the *ortho*-position of the phenylsulfonyl ring and closure of the resulting dipole leads to iodinane **B**. Such a nucleophilic attack constitutes the initial step of the Truce–Smiles rearrangement,[12] observed in carbanions of diaryl sulfones with an *ortho*-methyl group. Elimination of iodobenzene from the iodinane **B**, followed by sulfur dioxide extrusion, or vice versa, and subsequent aromatization by a hydrogen atom shift affords the observed indane products **4**.

When an electron-donating substituent, i.e. a methyl or a methoxy group, exists in the aryl moiety of the chalcone, then the positive charge in the intermediate **A** is delocalized into the aryl ring, which reduces the electrophilic character at the benzyl carbon. Presumably, the cycloaddition proceeds slower and side reactions may compete, e.g. hydrogen abstraction and iodobenzene elimination to afford the alkene (*Z*)-**5** as insertion product (Scheme 3), or oxidative degradation of intermediate **A** to generate propanone **6** and 4-methylbenzaldehyde (Scheme 4).

In summary, we have demonstrated that the unprecedented diastereoselective formation of functionalized 1,2,3-trisubstituted indanes is quite general, by extending the [3+2] cycloaddition of iodonium bis(arylsulfonyl)methylides also to the electron-deficient α,β-enones. Although the yields are moderate for this direct process, to prepare such *trans*,*trans*-configured 1,2,3-trisubstituted indanes **4** would be considerably more cumbersome by alternative existing synthetic methodology.

Melting points (uncorrected) were determined on a Buchi B-510 apparatus. For the IR spectra, a Perkin–Elmer 257 ratio recording IR spectrophotometer was used. ^{1}H and ^{13}C NMR spectra were recorded on Bruker AMX 250 and Bruker Avance 400 instruments. Mass spectra were carried out on a Finnigan MAT 8200 spectrometer; exact masses were determined on a Finnigan MAT 90 spectrometer. Elemental analyses were carried out by the Microanalytical Division of the Institute of Inorganic Chemistry, University of Würzburg. TLC analysis was conducted on precoated silica gel glass plates from Merck, Darmstadt, Germany. The spots were visualized either by UV irradiation (254 nm) or with a 5% polymolybdic acid solution in EtOH. Silica gel (0.040–0.063 μm) from Merck, Darmstadt, Germany was used for flash column chromatography. All commercial reagents were used without further purification. Solvents were dried by standard methods and purified by distillation before use. Iodonium ylides **1**[1] and chalcones **3**[13] were synthesized following the literature procedures.

Thermal Decomposition of Ylide 1a Catalyzed by Cu(acac)$_2$

A suspension of phenyliodonium bis(phenylsulfonyl)methylide (**1a**; 0.50 g, 1.0 mmol) and a catalytic amount of Cu(acac)$_2$ (1.0 mg) in MeCN (10 mL) was refluxed for 12 min (clear soln). The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2) to afford *S*-phenyl benzenesulfonothioate[14] (135 mg, 54%) as a colorless oil, and bis(phenylsulfonyl)methane[15] (**2a**; 65.0 mg, 22%) as colorless needles.

Thermal Decomposition of Ylide 1a Catalyzed by Rh$_2$(OAc)$_4$

A suspension of phenyliodonium bis(phenylsulfonyl)methylide (**1a**; 0.50 g, 1.0 mmol) and a catalytic amount of $Rh_2(OAc)_4$ (1.0 mg) in MeCN (10 mL) was refluxed for 8 h. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2) to afford bis(phenylsulfonyl)methane (**2a**; 172 mg, 58%) as colorless needles.

Reaction of the Ylides 1 with the Enones 3; General Procedure

A suspension of an iodonium ylide **1** (0.37–1.0 mmol) and an α,β-enone **3** (0.90–6.2 mmol) in MeCN or CH_2Cl_2 (5–10 mL) in the presence of a catalytic amount of $Rh_2(OAc)_4$ (0.1–0.2 mol%) was stirred at r.t. for 12–132 h. The solvent was evaporated (20 °C/15 Torr) and the residue was flash-chromatographed on silica gel to afford the indane derivative **4**, and in some cases the side products **5**, **6**, and **7**.

Reaction of Ylide 1a with Chalcone 3a

A suspension of ylide **1a** (0.50 g, 1.0 mmol) and (*E*)-1,3-diphenylprop-2-en-1-one (**3a**; 0.58 g, 2.78 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (10 mL) was stirred for 62 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield phenyl[1-phenyl-3-(phenylsulfonyl)indan-2-yl]methanone[3] (**4a**; 220 mg, 52%) as colorless needles; mp 150–151 °C ($CHCl_3$–PE).

Indane **4a** was also isolated (210 mg, 48%) as colorless needles by following the above general procedure, in which a mixture of the ylide **1a** (0.5 g, 1.0 mmol) and (*E*)-1,3-diphenylprop-2-en-1-one (**3a**; 0.58 g, 2.78 mmol) in CH_2Cl_2 (10 mL) was stirred for 162 h.

Reaction of Ylide 1b with Chalcone 3a

A suspension of ylide **1b** (0.53 mg, 1.0 mmol) and (*E*)-1,3-diphenylprop-2-en-1-one (**3a**; 1.0 g, 4.8 mmol) in CH_2Cl_2 (10 mL) was stirred for 12 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield [5-methyl-1-phenyl-3-(4-tolylsulfonyl)indan-2-yl](phenyl)methanone (**4b**; 360 mg, 77%) as colorless needles; mp 187–189 °C (EtOH).

IR (KBr): 3053, 1678, 1595, 1491, 1450, 1362, 1316, 1300, 1240, 1220, 1179, 1148, 1085, 1000, 976, 935, 910, 886, 810, 781, 751, 718 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 2.24 (s, 3 H), 2.38 (s, 3 H), 4.15 (d, *J* = 7.8 Hz, 1 H), 4.48 (t, *J* = 7.6 Hz, 1 H), 5.65 (d, *J* = 7.2 Hz, 1

H), 6.69 (d, *J* = 7.9 Hz, 1 H), 6.70–6.89 (m, 2 H), 7.01–7.25 (m, 10 H), 7.37–7.43 (m, 1 H), 7.58–7.61 (m, 3 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 21.3 (+), 21.4 (+), 56.1 (+), 57.6 (+), 71.6 (+), 125.1 (+), 126.4 (+), 127.3 (+), 128.0 (+), 128.6 (+), 128.7 (+), 128.9 (+), 129.0 (+), 129.6 (+), 130.7 (+), 133.3 (+), 134.0, 134.3, 135.5, 137.9, 142.6, 143.2, 144.7, 198.6.

Anal. Calcd for $C_{30}H_{26}O_3S$ (466.16): C, 77.22; H, 5.62; S, 6.97. Found: C, 77.10; H, 5.55; S, 6.95.

Reaction of Ylide 1a with α,β-Enone 3b

A suspension of ylide **1a** (0.5 g, 1.0 mmol) and (*E*)-4-phenylbut-3-en-2-one (**3b**; 0.35 g, 2.4 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (10 mL) was stirred for 84 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield 1-[1-phenyl-3-(phenylsulfonyl)indan-2-yl]ethanone (**4c**; 67.0 mg, 18%) as colorless needles; mp 115–116 °C ($CHCl_3$–PE).

IR (KBr): 2940, 1760, 1470, 1390, 1375, 1335, 1310, 1245, 1230, 1205, 1180, 1150, 1105, 1095, 1040, 1015, 830, 780, 745 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.98 (s, 3 H), 3.76 (t, *J* = 7.4 Hz, 1 H), 4.25 (d, *J* = 7.4 Hz, 1 H), 5.48 (d, *J* = 7.4 Hz, 1 H), 6.78 (d, *J* = 7.4 Hz, 1 H), 6.93–6.95 (m, 2 H), 7.25–7.33 (m, 5 H), 7.50–7.53 (m, 2 H), 7.64–7.69 (m, 2 H), 7.82–7.84 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 30.3 (q), 54.3 (d), 61.9 (d), 70.4 (d), 125.4 (d), 126.0 (d), 127.5 (d), 128.0 (d), 128.3 (d), 129.0 (d), 129.2 (d), 129.5 (d), 129.8 (d), 133.5 (s), 134.0 (d), 137.1 (s), 142.9 (s), 145.9 (s), 205.3 (s).

HRMS [CI (NH_3)]: *m*/*z* [M + NH_4]$^+$ calcd for $C_{23}H_{20}O_3S{\cdot}NH_4^+$: 394.1477; found: 394.1481.

Reaction of Ylide 1b with α,β-Enone 3c

A suspension of ylide **1b** (0.53 g, 1.0 mmol) and methyl cinnamate (**3c**; 1.0 g, 6.2 mmol) in CH_2Cl_2 (5 mL) was stirred for 48 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield methyl 5-methyl-1-phenyl-3-(4-tolylsulfonyl)indane-2-carboxylate (**4d**; 140 mg, 33%) as colorless needles; mp 99–103 °C (PE).

IR (KBr): 3066, 3032, 1735, 1596, 1493, 1440, 1378, 1340, 1299, 1240, 1130, 1083, 1041, 1008, 979, 889, 854, 830, 813 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 2.41 (s, 3 H), 2.42 (s, 3 H), 3.46 (t, *J* = 7.4 Hz, 1 H), 3.53 (s, 3 H), 4.38 (d, *J* = 7.5 Hz, 1 H), 5.35 (d, *J* = 7.2 Hz, 1 H), 6.73 (d, *J* = 7.8 Hz, 1 H), 6.86–6.90 (m, 2 H), 7.10–7.27 (m, 6 H), 7.65–7.71 (m, 3 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 21.2 (+), 21.5 (+), 52.2 (+), 54.4 (+), 55.1 (+), 71.4 (+), 125.0 (+), 126.4 (+), 127.1 (+), 128.0 (+), 128.5 (+), 129.5 (+), 129.6 (+), 130.6 (+), 133.6, 133.7, 137.8, 142.6, 142.7, 144.8, 172.6.

Anal. Calcd for $C_{25}H_{24}O_4S$ (420.14): C, 71.40; H, 5.75; S, 7.63. Found: C, 71.60; H, 5.65; S, 7.55.

Reaction of Ylide 1a with Chalcone 3d

A suspension of ylide **1a** (0.187 g, 0.37 mmol) and (*E*)-3-phenyl-1-(4-tolyl)prop-2-en-1-one (**3d**; 0.20 g, 0.90 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (5 mL) was stirred for 18 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield [1-phenyl-3-(phenylsulfonyl)indan-2-yl](4-tolyl)methanone (**4e**; 92.0 mg, 54%) as colorless plates; mp 127–129 °C ($CHCl_3$–PE).

IR (KBr): 3130, 3100, 1710, 1640, 1505, 1470, 1435, 1325, 1265, 1200, 1165, 1100, 1015, 935, 905, 840, 775 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.21 (s, 3 H), 4.10 (d, *J* = 7.7 Hz, 1 H), 4.41–4.45 (m, 1 H), 5.65 (d, *J* = 7.1 Hz, 1 H), 6.71 (d, *J* = 7.6 Hz, 1 H), 6.76 and 6.88 (AA′BB′ system, 4 H), 7.07–7.26 (m, 10 H), 7.66–7.72 (m, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.5 (q), 56.3 (d), 56.9 (d), 71.5 (d), 125.5 (d), 126.0 (d), 127.4 (d), 128.0 (d), 128.6 (d), 128.7 (d), 128.9 (d), 129.0 (d), 129.1 (d), 129.2 (d), 129.7 (d), 130.5 (d), 133.0 (s), 134.0 (s), 142.5 (s), 142.6 (s), 144.4 (s), 146.2 (s), 197.8 (s).

HRMS [CI (NH_3)]: *m*/*z* [M + NH_4]$^+$ calcd for $C_{29}H_{24}O_3S{\cdot}NH_4^+$: 470.1790; found: 470.1787.

Reaction of Ylide 1b with Chalcone 3d

A suspension of ylide **1b** (0.53 g, 1.0 mmol) and (*E*)-3-phenyl-1-(4-tolyl)prop-2-en-1-one (**3d**; 0.68 g, 3.1 mmol) in CH_2Cl_2 (10 mL) was stirred for 12 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield [5-methyl-1-phenyl-3-(4-tolylsulfonyl)indan-2-yl](4-tolyl)methanone (**4f**; 200 mg, 41%) as colorless needles; mp 196–199 °C (EtOH).

IR (KBr): 3049, 1678, 1595, 1491, 1448, 1382, 1316, 1299, 1238, 1147, 1110, 1085, 1022, 979, 891, 840, 814, 776, 716 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 2.26 (s, 3 H), 2.32 (s, 3 H), 2.40 (s, 3 H), 4.15 (d, *J* = 7.5 Hz, 1 H), 4.49 (t, *J* = 7.5 Hz, 1 H), 5.68 (d, *J* = 7.2 Hz, 1 H), 6.71 (d, *J* = 7.9 Hz, 1 H), 6.78 and 7.01 (AA′BB′ system, 4 H), 7.05 and 7.62 (AA′BB′ system, 4 H), 7.09–7.67 (m, 6 H), 7.94–8.00 (m, 1 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 21.0, 21.3, 21.4, 55.7, 57.5, 71.6, 125.0, 126.3, 127.9, 128.4, 128.7, 129.0, 129.3, 129.5, 130.6, 133.2, 133.9, 134.3, 135.5, 136.9, 137.8, 139.6, 143.4, 144.7, 198.7.

Anal. Calcd for $C_{31}H_{28}O_3S$ (480.18): C, 77.47; H, 5.87; S, 6.67. Found: C, 77.20; H, 5.85; S, 6.75.

Reaction of Ylide 1a with Chalcone 3e

A suspension of ylide **1a** (0.436 g, 0.87 mmol) and (*E*)-1-(4-methoxyphenyl)-3-phenylprop-2-en-1-one (**3e**; 0.50 g, 2.10 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (10 mL) was stirred for 132 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield (4-methoxyphenyl)[1-phenyl-3-(phenylsulfonyl)indan-2-yl]methanone (**4g**; 201 mg, 49%) as colorless plates; mp 149–150 °C ($CHCl_3$–PE).

IR (KBr): 1715, 1635, 1610, 1540, 1515, 1475, 1440, 1365, 1330, 1275, 1260, 1235, 1195, 1160, 1130, 1100, 1030, 1005, 890, 860, 845, 775 cm^{-1}.

^{1}H NMR (250 MHz, $CDCl_3$): δ = 3.80 (s, 3 H), 4.21 (d, *J* = 7.5 Hz, 1 H), 4.46–4.53 (m, 1 H), 5.76 (d, *J* = 7.5 Hz, 1 H), 6.66 (d, *J* = 9.0 Hz, 2 H), 6.81–6.91 (m, 3 H), 7.16–7.51 (m, 10 H), 7.76–7.84 (m, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 55.3 (+), 56.3 (+), 56.6 (+), 71.4 (+), 113.6 (+), 125.8 (+), 126.3 (+), 127.7 (+), 128.3 (+), 128.8, 129.0 (+), 129.1 (+), 129.3 (+), 129.5 (+), 130.0 (+), 131.6 (+), 134.1 (+), 134.4, 137.7, 143.0, 146.6, 164.4, 197.3.

HRMS (EI): *m*/*z* [M$^+$] calcd for $C_{29}H_{24}O_4S$: 468.1395; found: 468.1391.

Reaction of Ylide 1b with Chalcone 3e

A suspension of ylide **1b** (0.53 g, 1.0 mmol) and (*E*)-1-(4-methoxyphenyl)-3-phenylprop-2-en-1-one (**3e**; 1.0 g, 4.2 mmol) in CH_2Cl_2 (10 mL) was stirred for 12 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield (4-methoxyphenyl)[5-methyl-1-phenyl-3-(4-tolylsulfonyl)indan-2-yl]meth-

anone (**4h**; 170 mg, 33%) as colorless needles; mp 195–197 °C (EtOH).

IR (KBr): 3063, 3027, 1665, 1596, 1572, 1494, 1453, 1361, 1295, 1264, 1242, 1171, 1094, 1027, 898, 881, 820, 767, 707 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 2.27 (s, 3 H), 2.40 (s, 3 H), 3.80 (s, 3 H), 4.17 (d, *J* = 7.5 Hz, 1 H), 4.44 (t, *J* = 7.5 Hz, 1 H), 5.67 (d, *J* = 7.5 Hz, 1 H), 6.62–6.72 (m, 3 H), 6.88–6.92 (m, 2 H), 7.05–7.23 (m, 8 H), 7.60–7.66 (m, 3 H).

^{13}C NMR (63 MHz, $CDCl_3$): δ = 21.4 (+), 21.5 (+), 55.4 (+), 56.2 (+), 57.3 (+), 71.7 (+), 113.2 (+), 125.1 (+), 126.5 (+), 127.3 (+), 128.69 (+), 128.71 (+), 128.8, 129.1 (+), 129.6 (+), 130.7 (+), 131.2 (+), 134.3, 134.5, 137.9, 142.9, 143.3, 144.7, 163.8, 196.9.

Anal. Calcd for $C_{31}H_{28}O_4S$ (496.17): C, 74.97; H, 5.68; S, 6.46. Found: C, 74.80; H, 5.40; S, 6.35.

Reaction of Ylide 1a with Chalcone 3f

A suspension of ylide **1a** (0.40 g, 0.8 mmol) and (*E*)-1,3-bis(4-methoxyphenyl)prop-2-en-1-one (**3f**; 0.50 g, 1.87 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (10 mL) was stirred for 84 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield (*Z*)-2-[bis(phenylsulfonyl)methyl]-1,3-bis(4-methoxyphenyl)prop-2-en-1-one [(*Z*)-**5**; 152 mg, 34%] as white needles; mp 179–181 °C ($CHCl_3$–PE).

IR (KBr): 1625, 1595, 1530, 1465, 1350, 1330, 1275, 1185, 1175, 1160, 1090, 1040, 770 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 3.70 (s, 3 H), 3.72 (s, 3 H), 5.74 (s, 1 H), 6.58 and 6.87 (AA′BB′ system, 4 H), 6.62 and 7.95 (AA′BB′ system, 4 H), 7.50–7.72 (m, 8 H), 7.94 (s, 2 H), 8.08 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 55.1, 55.2, 83.5, 113.6, 113.8, 121.3, 127.3, 128.6, 129.3, 130.1, 132.1, 132.7, 134.9, 138.9, 144.9, 161.9, 163.9, 195.4.

Anal. Calcd for $C_{30}H_{26}O_7S_2$ (562.11): C, 64.04; H, 4.66; S, 11.40. Found: C, 64.10; H, 4.88; S, 11.45.

Reaction of Ylide 1a with Chalcone 3g

A suspension of ylide **1a** (0.50 g, 1.0 mmol) and (*E*)-1,3-di(4-tolyl)prop-2-en-1-one (**3g**; 0.57 g, 2.40 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (10 mL) was stirred for 72 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield [1-(phenylsulfonyl)-3-(4-tolyl)indan-2-yl](4-tolyl)methanone (**4j**; 131 mg, 28%) as colorless needles; mp 116–117 °C ($CHCl_3$–PE).

IR (KBr): 1705, 1640, 1475, 1340, 1330, 1320, 1305, 1270, 1200, 1170, 1150, 1100, 845, 790, 770 cm^{-1}.

^1H NMR (250 MHz, $CDCl_3$): δ = 2.32 (s, 3 H), 2.33 (s, 3 H), 4.17 (d, *J* = 7.1 Hz, 1 H), 4.49 (t, *J* = 7.1 Hz, 1 H), 5.75 (d, *J* = 7.1 Hz, 1 H), 6.74 (d, *J* = 7.9 Hz, 2 H), 6.81 (d, *J* = 7.0 Hz, 1 H), 7.00 (d, *J* = 7.3 Hz, 4 H), 7.22–7.36 (m, 6 H), 7.47 (t, *J* = 7.2 Hz, 1 H), 7.75–7.82 (m, 3 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 20.7 (+), 21.3 (+), 55.9 (+), 56.8 (+), 71.5 (+), 125.6 (+), 126.3 (+), 128.2 (+), 128.9 (+), 129.2 (+), 129.3 (+), 129.4 (+), 129.5 (+), 129.7 (+), 130.0 (+), 133.4, 134.1 (+), 134.2, 137.4, 137.7, 140.0, 144.8, 146.9, 198.8.

HRMS [CI (NH_3)]: *m/z* [M + NH_4]$^+$ calcd for $C_{30}H_{26}O_3S{\cdot}NH_4^+$: 484.1946; found: 484.1941.

Also obtained was 3,3-bis(phenylsulfonyl)-1-(4-tolyl)propan-1-one (**6**; 154 mg, 36%) as colorless needles; mp 173–174 °C ($CHCl_3$–PE).

IR (KBr): 1685, 1610, 1450, 1410, 1360, 1335, 1325, 1295, 1235, 1215, 1195, 1185, 1155, 1140, 1080, 975, 815, 765 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 2.42 (s, 3 H), 3.89 (d, *J* = 5.7 Hz, 2 H), 5.69 (t, *J* = 5.7 Hz, 1 H), 7.28 and 7.82 (AA′BB′ system, 4 H), 7.49–7.53 (m, 4 H), 7.63–7.68 (m, 2 H), 7.88–7.91 (m, 4 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.7 (q), 33.8 (t), 78.7 (d), 128.4 (d), 129.2 (d), 129.3 (d), 129.5 (d), 132.7 (s), 134.5 (d), 138.1 (s), 145.1 (s), 192.2 (s).

Anal. Calcd for $C_{22}H_{20}O_5S_2$ (428.4): C, 61.66; H, 4.70; S, 14.96. Found: C, 61.71; H, 4.88; S, 14.85.

Reaction of Ylide 1a with Chalcone 3h

A suspension of ylide **1a** (0.321 g, 0.64 mmol) and (*E*)-1-(5-chloro-2-hydroxyphenyl)-3-phenylprop-2-en-1-one (**3h**; 0.40 g, 1.55 mmol) in the presence of a catalytic amount of $Rh_2(OAc)_4$ in MeCN (10 mL) was stirred for 16 h according to the above general procedure. The solvent was evaporated (20 °C/15 Torr) and the residue was chromatographed on silica gel (CH_2Cl_2–PE) to yield 6-chloro-2-phenyl-2,3-dihydro-4*H*-chromen-4-one (**7**; 107 mg, 67%) as colorless needles; mp 98–99 °C ($CHCl_3$–PE).

IR (KBr): 1715, 1630, 1600, 1495, 1450, 1420, 1405, 1375, 1340, 1295, 1240, 1230, 1200, 1150, 1080, 1000, 930, 915, 880, 840, 780, 775 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 2.91 (dd, *J* = 3.0, 17.0 Hz, 1 H), 3.08 (dd, *J* = 13.2, 17.0 Hz, 1 H), 5.47 (dd, *J* = 3.0, 13.2 Hz, 1 H), 7.02 (d, *J* = 8.8 Hz, 1 H), 7.38–7.49 (m, 6 H), 7.89 (d, *J* = 2.6 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 44.2 (t), 79.8 (d), 119.8 (d), 121.7 (s), 126.1 (d), 126.3 (d), 127.1 (s), 128.8 (d), 128.9 (d), 135.9 (d), 138.2 (s), 159.9 (s), 190.7 (s).

Anal. Calcd for $C_{15}H_{11}ClO_2$ (258.7): C, 69.64; H, 4.29. Found: C, 69.50; H, 4.61.

Also obtained was (5-chloro-2-hydroxyphenyl)[1-phenyl-3-(phenylsulfonyl)indan-2-yl]methanone (**4k**; 68.0 mg, 22%) as colorless needles; mp 176–177 °C ($CHCl_3$–PE).

IR (KBr): 3130, 3090, 1665, 1495, 1430, 1420, 1345, 1335, 1320, 1305, 1260, 1250, 1235, 1195, 1175, 1100, 1040, 995, 930, 910, 850, 770 cm^{-1}.

^1H NMR (200 MHz, $CDCl_3$): δ = 4.24 (d, *J* = 8.0 Hz, 1 H), 4.40 (t, *J* = 8.0 Hz, 1 H), 5.75 (d, *J* = 8.0 Hz, 1 H), 6.48 (d, *J* = 2.4 Hz, 1 H), 6.79–6.92 (m, 4 H), 7.27–7.55 (m, 9 H), 7.78 (d, *J* = 7.2 Hz, 2 H), 7.88 (d, *J* = 7.2 Hz, 1 H).

^{13}C NMR (50 MHz, $CDCl_3$): δ = 56.6 (+), 57.4 (+), 71.0 (+), 119.2, 119.9 (+), 123.8, 125.9 (+), 126.3 (+), 128.5 (+), 128.7 (+), 128.8 (+), 129.5 (+), 130.3 (+), 130.4 (+), 134.0, 134.4 (+), 137.2 (+), 137.3, 141.8, 145.8, 161.9, 203.6.

Anal. Calcd for $C_{28}H_{21}ClO_4S$ (488.08): C, 68.78; H, 4.33; S, 6.56. Found: C, 68.91; H, 4.48; S, 6.18.

Acknowledgment

We thank the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie for generous funding. E.P.G. thanks the Greek Ministery of Education (Hraklitos and INTEREG II) and DAAD for doctoral fellowships, and I.A.N. thanks the Propondis Foundation for a fellowship.

References

(1) (a) Hadjiarapoglou, L.; Spyroudis, S.; Varvoglis, A. *J. Am. Chem. Soc.* **1985**, *107*, 7178. (b) Hadjiarapoglou, L.; Varvoglis, A.; Alcock, N. W.; Pike, G. A. *J. Chem. Soc., Perkin Trans. 1* **1988**, 2839.

(2) (a) Hadjiarapoglou, L.; Varvoglis, A. *Synthesis* **1988**, 913. (b) Hadjiarapoglou, L.; Varvoglis, A. *J. Heterocycl. Chem.* **1988**, *25*, 1599.

(3) Adam, W.; Bosio, S.; Gogonas, E. P.; Hadjiarapoglou, L. P. *Synthesis* **2002**, 2084.

(4) Adam, W.; Gogonas, E. P.; Hadjiarapoglou, L. P. *J. Org. Chem.* **2003**, *68*, 9155.

(5) (a) Li, A. H.; Dai, L.-X.; Aggarwal, V. K. *Chem. Rev.* **1997**, *97*, 2341. (b) Barluenga, J.; Fanlo, H.; Lopez, S.; Florez, J. *Angew. Chem. Int. Ed.* **2007**, *46*, 4136.

(6) (a) Rozen, S.; Lerman, O.; Kol, M.; Hebel, D. *J. Org. Chem.* **1985**, *50*, 4753. (b) Jensen, J. L.; Carre, D. J. *J. Org. Chem.* **1974**, *39*, 2103. (c) Adam, W.; Hadjiarapoglou, L.; Smerz, A. *Chem. Ber.* **1991**, *124*, 227.

(7) (a) Guziec, F. S. Jr.; Luzzio, F. A. *J. Org. Chem.* **1983**, *48*, 2434. (b) Jung, M. E.; Min, S.-J.; Houk, K. N.; Ess, D. *J. Org. Chem.* **2004**, *69*, 9085.

(8) Simpkins, N. S. *Sulphones in Organic Synthesis*; Pergamon: Exeter, **1993**.

(9) (a) Rendy, R.; Zhamg, Y.; McElrea, A.; Gomez, A.; Klumpp, D. A. *J. Org. Chem.* **2004**, *69*, 2340. (b) Minami, K.; Saito, H.; Tsutsui, H.; Nambu, H.; Anada, M.; Hashimoto, S. *Adv. Synth. Catal.* **2005**, *347*, 1483.

(10) Sander, W.; Strehl, A.; Winkler, M. *Eur. J. Org. Chem.* **2001**, 3771.

(11) (a) Reich, H. J.; Cooperman, C. S. *J. Am. Chem. Soc.* **1973**, *95*, 5077. (b) Musher, J. I. *J. Am. Chem. Soc.* **1972**, *94*, 1370.

(12) (a) Truce, W. E.; Ray, W. J. Jr.; Norman, O. L.; Eickemeyer, D. B. *J. Am. Chem. Soc.* **1958**, *80*, 3625. (b) Truce, W. E.; Robbins, C. R.; Kreider, E. M. *J. Am. Chem. Soc.* **1966**, *88*, 4027. (c) Madaj, E. J. Jr.; Snyder, D. M.; Truce, W. E. *J. Am. Chem. Soc.* **1986**, *108*, 3466.

(13) (a) Bergmann, E.; Wolff, H. A. *J. Am. Chem. Soc.* **1932**, *54*, 1644. (b) Wheeler, O. H.; Gore, P. H.; Santiago, M.; Baez, R. *Can. J. Chem.* **1964**, *42*, 2580.

(14) Palumbo, G.; Caputo, R. *Synthesis* **1981**, 888.

(15) Kohler, E. P.; Tiechler, M. *J. Am. Chem. Soc.* **1935**, *57*, 217.