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Synthesis of Diarylacetylenes Bearing Electron-Withdrawing Groups via the Smiles Rearrangement

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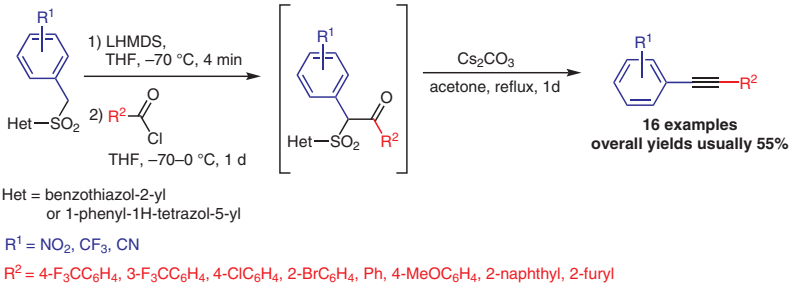

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Abstract Nitrobenzyl benzothiazol-2-yl sulfones and nitrobenzyl 1-phenyl-1*H*-tetrazol-5-yl sulfones react with chlorides of aromatic acids to form β-acyl derivatives. These products undergo the Smiles rearrangement resulting in the formation of the corresponding nitrophenyl arylacetylenes in 50–60% overall yields (approx. 75% per step). Sulfones bearing CF_3 or CN groups instead of a NO_2 substituent form mixtures of the acetylenes in moderate yields and benzyl aryl ketones in yields above 40%.

Key words acetylenes, sulfones, Smiles rearrangement, Julia–Kocienski olefination, benzyl ketones

Substituted acetylenes are widely used as versatile starting materials in modern organic synthesis. Of particular value is the synthesis of different heterocycles: indoles,[1] anthranils,[2] quinolines,[3] etc., via transition-metal-catalyzed addition of nitrogen nucleophiles to carbon–carbon triple bonds. The common way to synthesize aryl acetylenes is by way of the Sonogashira reaction, which involves the transition-metal-catalyzed replacement of halogens on aromatic rings by acetylenic moieties.[4] This reaction is presently the most common and widely used tool for the preparation of diarylacetylenes. The coupling usually proceeds with high yield, however, the high cost of transition metals can be a problem for large-scale synthesis. Moreover, if the products have potential pharmaceutical applications, they should be meticulously purified to remove the transition metals.[5]

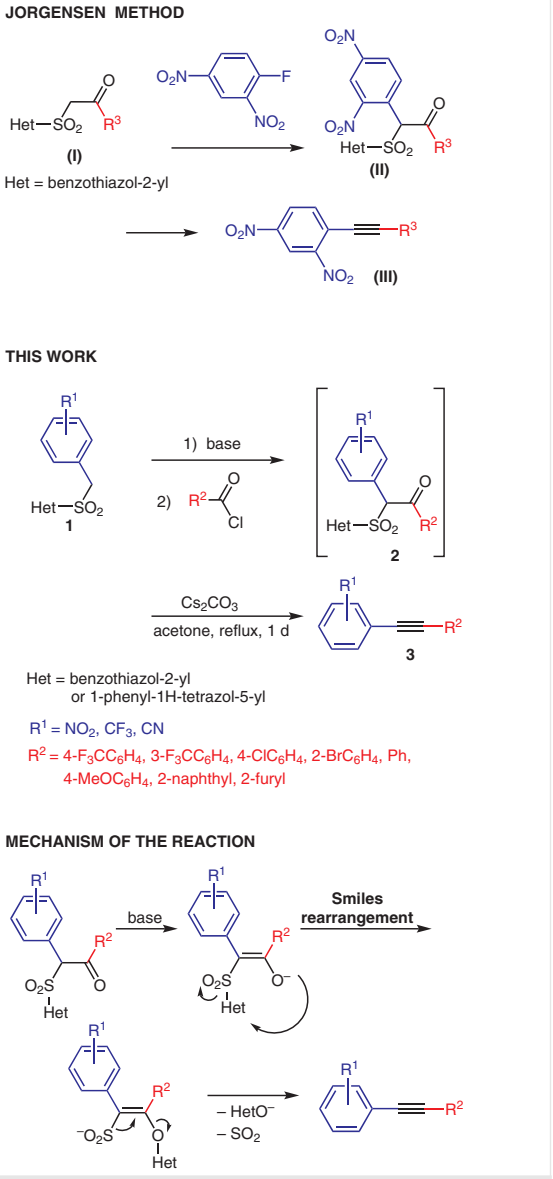
Nitroaryl acetylenes can also be prepared by substitution of fluorine[6a] or hydrogen[6b] in nitroarenes via nucleophilic aromatic substitution (S_NAr) or by oxidative substitution of hydrogen (ONSH) via reactions with acetylenic carbanions. The latter method is the simplest way to introduce an acetylenic moiety into nitroaromatic rings, however, due to the low nucleophilicity of the acetylenic carbanion, ONSH proceeds efficiently only in highly active nitroarenes such as dinitrobenzenes or nitropyridines.

Recently, an interesting synthesis of dinitroaryl acetylenes via Smiles rearrangement of the enolates of benzothiazolyl dinitroarylketones, in a similar manner to the Julia–Kocienski olefination,[7] was described by Jorgensen (Scheme 1).[8] The starting dinitroaryl ketosulfones **II** were prepared via reaction of chloromethylketones with 2-mercaptobenzothiazole, followed by oxidation of the formed sulfides to give ketosulfones **I**. Subsequent nitroarylation of the ketosulfones **I** gave dinitroaryl ketosulfones **II**. The carbanions of the ketosulfones **I** are weak nucleophiles, so this method is limited to highly electrophilic fluorodinitroarenes. Treatment of the formed ketonitroaryl sulfones **II** with a base results in the Smiles rearrangement of the generated enolates and the formation of dinitroaryl acetylenes **III** (Scheme 1).

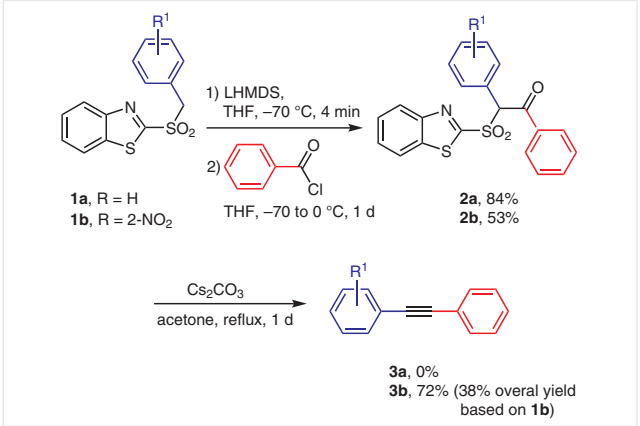
The Jorgensen synthesis inspired us to extend this approach and test the generality of the methodology (Scheme 1). In particular, we expected that changing the order of events and synthesizing the key intermediate ketosulfones **2** via acylation of benzothiazolylsulfones **1** would offer a more general approach. Subsequent Smiles rearrangement of the ketosulfones **2** produced via acylation should give expected diarylacetylenes **3** (see mechanism in Scheme 1).

As a model compound we chose sulfone **1a** (Scheme 2), which is readily available via benzylation of 2-mercaptobenzothiazole and oxidation of the formed sulfide. Acylation of **1a** with benzoyl chloride was carried out according to the procedure described by Pospisil[9] to give the expected ketosulfone **2a** in high yield (84% after chromatographic purification).

Unfortunately, all attempts to perform the Smiles rearrangement of the enolate of **2a** gave negative results. Regardless of the tested conditions: Cs_2CO_3/boiling acetone;



Scheme 1 Synthesis of nitroaryl acetylenes via Smiles rearrangements of ketoaryl sulfones



Scheme 2 Attempted synthesis of acetylenes **3a**,**b** from purified model sulfones **2a**,**b**. Yields of isolated products are given.

NaH/DMF, 45 °C; *t*-BuOK/DMF, 60 °C; LHMDS/THF, 45 °C and KOH/MeOH, 45 °C, ketosulfone **2a** was partially decomposed or was recovered unchanged, whilst no acetylene **3a** was found in the reaction mixture.

Compound **2a** is a relatively strong CH-acid, so under the tested conditions it should be completely deprotonated. At present, it is not clear why the enolate of **2a** does not undergo the rearrangement. One reason might be that the enolate is formed as the wrong geometric isomer.

As we mentioned previously, dinitroaryl ketosulfones **II** (Scheme 1) undergo the Smiles rearrangement to produce dinitrophenyl aryl acetylenes **III**, hence it appears that the presence of a nitro group on the benzylic substituent is a crucial factor for the reaction. We therefore tested the possibility to perform such a sequence of reactions with 2-nitrobenzyl benzothiazol-2-yl sulfone (**1b**) (Scheme 2). Benzoylation of **1b** proceeded smoothly (TLC analysis), however, the yield of the product **2b** after chromatographic purification was moderate (53%), leading to the assumption that product **2b** partially decomposes on silica gel.

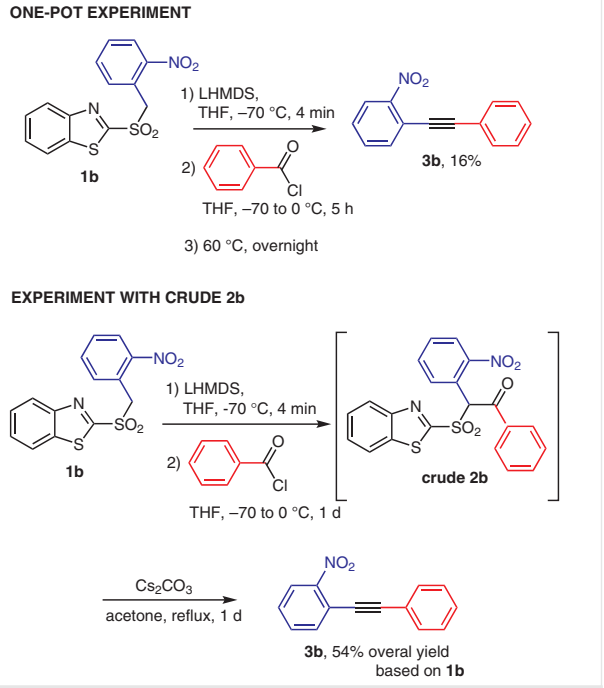
To our satisfaction, ketosulfone **2b** underwent the Smiles rearrangement in the presence of Cs_2CO_3 in boiling acetone to afford the desired product, 2-nitrophenyl phenyl acetylene (**3b**), in a good yield of 72%. However, the overall yield (38%) of acetylene **3b** based on sulfone **1b** was unsatisfactory, mostly due to loss of ketosulfone **2b** during purification.

Since the acylation of sulfone **1b** is carried out in the presence of an excess of the base, we tried to perform the acylation and rearrangement steps as a one-pot process (Scheme 3), however, under such conditions, the yield of acetylene **3b** was poor (16%).

On the other hand, when crude sulfone **2b** was used in the rearrangement step, a much better result was obtained. On this occasion, the overall yield of acetylene **3b** based on starting material **1b** was 54% (Scheme 3).

The latter result confirms that compound **2b** partially decomposes during column chromatographic purification, therefore, all subsequently prepared sulfones **2** were used in the rearrangement step without purification.

In order to clarify whether the presence of the 2-nitro group in compound **2b** favors the Smiles rearrangement due to steric or electronic effects, we prepared 4-nitrobenzyl benzothiazol-2-yl sulfone (**1c**) in a similar manner to that used to prepare **1b**. The benzoylation of **1c** and the Smiles rearrangement of crude **2c** proceeded similarly to sulfone **2b** and gave 4-nitrophenyl phenyl acetylene (**3f**) in a good overall yield of 62% (Scheme 4). Thus, the beneficial influence of the nitro groups in compounds **1b** and **1c** on the Smiles rearrangement is due to their electronic effects.



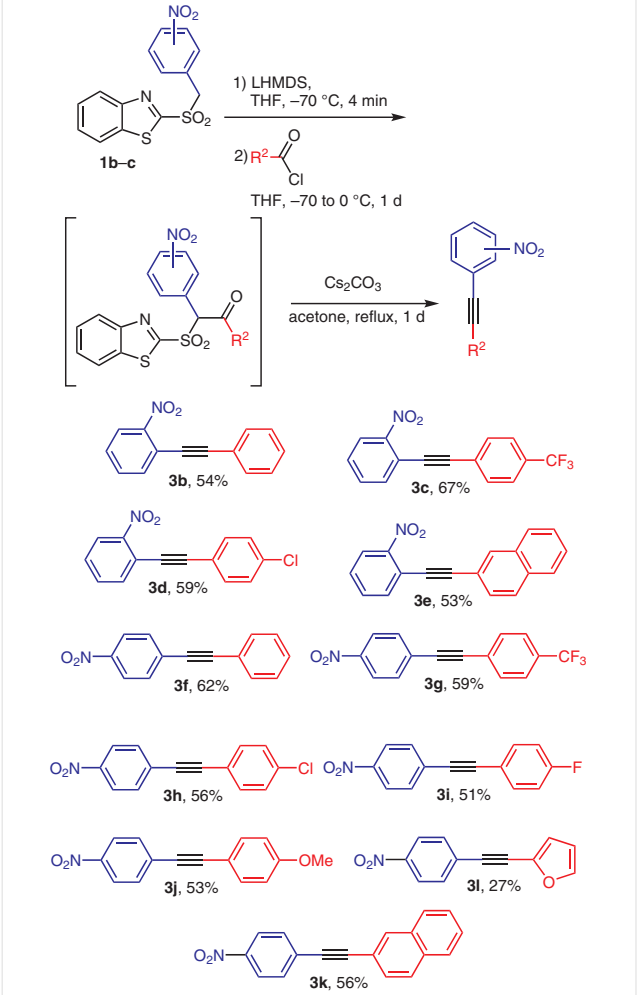
Scheme 3 One-pot synthesis of the acetylene **3b** and the synthesis from the crude sulfone **2b**. Yields of isolated products are given.

Conversion of 2- and 4-nitrobenzyl benzothiazol-2-yl sulfones (**1b**) and (**1c**) into nitrophenyl aryl acetylenes **3** via acylation with aroyl chlorides and the Smiles rearrangement is a general process exemplified by the results shown in Scheme 4. Good overall yields (50–60%; approx. 75% per step) were obtained for benzoyl chlorides bearing both electron-withdrawing and electron-donating substituents on the phenyl ring. Also, the use of 2-naphthoyl chloride gave good results.

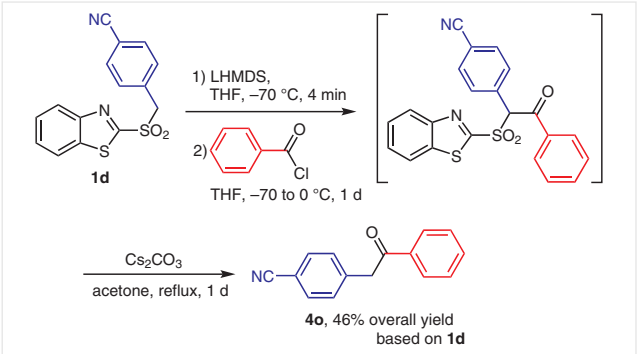
The furan ring is probably less stable under the conditions of both steps. TLC analysis indicated that the acylation and the Smiles rearrangement were less selective and product **3l** was obtained in only moderate yield (27%; 52% per step).

An attempt to apply the elaborated reaction sequence for the synthesis of 4-cyanophenyl aryl acetylenes from sulfone **1d** was unsuccessful (Scheme 5). Treatment of the crude benzoyl ketosulfone with Cs_2CO_3 under standard conditions resulted in elimination of the benzothiazol-2-yl sulfonyl group without the Smiles rearrangement, resulting in the corresponding ketone **4o** being isolated in 46% overall yield.

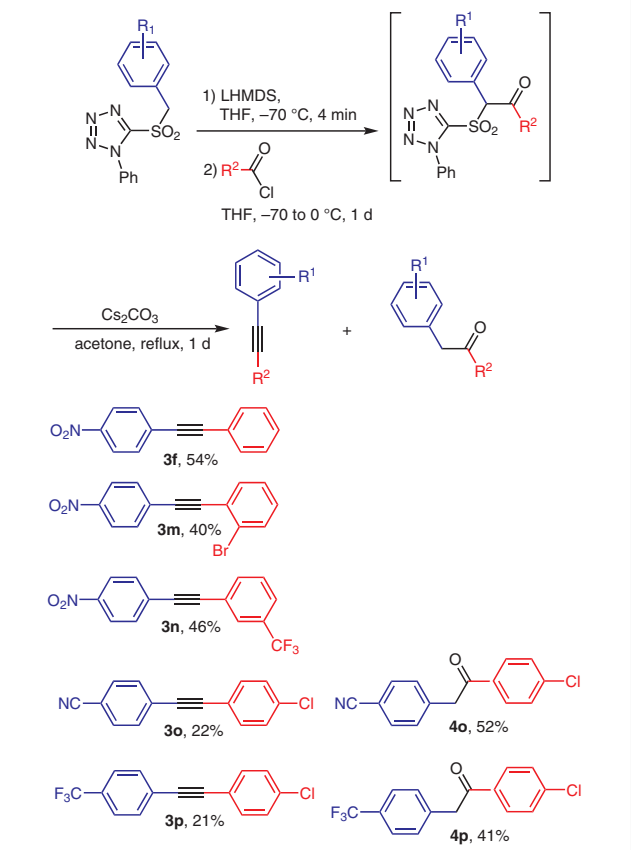
For the Julia–Kocienski olefination via the Smiles rearrangement, the 1-phenyl-1*H*-tetrazol-5-yl sulfones are often used. Hence, we prepared a series of the corresponding sulfones **1e–g** bearing NO_2, CN and CF_3 groups at the 4-position of the phenyl ring in order to investigate the effect of the heterocyclic leaving group (Scheme 6).



Scheme 4 Synthesis of nitrophenyl aryl acetylenes **3** from the benzothiazol-2-yl sulfones **1b**,**c**. Yields of isolated products are given.



Scheme 5 Attempted synthesis of the 4-cyanophenyl acetylene from the 4-cyanobenzyl sulfone **1d**. Yields of isolated product is given.



Scheme 6 Synthesis of arylacetylenes from 1-phenyl-tetrazol-5-yl sulfones **1e–g**. Yields of isolated products are given.

The acylation step proceeded smoothly in all cases. The crude ketosulfones obtained from 1-phenyl-1*H*-tetrazol-5-yl nitrobenzyl sulfone **1e** reacted in similar manner to the benzothiazol-2-yl analog **1c**. The corresponding acetylenes **3f**, **3m** and **3n** were isolated in satisfactory yields (40–54%). The results were slightly worse than for the benzothiazol-2-yl sulfone **1c**, because of a drop in the selectivity of the rearrangement step, but the desired acetylenes were still the main products of the reactions.

Under the standard rearrangement conditions acylation products formed from the sulfones **1f**,**g** bearing weaker electron-withdrawing groups (CN, CF_3) to give mixtures of the corresponding acetylenes **3o**,**p** (approx. 22%) and ketones **4o**,**p** (41–52%). The formation of ketones from a side reaction during the rearrangement step was reported by Jorgensen for sulfones **II** (see Scheme 1).[8] It is noteworthy that ketones such as **4o** are also interesting compounds.[8,10]

In contrast to the benzothiazol-2-yl sulfone **1d**, compound **1f** bearing a 1-phenyl-1*H*-tetrazol-5-yl group formed the desired acetylene **3o** (22%), but still the corresponding ketone **4o** was the main product of the reaction. Thus tetrazol-5-yl sulfone **1f** reacts in a different way than the benzothiazol-2-yl sulfone **1d**. Tetrazol-5-yl sulfones are more reactive than benzothiazole sulfones, but the reactions proceed less selectively. This is typical situation, i.e., more active reagents react with lower selectivity.

In conclusion, we have described a new approach for the synthesis of diaryl acetylenes containing electron-withdrawing groups via the benzothiazol-2-yl and the 1-phenyl-1*H*-tetrazol-5-yl ketosulfones, themselves prepared by acylation of the corresponding sulfones. This methodology is of general applicability for nitroaryl aryl acetylenes. The products bearing electron-withdrawing and electron-donating substituents were synthesized in good overall yields, usually 50–60% (approx. 75% per step). Inferior results were obtained for 4-cyano- and 4-trifluoromethyl groups, the corresponding acetylenes being isolated in moderate overall yields (approx. 22%; 46% per step). In these cases, the corresponding ketones were the main products of the reactions.

Column chromatography was accomplished using Merck silica gel 230-400 mesh. Analytical TLC was performed on Merck 60 silica gel plates. Melting points were determined using a Franz Kurstner Nach KG Dresden HMK 713398 instrument. IR spectra were recorded on a JASCO FT/IR-6200 spectrophotometer. ^{1}H and ^{13}C NMR spectra were recorded on Bruker DRX 500 "Avance" 500 MHz (500 MHz for ^{1}H and 125 MHz for ^{13}C spectra) or Varian-NMR-VNMRS-500 (500 MHz for ^{1}H and 125 MHz for ^{13}C spectra) instruments. Chemical shifts (δ) are expressed in ppm referred to TMS (internal standard), and coupling constants are in hertz. Multiplicities are reported as follows: singlet (s), doublet (d), doublet of doublets (dd), triplet (t), quartet (q) and multiplet (m). ESI mass spectra were obtained on SYNAPT G2-S HDMS instrument. EI mass spectra were recorded on gas chromatograph 7890A (Agilent) coupled with magnetic sector mass spectrometer AutoSpec Premier. Elemental analysis was performed using VARIO EL III instrument.

Sulfones 1a–g

Sulfones **1a–g** were obtained from commercial 2-mercaptobenzothiazole or 1-phenyl-1*H*-tetrazole-5-thiol via alkylation with the corresponding benzyl bromide followed by oxidation with *m*CPBA according to the procedure described for sulfone **1a**.[7a]

2-(2-Nitrophenylmethanesulfonyl)benzothiazole (1b)

The crude product was purified by column chromatography (hexanes/EtOAc, 2:1).

White solid (2.65 g, 72% based on 2-mercaptobenzothiazole); mp 132–135 °C; R_f = 0.38 (SiO_2, hexanes/EtOAc, 2:1).

IR (KBr): 3067, 3022, 2961, 1724, 1605, 1577, 1521, 1466, 1416, 1350, 1311, 1241, 1147, 1082, 1016, 861, 859, 793, 766, 701, 632, 547, 513, 455, 432 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.22 (d, *J* = 7.5 Hz, 1 H), 8.03 (dd, *J* = 7.5 Hz, 1.5 Hz, 1 H), 7.98–7.96 (m, 1 H), 7.65–7.63 (m, 1 H), 7.61–7.50 (m, 4 H), 5.38 (s, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 164.7, 152.5, 149.6, 136.9, 134.4, 133.4, 130.5, 128.4, 127.8, 125.8, 125.6, 122.3, 121.7, 57.0.

HRMS–EI: *m*/*z* [M]$^+$ calcd for $C_{14}H_{10}N_2O_4S_2$: 334.0082; found: 334.0084.

2-(4-Nitrophenylmethanesulfonyl)benzothiazole (1c)

The crude product was used in the next step without further purification.

White solid (3.5 g, 95% based on 2-mercaptobenzothiazole); mp 210–211 °C (dec.).

IR (KBr): 3110, 3069, 2932, 1606, 1523, 1469, 1345, 1315, 1234, 1147, 1123, 1102, 1012, 864, 853, 767, 698, 651, 610, 558, 517, 504, 460, 434 cm^{-1}.

^1H NMR (500 MHz, DMSO-d_6): δ = 8.32–8.29 (m, 2 H), 8.22–8.20 and 7.62–7.60 (AA′XX′, 4 H), 7.77–7.69 (m, 2 H), 5.35 (s, 2 H).

^{13}C NMR (125 MHz, DMSO-d_6): δ = 165.3, 152.0, 147.7, 136.4, 134.7, 132.6, 128.3, 128.0, 124.9, 123.5, 59.0.

HRMS–EI: *m*/*z* $[M]^+$ calcd for $C_{14}H_{10}N_2O_4S_2$: 334.0082; found: 334.0089.

2-(4-Cyanophenylmethanesulfonyl)benzothiazole (1d)

The crude product was used in the next step without further purification.

White solid (2.8 g, 89% based on 2-mercaptobenzothiazole); mp 182–184 °C.

IR (KBr): 3067, 2224, 1693, 1603, 1550, 1501, 1468, 1411, 1335, 1315, 1147, 1083, 1023, 852, 767, 728, 622, 569, 544 cm^{-1}.

^1H NMR (500 MHz, DMSO-d_6): δ = 8.33–8.29 (m, 2 H), 7.84–7.82 and 7.52–7.51 (AA′XX′, 4 H), 7.77–7.69 (m, 2 H), 5.28 (s, 2 H).

^{13}C NMR (125 MHz, DMSO-d_6): δ = 165.3, 152.0, 136.4, 132.8, 132.3, 132.2, 128.3, 128.1, 124.9, 123.5, 118.4, 111.7, 59.3.

HRMS–EI: *m*/*z* $[M]^+$ calcd for $C_{15}H_{10}N_2O_2S_2$: 314.0184; found: 314.0177.

5-(4-Nitrophenylmethanesulfonyl)-1-phenyl-1*H*-tetrazole (1e)

The crude product was used in the next step without further purification.

White solid (2.7 g, 98% based on 1-phenyl-1*H*-tetrazole-5-thiol); mp 173–176 °C (dec.).

IR (KBr): 3074, 2990, 2941, 1695, 1599, 1526, 1494, 1462, 1416, 1400, 1349, 1152, 1101, 1077, 1053, 1012, 861, 765, 688, 652, 597, 519 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.26–8.22 and 7.63–7.60 (AA′XX′, 4 H), 7.68–7.64 (m, 1 H), 7.54–7.52 (m, 4 H), 5.45 (s, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.9, 148.0, 133.2, 133.0, 132.7, 131.4, 129.2, 126.1, 123.6, 60.6.

HRMS–ESI$^+$ (MeOH): *m*/*z* $[M + Na]^+$ calcd for $C_{14}H_{11}N_5O_4SNa$: 368.0429; found: 368.0422.

5-(4-Cyanophenylmethanesulfonyl)-1-phenyl-1*H*-tetrazole (1f)

The crude product was used in the next step without further purification.

White solid,(4.9 g, ~100% based on 1-phenyl-1*H*-tetrazole-5-thiol); mp 178–180 °C (dec.).

IR (KBr): 3067, 2960, 2904, 2227, 1593, 1494, 1399, 1351, 1269, 1165, 1137, 870, 849, 764, 689, 580, 523 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.68–7.66 (m, 2 H), 7.61–7.51 (m, 7 H), 5.05 (s, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.8, 132.6, 132.5, 131.6, 130.0, 129.7, 125.0, 117.8, 113.9, 61.6.

HRMS–ESI$^+$ (MeOH): *m*/*z* $[M + Na]^+$ calcd for $C_{15}H_{11}N_5O_2SNa$: 348.0531; found: 348.0521.

1-Phenyl-5-(4-trifluoromethyl-phenylmethanesulfonyl)-1*H*-tetrazole (1g)

The crude product was used in the next step without further purification.

White solid (5.6 g, ~100% based on 1-phenyl-1*H*-tetrazole-5-thiol); mp 138–140 °C.

IR (KBr): 3076, 2990, 2942, 1696, 1620, 1593, 1553, 1496, 1418, 1355, 1324, 1175, 1153, 1112, 1065, 1015, 853, 762, 731, 688, 656, 588, 520 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.64–7.62 (m, 2 H), 7.61–7.57 (m, 1 H), 7.55–7.50 (m, 4 H), 7.44–7.42 (m, 2 H), 5.03 (s, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.8, 132.7, 132.1, 131.5, 129.5, 128.8, 126.0 (q, *J* = 3.5 Hz), 125.1, 123.6 (q, *J* = 273 Hz), 61.6.

HRMS–ESI$^+$ (MeOH): *m*/*z* $[M + Na]^+$ calcd for $C_{15}H_{11}N_4O_2SF_3Na$: 391.0453; found: 391.0440.

Ketosulfones 2a,b

To a solution of sulfone **1** (1.0 mmol) in dry THF (10 mL) cooled to –70 °C under an argon atmosphere was added LHMDS (1.7 mL, 1.3 M in THF, 2.2 mmol) via a microsyringe (in two portions over 30 s) and the mixture then stirred for 3–4 min. The acyl chloride (1.5 mmol) was added, the cooling bath removed and the reaction mixture allowed to warm to 5 °C over 15 min and then stirred overnight at 5 °C. 2 M HCl (1 mL) was added, the mixture was extracted with EtOAc (20 mL) and the extract dried and evaporated. The crude product was purified by column chromatography on silica gel (hexanes/EtOAc).

2-(Benzothiazole-2-sulfonyl)-1,2-diphenyl-ethanone (2a)

White solid (0.331 g, 84%); mp 141–142 °C; R_f = 0.31 (SiO_2, hexanes/EtOAc, 4:1).

IR (KBr): 3435, 3060, 1676, 1594, 1468, 1450, 1340, 1279, 1207, 1148, 1081, 1024, 991, 855, 767, 725, 697, 617, 546, 518, 501 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.15–8.13 (m, 1 H), 7.95–7.93 (m, 1 H), 7.89–7.87 (m, 2 H), 7.61–7.50 (m, 5 H), 7.42–7.31 (m, 5 H), 6.81 (s, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 189.5, 165.8, 152.2, 137.2, 135.2, 134.2, 131.0, 130.1, 129.4, 129.0, 128.8, 128.0, 127.5, 126.5, 125.4, 122.3, 75.0.

HRMS–ESI$^+$ (MeOH): *m*/*z* $[M + Na]^+$ calcd for $C_{21}H_{15}NO_3S_2Na$: 416.0391; found: 416.0382.

2-(Benzothiazole-2-sulfonyl)-2-(2-nitrophenyl)-1-phenyl-ethanone (2b)

Light-brown solid (0.235 g, 53%); mp 93–95 °C; R_f = 0.17 (SiO_2, hexanes/EtOAc, 4:1).

IR (KBr): 1670, 1595, 1577, 1528, 1466, 1346, 1216, 1148, 1002, 876, 844, 759, 698, 625, 554, 521 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.14–8.12 (m, 1 H), 8.09–8.07 (m, 4 H), 7.96–7.93 (m, 2 H), 7.68–7.65 (m, 1 H), 7.62–7.54 (m, 4 H), 7.45–7.42 (m, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 188.8, 164.5, 152.1, 149.7, 137.0, 135.1, 134.6, 133.5, 133.1, 130.9, 129.3, 129.0, 128.3, 127.7, 125.7, 122.2, 121.2, 67.4.

HRMS–ESI$^+$ (MeOH): m/z [M + Na]$^+$ calcd for $C_{21}H_{14}N_2O_5S_2Na$: 461.0242; found: 461.0230.

Acetylenes 3 from Sulfones 1 without Purification of Ketosulfones 2; General Procedure

The crude ketosulfones were obtained in similar manner to sulfones **2a**,**b**. Next, Cs_2CO_3 (0.195 g, 0.60 mmol) and acetone (15 mL) were added and the mixture was refluxed for 1–2 d. The solvent was evaporated, H_2O (6 mL) was added and the mixture was extracted with EtOAc (2 × 20 mL). The combined extracts were dried and evaporated. The crude product was purified by column chromatography on silica gel (hexanes/EtOAc) to afford acetylenes **3**.

1-Nitro-2-(phenylethynyl)benzene (3b)[4a]

Orange oil (0.085 g, 54%); TLC (SiO_2): R_f = 0.40 (SiO_2, hexanes/EtOAc, 9:1)

IR (film): 3053, 2220, 1608, 1568, 1523, 1495, 1442, 1343, 1293, 1143, 1070, 888, 834, 784, 757, 744, 690, 520 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.08 (dd, J = 8.2 Hz, 1.1 Hz, 1 H), 7.71 (dd, J = 7.7 Hz, 1.4 Hz, 1 H), 7.61–7.58 (m, 3 H), 7.48–7.44 (m, 1 H), 7.40–7.36 (m, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 149.6, 134.6, 132.8, 132.0, 129.2, 128.5, 128.4, 124.7, 122.4, 118.8, 97.1, 84.8.

1-Nitro-2-{[4-(trifluoromethyl)phenyl]ethynyl}benzene (3c)

Orange solid (0.252 g, 67%); mp 52–54 °C (Lit.[11] 46–48 °C); R_f = 0.35 (SiO_2, hexanes/EtOAc, 9:1).

IR (KBr): 2221, 1924, 1611, 1523, 1319, 1177, 1121, 1062, 842, 744, 688, 595, 516 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.11 (dd, J = 8.2 Hz, 1.1 Hz, 1 H), 7.74 (dd, J = 7.8 Hz, 1.4 Hz, 1 H), 7.70–7.68 (m, 2 H), 7.64–7.61 (m, 3 H), 7.53–7.49 (m, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 149.7, 134.7, 132.9, 132.2, 130.8 (q, J = 33 Hz), 129.2, 126.2, 125.3 (q, J = 4 Hz), 124.8, 123.8 (q, J = 271 Hz), 118.0, 95.2, 86.8.

2-(4-Chlorophenylethynyl)-1-nitrobenzene (3d)

Orange solid (0.193 g, 59%); mp 93–95 °C; R_f = 0.39 (SiO_2, hexanes/EtOAc, 4:1).

IR (KBr): 2219, 1605, 1566, 1518, 1341, 1291, 1088, 1011, 825, 743, 513 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.09 (dd, J = 8.2 Hz, 0.9 Hz, 1 H), 7.71 (dd, J = 7.8 Hz, 1.4 Hz, 1 H), 7.62–7.59 (m, 1 H), 7.53–7.51 and 7.37–7.34 (AA'XX, 4 H), 7.50–7.46 (m, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 149.5, 135.4, 134.5, 133.2, 132.9, 128.8, 128.7, 124.8, 120.9, 118.5, 95.9, 85.7.

HRMS–EI: m/z [M]$^+$ calcd for $C_{14}H_8NO_2Cl$: 257.0244; found: 257.0234.

2-(2-Nitrophenylethynyl)naphthalene (3e)

Orange solid (0.195 g, 53%); mp 78–81 °C; R_f = 0.36 (SiO_2, hexanes/EtOAc, 4:1).

IR (KBr): 2202, 1605, 1567, 1517, 1334, 1289, 739, 472 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.13 (br s, 1 H), 8.10 (dd, J = 8.2 Hz, 0.9 Hz, 1 H), 7.85–7.82 (m, 3 H), 7.76 (dd, J = 7.9 Hz, 1.3 Hz, 1 H), 7.64–7.59 (m, 2 H), 7.54–7.50 (m, 2 H), 7.48–7.45 (m, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 149.6, 134.6, 133.3, 132.9, 132.8, 132.4, 128.5, 128.3, 128.2, 128.0, 127.8, 127.2, 126.7, 124.8, 119.7, 118.8, 97.6, 85.1.

HRMS–EI: m/z [M]$^+$ calcd for $C_{18}H_{11}NO_2$: 273.0790; found: 273.0797.

1-Nitro-4-(phenylethynyl)benzene (3f)

Yellow solid (0.207 g, 62%); mp 114–116 °C (Lit.[4a] 110–114 °C); R_f = 0.52 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2214, 1591, 1511, 1345, 1103, 858, 765, 688, 506 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.23–8.20 and 7.68–7.64 (AA'XX', 4 H), 7.58–7.54 (m, 2 H), 7.41–7.37 (m, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.0, 132.3, 131.8, 130.3, 129.3, 128.5, 123.6, 122.1, 94.7, 87.5.

1-Nitro-4-{[4-(trifluoromethyl)phenyl]ethynyl}benzene (3g)

Light-yellow solid (0.168 g, 59%); mp 108–110 °C (Lit.[4b] 110–111 °C); R_f = 0.46 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 3115, 2222, 1926, 1593, 1513, 1346, 1319, 1173, 1125, 1105, 1063, 855, 839, 749, 687, 595, 507 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.26–8.23 and 7.71–7.68 (AA'XX', 4 H), 7.67–7.65 (m, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.4, 132.5, 132.1, 130.9 (q, J = 33 Hz), 129.4, 125.9, 125.5 (q, J = 4 Hz), 124.3 (q, J = 272 Hz), 123.7, 92.8, 89.5.

4-(4-Chlorophenylethynyl)-1-nitrobenzene (3h)

Yellow solid (0.177 g, 56%); mp 152–155 °C (Lit.[12] 155–156 °C); R_f = 0.51 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2210, 1586, 1535, 1343, 1088, 1010, 834, 746, 505 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.23–8.21 and 7.66–7.64 (AA'XX, 4 H), 7.49–7.48 and 7.37–7.36 (AA'XX, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.2, 135.5, 133.0, 132.3, 129.9, 128.9, 123.7, 120.6, 93.4, 88.4.

4-(4-Fluorophenylethynyl)-1-nitrobenzene (3i)

Yellow solid (0.122 g, 51%); mp 107–109 °C (Lit.[4c] 111–113 °C); R_f = 0.48 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2209, 1589, 1516, 1343, 1232, 1179, 1105, 852, 838, 747, 685, 511 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.23–8.21 and 7.66–7.64 (AA'XX, 4 H), 7.56–7.54 (m, 2 H), 7.10–7.07 (m, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 163.1 (d, J = 250 Hz), 147.0, 133.8 (d, J = 9 Hz), 132.2 (d, J = 7 Hz), 130.1, 123.7, 118.2, 115.9 (d, J = 22 Hz), 93.6, 87.3.

4-(4-Methoxyphenylethynyl)-1-nitrobenzene (3j)

Yellow solid (0.204 g, 53%); mp 113–115 °C (Lit.[4a] 110–111 °C); R_f = 0.38 (SiO_2, hexanes/EtOAc, 9:1).

IR (KBr): 2963, 2838, 2209, 1588, 1513, 1337, 1246, 1173, 1105, 1027, 858, 836, 747, 687 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.21–8.19 and 7.64–7.62 (AA'XX, 4 H), 7.51–7.49 and 6.92–6.90 (AA'XX, 4 H), 3.85 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 160.4, 146.7, 133.4, 132.0, 130.7, 123.6, 114.2, 114.1, 95.1, 86.6, 55.4.

2-(4-Nitrophenylethynyl)naphthalene (3k)

Yellow solid (0.152 g, 56%); mp 135–138 °C (Lit.[4d] 141–144 °C); R_f = 0.47 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2207, 1592, 1513, 1337, 1103, 850, 822, 746, 684, 472 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.25–8.22 and 7.71–7.69 (AA'XX, 4 H), 8.10 (br s, 1 H), 7.85–7.83 (m, 3 H), 7.58 (dd, *J* = 8.6 Hz, 1.5 Hz, 1 H), 7.54–7.52 (m, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.0, 133.2, 132.9, 132.3, 132.2, 130.3, 128.3, 128.1, 127.9, 127.8, 127.3, 126.8, 123.7, 119.4, 95.2, 87.9.

2-(4-Nitrophenylethynyl)furan (3l)

Yellow solid (0.080 g, 27%); mp 143–144 °C (dec.); R_f = 0.42 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2200, 1596, 1513, 1339, 1213, 1103, 850, 822, 746, 684, 472 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.23–8.21 and 7.66–7.64 (AA'XX, 4 H), 7.49–7.48 (m, 1 H), 6.77 (d, *J* = 3.2 Hz, 1 H), 6.49–6.47 (m, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.1, 144.7, 136.2, 131.9, 129.2, 123.7, 117.1, 111.4, 91.7, 84.6.

HRMS–EI: *m*/*z* $[M]^+$ calcd for $C_{12}H_7NO_3$: 213.0413; found: 213.0418.

4-(2-Bromophenylethynyl)-1-nitrobenzene (3m)

Light-yellow solid (0.096 g, 40%); mp 115–117 °C; R_f = 0.44 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2218, 1595, 1527, 1492, 1343, 1104, 1041, 1025, 864, 850, 762, 745, 683, 657, 443 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.24–8.22 and 7.73–7.71 (AA'XX, 4 H), 7.65 (dd, *J* = 8.0 Hz, 1.0 Hz, 1 H), 7.58 (dd, *J* = 7.7 Hz, 1.6 Hz, 1 H), 7.35–7.31 (m, 1 H), 7.27–7.23 (m, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.3, 133.5, 132.7, 132.4, 130.4, 129.8, 127.2, 125.9, 124.4, 123.7, 93.0, 91.7.

HRMS–EI: *m*/*z* $[M]^+$ calcd for $C_{14}H_8NO_2{}^{79}Br$: 300.9738; found: 300.9744.

1-Nitro-4-{[3-(trifluoromethyl)phenyl]ethynyl}benzene (3n)

Yellow solid (0.113 g, 46%); mp 138–140 °C; R_f = 0.40 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2214, 1592, 1535, 1496, 1432, 1347, 1296, 1271, 1117, 1071, 901, 891, 854, 808, 747, 719, 693, 660 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 8.25–8.23 and 7.70–7.68 (AA'XX, 4 H), 7.83 (br s, 1 H), 7.73 (d, *J* = 7.5 Hz, 1 H), 7.65 (d, *J* = 8.0 Hz, 1 H), 7.54–7.51 (m, 1 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.3, 134.8, 132.4, 131.2 (q, *J* = 33 Hz), 129.4, 129.1, 128.6 (q, *J* = 4 Hz), 125.7 (q, *J* = 4 Hz), 123.8, 123.6 (q, *J* = 271 Hz), 123.1, 92.7, 88.8.

HRMS–EI: *m*/*z* $[M]^+$ calcd for $C_{15}H_8NO_2F_3$: 291.0507; found: 291.0514.

4-(4-Chlorophenylethynyl)benzonitrile (3o)

The reaction was carried out on 2 mmol scale.

Light-yellow solid (0.101 g, 22%); mp 175–177 °C (Lit.[4e] 179.4–180.5 °C); R_f = 035 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2229, 2208, 1602, 1587, 1500, 1401, 1273, 1092, 1010, 832, 680, 553, 526 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.65–7.63 and 7.60–7.58 (AA'XX, 4 H), 7.48–7.46 and 7.37–7.35 (AA'XX, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 135.3, 133.0, 132.1, 129.7, 128.9, 127.9, 120.7, 118.4, 111.7, 92.5, 88.6.

4-[2-(4-Chlorophenyl)-2-oxo-ethyl]benzonitrile (4o)

Light-yellow solid (0.257 g, 52%); mp 113–114 °C (Lit.[10b] 119–120 °C); R_f = 0.42 (SiO_2, hexanes/EtOAc, 4:1).

IR (KBr): 2220, 1687, 1589, 1398, 1338, 1218, 1199, 1093, 994, 829, 816, 794, 567, 550, 527 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.94–7.91 and 7.63–7.61 (AA'XX, 4 H), 7.47–7.45 and 7.36–7.34 (AA'XX, 4 H), 4.32 (s, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 194.9, 140.2, 139.5, 134.5, 132.4, 130.5, 129.8, 129.2, 118.7, 111.1, 45.2.

4-(4-Chlorophenylethynyl)trifluoromethylbenzene (3p)

The reaction was carried out on 2 mmol scale.

Light-yellow solid (0.120 g, 21%); mp 108–110 °C (Lit.[13] 109–111 °C); R_f = 0.83 (SiO_2, hexanes/EtOAc, 19:1).

IR (KBr): 2215, 1914, 1611, 1587, 1484, 1404, 1322, 1181, 1135, 1064, 1011, 831, 632, 598, 512 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.63–7.59 (m, 4 H), 7.48–7.46 and 7.35–7.33 (AA'XX, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 134.9, 132.9, 131.8, 130.1 (q, *J* = 32 Hz), 128.8, 126.7, 125.3, 123.9 (q, *J* = 270 Hz), 121.0, 90.6, 88.8.

4-[2-(4-Chlorophenyl)-2-oxo-ethyl]trifluoromethylbenzene (4p)

Light-yellow solid (0.247 g, 41%); mp 118–121 °C; R_f = 0.36 (SiO_2, hexanes/EtOAc, 9:1).

IR (KBr): 2908, 1927, 1691, 1586, 1488, 1422, 1403, 1325, 1201, 1165, 1113, 1065, 990, 866, 821, 796, 757, 703, 593, 563, 526 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.95–7.93 and 7.60–7.59 (AA'XX, 4 H), 7.46–7.44 and 7.37–7.35 (AA'XX, 4 H), 4.32 (s, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 195.4, 140.0, 138.1, 138.0, 134.6, 129.9, 129.5, 129.1, 125.6 (q, *J* = 4 Hz), 124.1 (q, *J* = 270 Hz), 45.0.

Anal. Calcd for $C_{15}H_{10}ClF_3O$: C, 60.32; H, 3.37; N, 11.87. Found: C, 60.22; H, 3.36; N, 11.70.

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Supporting Information

Supporting information for this article is available online at https://doi.org/10.1055/s-0037-1612423.

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