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Gold Catalysis: Oxepines from γ-Alkynylfurans

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Dedicated to Prof. Dr. Peter Hofmann on the occasion of his 60th birthday.

Abstract: A ketal group in a furyl position affords arene oxides from γ-alkynylfurans even with the simple gold(III) chloride ($AuCl_3$) catalyst. These can either undergo Diels–Alder reactions, isomerise to stable oxepines by an oxygen-walk reaction or by the addition of water selectively be converted to phenols which differ in the position of the hydroxy group from the normal phenols formed in the gold-catalysed phenol synthesis. With a phenyl substituent on the furan, the 2-hydroxymethylpyridinato-gold(III) complex, not the usual arene oxide but an oxepine is obtained, still the arene oxide can be trapped from the valence-tautomeric equilibrium by a Diels–Alder reaction.

Keywords: alkynes; furans; gold; heterocycles; homogeneous catalysis; oxepines

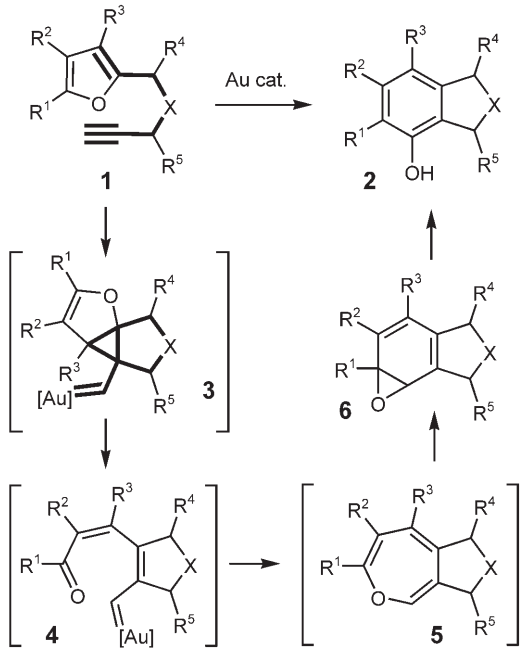
Introduction

Gold catalyst have recently attracted much attention.[1,2] Among the new achievements in homogeneous gold-catalysed reactions,[2] the gold-catalysed phenol synthesis[3] has added a new pathway to the family of the enyne cycloisomerisations.

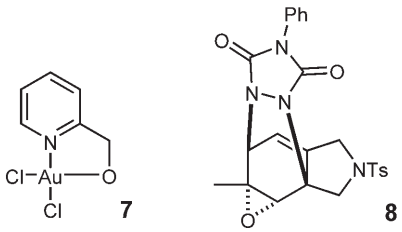
In these reactions an ω-alkynyl furan **1**, which possesses a 1,6-enyne substructure (bold in **1**), furnishes a phenol **2** (Scheme 1). Mechanistic investigations revealed the close relationship to other gold-catalysed reactions of 1,6-enynes, with the formation of cyclopropyl carbenoids **3** being the initial step.[4] Then the reaction pathway diverts from that of the other enyne cycloisomerisations, a subsequent ring-opening provides the conjugated carbenoid **4** which cyclises to the oxepine **5**, the latter is in a valence tautomeric equilibrium with the corresponding arene oxide **6**. Finally, the regioselective ring-opening of **6** leads to **2**.[5]

Side products in platinum-[5] and gold-catalysed[3k] reactions of substrates of type **1** provided evidence for the intermediate **4**, computational chemistry[5] confirmed the other intermediates. The first mechanistic experiments had already revealed the intramolecular migration of the furan oxygen to become the phenolic oxygen atom,[3a] but only with the pre-catalyst **7** (Scheme 2) could up to 80% of an arene oxide **6** be observed by *in situ* NMR spectroscopy and intercepted by a Diels–Alder reaction to afford the stable, diastereomerically pure and crystalline oxirane **8**.[3g]

Here we report further findings concerning the participation of arene oxides and oxepines in these reactions.



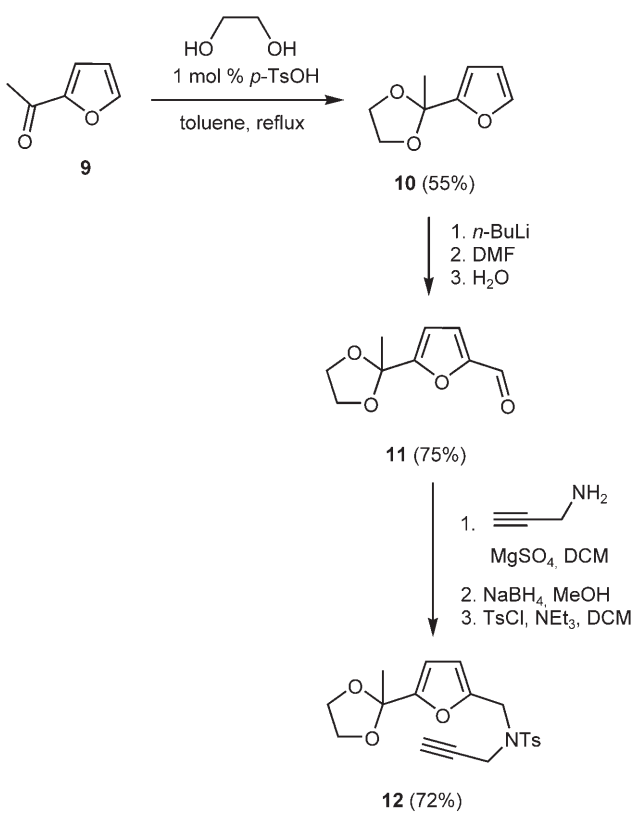
Scheme 1. The gold-catalyzed phenol synthesis (X = CR_2, NR, O, CR_2CR_2, $NRCR_2$, OCR_2).



Scheme 2. Catalyst **7** selectively led to an oxirane which could be trapped as Diels–Alder adduct **8**.

Results and Discussion

The substrate **12** was prepared from 2-acetylfuran **9** by protection of the carbonyl group as ethylene glycol ketal **10**, formylation to **11** and a subsequent one-pot sequence of an imine formation with propargylamine, reduction to the secondary amine and *N*-tosylation (Scheme 3). Both ethylene glycol ketals **11** and **12** gave single crystals for crystal structure investigation (Figure 1),[6] which show that in both one C–O bond of the ketal group is oriented parallel to the π-system of the furan ring. In **12** the alkyne subunit (C-11/C-12) has a large distance to the furan ring (C-1 to C-4, O-1), a conformation which is typical for these substrates.[3l]



Scheme 3. Synthesis of substrate **12**.

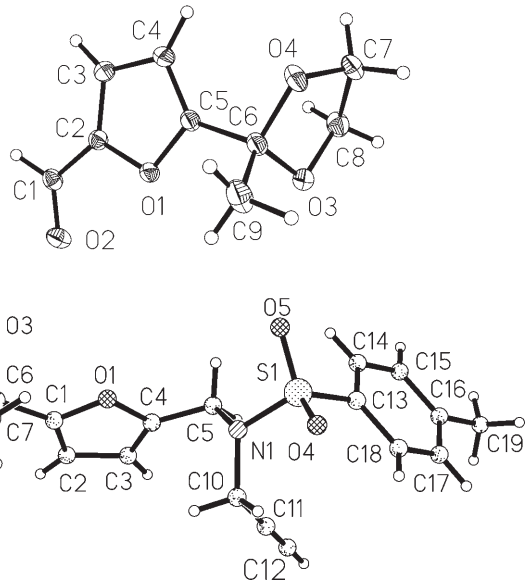
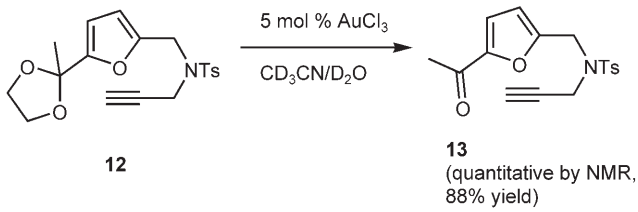


Figure 1. Structures of aldehyde **11** (*top*) and substrate **12** (*bottom*) in the solid state.

The first gold-catalysed reaction of the ketal **12** was disappointing; instead of the formation of the expected phenol **14**, a quantitative deprotection of the ketal to **13** was observed (88% yield after work-up, Scheme 4). Usually, water does not disturb the phenol

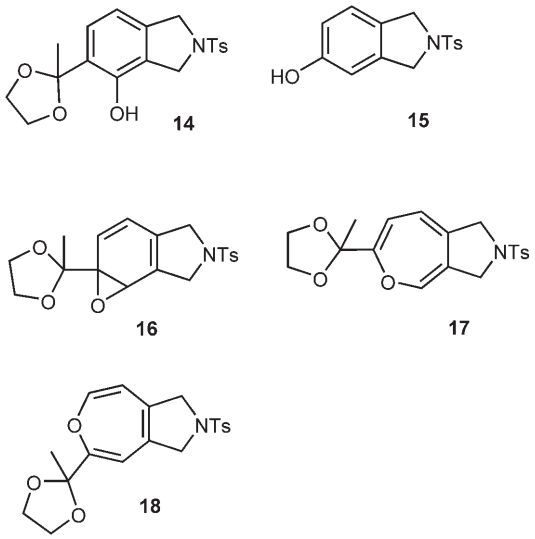


Scheme 4. $AuCl_3$ efficiently catalyzes the deprotection of ketal **12**.

synthesis,[3a] but with the reactive benzyl-like ketal it does. After the deprotection the acetyl substituent on the furan ring prevents a gold-catalysed phenol synthesis, this effect of acceptors in the phenol synthesis has been reported previously.[3l]

A similar experiment with 5 mol% $AuCl_3$ in absolute solvent and monitoring by ^{1}H NMR showed that traces of water still present led to a fast initial deprotection to a small extent, but once the water was consumed, a new set of signals was observed in the ^{1}H NMR spectra.

Work-up by column chromatography afforded four products: ketone **13**, phenol **15** and two unknown products. The spectra of these unknown products suggested for one of them the arene oxide structure **16**, for the other the oxepine structure **17** (Scheme 5). The arene oxide could not be isolated in pure form



Scheme 5. Phenols **14** and **15**, arene oxide **16** and constitutional isomeric oxepines **17** and **18** (ratio in the crude reaction mixture of the reaction of **12** with $AuCl_3$ in absolute solvent determined by ^1H NMR; **13**:**15**:**16** = 2:1:8).

and seemed to isomerise to the oxepine product on the chromatography column. This was not in accordance with the structures **16** and **17**, which should be valence tautomers that equilibrate.

Most fortunately, single crystals of the assumed oxepine could be obtained. The crystal structure analysis clearly proved an oxepine structure, which was not **17** but rather its constitutional isomer **18** (Figure 2).[6]

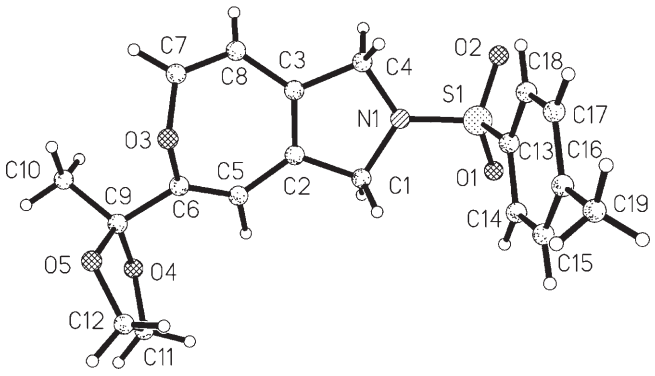
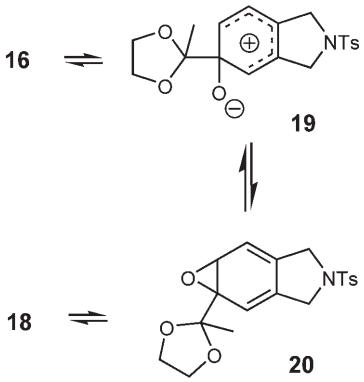


Figure 2. Structure of oxepine **18** in the solid state.

The migration of an oxygen atom in an arene oxide/oxepine system is well known in the literature as "oxygen walk";[7] in earlier work Vogel and Günther[8] have investigated related rearrangements. Kinetic investigations of Bruice et al.[9] proved that rather than an isomerisation to a dienone, the "oxygen walk" was the major route to the isomerisation products.

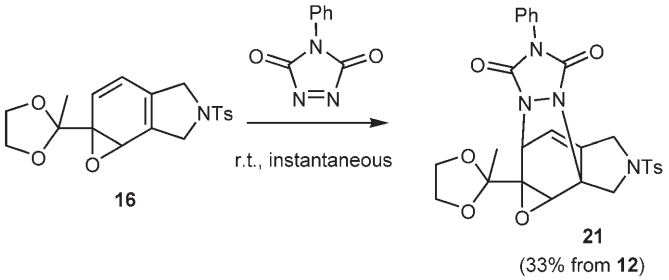
This mechanistic concept can explain the formation of oxepine **18**, too (Scheme 6).



Scheme 6. Oxygen-walk to oxepine **18**.

Opening of the oxirane ring of **16** gives the cyclohexadienyl cation **19**, which closes to the isomeric arene oxide **20**. The latter obviously is less stable than its valence tautomer **17**, in the literature there are numerous examples for one valence tautomer being clearly favoured.[10]

The structural assignment of the arene oxide was more difficult; in solution the species was stable for a long time, but it rearranged on all efforts to isolate it. Finally, besides precipitation at low temperatures (no single crystals were obtained), we succeeded in trapping it by a hetero-Diels–Alder reaction, which furnished the epoxide **21** and thus confirmed the structure suggested for **16** (Scheme 7). At room tempera-



Scheme 7. Trapping of arene oxide **16**.

ture the cycloaddition was instantaneous and could conveniently be monitored by the loss of the red colour of the *N*-phenyltriazolindione. Again, a crystal structure analysis unambiguously proved the constitution of the cycloadduct **21** (Figure 3).[6]

The spectroscopic data for **16** are clearly in accordance with an arene oxide structure, the epoxide proton at 4.10 ppm and the two vinylic protons at 6.30 and 6.47 ppm showing an *cis*-olefin-like $^3J_{H,H}$ of 9.80 Hz. These values are in good accordance with the previously reported arene oxide leading to **8** (3.87 ppm for the epoxide proton).[3g] As described there, the hydrogen atoms of the methylene groups are also non-equivalent and show a geminal coupling.

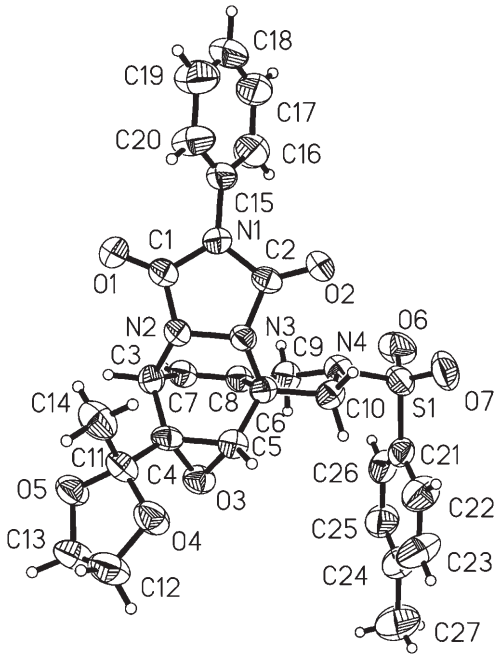
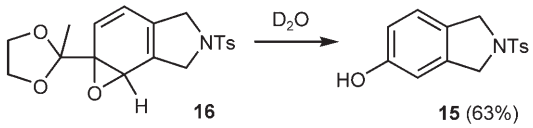


Figure 3. Structure of the Diels–Alder adduct **21** in the solid state.

When D_2O was added to the reaction mixture after a full conversion of **12** to **16**, a fast (about 30 min reaction time) formation of the phenol **15** was observed (Scheme 8).

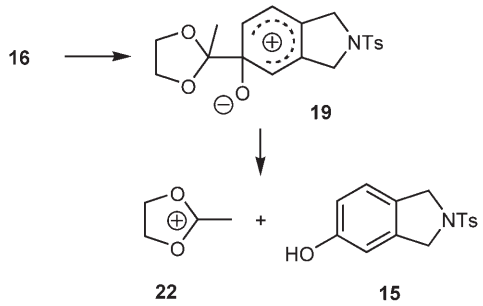


no 14

Scheme 8. With D_2O **16** forms **15**.

Why is phenol **15** and not the "normal" phenol **14** (coresponding to **2**) formed? The ring-opening of the arene oxides **6** to the phenols **2** proceeds *via* Wheland intermediates, which can aromatise by C–C bond cleavage if a stabilised cation can be eliminated. Similar C–C bond cleavages have been observed previously for the elimination of furyl cations.[3c] For **16** this means that **19** preferentially fragments to the stabilised cation **22** and the phenol **15** (Sheme 9)

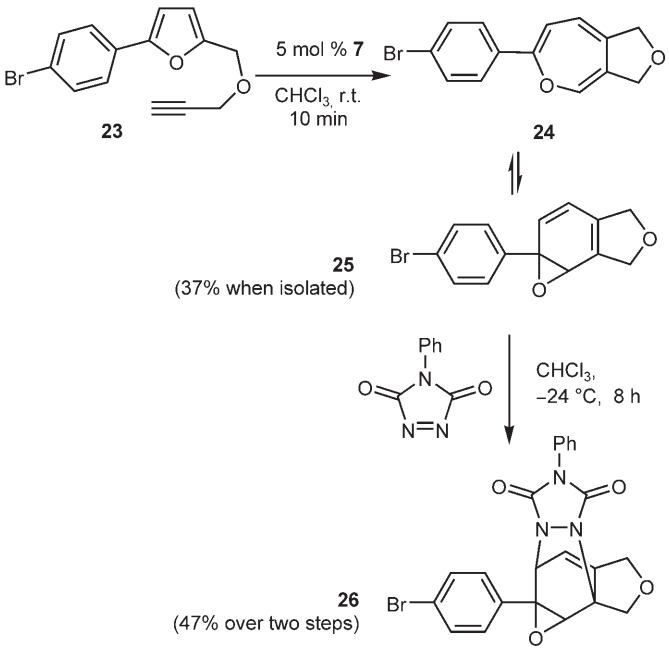
Synthetically, this is quite useful. If water is present from the beginning of the gold-catalysis, as shown in Scheme 4, **13** is formed by deprotection. If no water is present, the oxepine **18** is slowly formed from the initial product, the arene oxide **16**. If water is added to **16**, the constitutional isomer of the normal phenols of type **2**, the phenol **15**, is formed. So here the acetyl-di-



Scheme 9. Selective fragmentation to phenol **15**.

ethylene glycol acetal can be used as a directing group.

Next we tested the reaction of substrate **23**. When subjected to the pre-catalyst **7**, initially the oxepane **24** was observed (Scheme 10). The oxepane structure



Scheme 10. Generation of the oxepine **24** and reaction with *N*-phenyltriazolinedione.

was confirmed by the spectroscopic data, 5.55 ppm for the isolated olefinic proton, 6.24 and 6.34 ppm for the other two vinylic protons with a coupling constant of only 7.5 Hz and, most convincingly, no alkyl ^{13}C signals like the arene oxides discussed above but only olefinic ^{13}C methine signals between 117.05 and 132.39 ppm (in the arene oxides the epoxide methine signal occurred at 66.1 ppm). In **24** the hydrogen atoms of the methylene groups are homotopic and do not show a geminal coupling. As expected, the other valence tautomer is still present in low concentration. When *N*-phenyltriazolindione was added, the Diels–Alder adduct **26** was obtained from the equilibrium

with the arene oxide **25**, again as a single diastereomer. Adduct **26** shows the typical epoxide ^{1}H NMR signal at 3.95 ppm and a ^{13}C resonance of 53.28 ppm for the epoxy methine group.

Conclusions

The *in situ* formation of arene oxides is not always dependent on a specific ligand system; with the ketal substrate **12** only the arene oxide intermediate is formed, even with the simple $AuCl_3$ catalyst. Although the sensitive arene oxide intermediates cannot be isolated, these intermediates can selectively be converted to different products. The outcome depends on the reaction conditions, here a stable oxepine or a phenol with a specific substituion pattern were produced.

With the specific pre-catalyst **7** the aryl-substituted substrate **23** yields the oxepine **24** and not an arene oxide.

Experimental Section

General Remarks

The multiplicities were assigned to the ^{13}C NMR data *via* a combination of DEPT 135 and DEPT 90 spectra and are defined as follows: s (quarternary C), d (CH), t (CH_2), q (CH_3).

5-(2-Methyl-[1,3]dioxolan-2-yl)furan-2-carbaldehyde (11)

To **10**[11] (2.90 g, 18.8 mmol) in absolute THF (60 mL) under an atmosphere of nitrogen at −75 °C *n*-BuLi (1.6 mol/L *n*-BuLi in hexane, 11.7 mL, 1.00 equiv.) was added. After 3 h DMF (15 mL, large excess) was added, the reaction mixture was warmed to room temperature over night, hydrolysed with ice/water and then neutralised with 6 N HCl. After three extractions with ether (80 mL each) the combined organic phases dried over $MgSO_4$ filtered, the solvent evaporated and the residue purified by column chromatography on silica gel. Thus the known 2-acetylfurfural[11c,12] (420 mg, 16%) and the new **11** (680 mg, 20%) were obtained.

On account of these problems, the reaction was repeated with 3.00 g (19.5 mmol) of **10** and during the work-up no HCl was used. This led to **11** in a much higher yield (2.66 g, 75%). From diethyl ether single crystals of **11** for the X-ray crystal structure investigation were obtained.

2-Acetylfurfural: ^{1}H NMR (CD_3CN, 300 MHz): $\delta = 2.52$ (s, 3H), 7.30 (d, $J = 3.8$ Hz, 1H), 7.42 (d, $J = 3.8$ Hz, 1H), 9.75 (s, 1H). $C_7H_6O_3$ (138.12).

11: R_f (petrol ether:ethyl acetate, 2:1) = 0.29; column: petrol ether/ethyl acetate, 3:1; mp 34–36 °C; IR (film): $\nu =$ 3103, 2904, 1666, 1512, 1422, 1353, 1292, 1207, 1102, 1021, 982, 931, 824, 730 cm^{-1}; ^{1}H NMR (CD_3CN, 300 MHz): $\delta =$ 1.70 (s, 3H), 3.93–4.08 (m, 4H), 6.61 (d, $J = 3.4$ Hz, 1H), 7.31 (d, $J = 3.4$ Hz, 1H), 9.58 (s, 1H); ^{13}C NMR (CD_3CN, 126 MHz): $\delta = 23.34$ (q), 65.05 (t, 2C), 103.86 (d), 109.05 (d), 122.46 (s), 152.29 (s), 160.37 (s), 177.89 (d); MS (70 eV): *m/z* (%) = 182 (21) [M$^+$], 167 (100), 123 (63), 93 (23); anal. calcd. for $C_9H_{10}O_4$ (182.18): C 59.34, H 5.53; found: C 59.47, H 5.60.

4-Methyl-*N*-[5-(2-methyl-[1,3]dioxolan-2-yl)furan-2-ylmethyl]-*N*-prop-2-ynylbenzen-sulfonamide (12)

Substrate **11** (301 mg, 1.65 mmol), propargylamine (182 mg, 3.31 mmol, 2 equivs.) and $MgSO_4$ (1.00 g) in dichloromethane (6 mL) were stirred overnight. After filtration the solvent was removed under vacuum, the residue dissolved in methanol (15 mL) and $NaBH_4$ (62.5 mg, 1.65 mmol, 1 equiv.) were added. After 2 h water (20 mL) was added and it was extracted with ether (3 × 30 mL), dried over $MgSO_4$, filtered and the solvent evaporated under vacuum. To the residue tosyl chloride (285 mg, 1.49 mmol, 0.9 equiv.) and triethylamine (150 mg, 1.49 mmol, 0.9 equiv.) in dichloromethane (10 mL) was added. After two days the mixture was hydrolysed with water (20 mL), extracted with dichloromethane (3 × 30 mL), dried over $MgSO_4$, filtered and the solvent removed under vacuum. Column chromatography on silica gel furnished **12** as a colourless solid; yield: 403 mg (72%); R_f (petrol ether:ethyl acetate:dichloromethane, 10:1:2) = 0.12; mp 69–70 °C; IR (KBr): $\nu =$ 3231, 3098, 2972, 2875, 2082, 1678, 1588, 1417, 1340, 1250, 1150, 1075, 1021, 998, 876, 785, 640 cm^{-1}; ^{1}H NMR ($CDCl_3$, 500 MHz): $\delta = 1.64$ (s, 3H), 2.05 (t, $J = 2.5$ Hz, 1H), 2.40 (s, 3H), 3.94–4.02 (m, 6H), 4.40 (s, 2H), 6.19 (d, $J = 3.2$ Hz, 1H), 6.20 (d, $J = 3.2$ Hz, 1H), 7.27 (d, $J = 8.2$ Hz, 2H), 7.71 (d, $J = 8.2$ Hz, 2H); ^{13}C NMR ($CDCl_3$, 62.9 MHz): $\delta = 21.53$ (q), 24.07 (q), 36.32 (t), 42.92 (t), 65.11 (t, 2C), 73.89 (d), 76.51 (s), 104.40 (s), 107.28 (d), 110.13 (d), 127.72 (d, 2C), 129.51 (d, 2C), 135.97 (s), 143.62 (s), 148.59 (s), 154.94 (s); MS (70 eV): *m/z* (%) = 375 (16) [M$^+$], 360 (55), 220 (100), 204 (60), 192 (20), 176 (47), 91 (19); anal. calcd. for $C_{19}H_{21}NO_5S$ (375.45): C 60.78, H 5.64, N 3.73; found: C 60.83, H 5.69, N 3.65.

Evaporation of a solution of **12** in dichloromethane/ether delivered single crystals suitable for the crystal structure investigation.

Gold-Catalyzed Reaction of 12 in the Presence of Water

Substrate **12** (101 mg, 269 μmol) was dissolved in 0.5 mL CD_3CN in an NMR tube and D_2O (0.2 mL) were added. Then at room temperature a stock solution of $AuCl_3$ (10 wt% in CD_3CN, 40.8 mg, equivalent to 4.08 mg $AuCl_3$, 13.5 μmol) was added. The reaction was monitored by ^{1}H NMR spectroscopy. *In situ* NMR showed quantitative and selective deprotection within 20 min. After that the solvent was removed and the residue was purified by column chromatography on silica gel to afford *N*-(5-acetylfuran-2-ylmethyl)-4-methyl-*N*-prop-2-ynylbenzensulfonamide (**13**) as a yellow solid; yield: 78 mg (88%); R_f (petrol ether:ethyl acetate, 2:1) = 0.25; mp 72–74 °C; IR (film): $\nu =$ 3296, 3113, 1650, 1511, 1344, 1304, 1257, 1217, 1157, 1092, 1051, 980, 922, 873, 817, 736 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): $\delta = 2.10$ (t, $J =$ 2.5 Hz, 1H), 2.39 (s, 3H), 2.41 (s, 3H), 4.08 (d, $J = 2.5$ Hz, 2H), 4.49 (s, 2H), 6.44 (d, $J = 3.5$ Hz, 1H), 7.08 (d, $J =$ 3.5 Hz, 1H), 7.29 (d, $J = 8.3$ Hz, 2H), 7.72 (d, $J = 8.3$ Hz,

2H); ^{13}C NMR ($CDCl_3$, 75.5 MHz): $\delta = 21.61$ (q), 25.98 (q), 37.02 (t), 43.30 (t), 74.49 (d), 76.17 (s), 111.85 (d), 118.04 (d), 127.72 (d, 2C), 129.72 (d, 2C), 135.66 (s), 144.07 (s), 152.80 (s), 153.85 (s), 186.61 (s); MS (FAB positive ion, matrix: 3-nitrobenzyl alcohol): *m/z* (%) = 332 (100)[MH^+], 221 (16), 123 (40), 91 (12); anal. calcd. for $C_{17}H_{17}NO_4S$ (331.39): C 61.61, H 5.17, N 4.23; found: C 60.85, H 5.15, N 4.12; HR-MS (FAB positive ion, matrix: 3-nitrobenzyl ackohol): *m/z* = 332.0950, calcd. for $C_{17}H_{17}NO_4S + H^+$: 332.0957.

Gold-Catalyzed Conversion of 12 with $AuCl_3$ in Absolute Solvent

Substrate **12** (101 mg, 269 μmol) was dissolved in 0.5 mL CD_3CN in an NMR tube and at room temperature a stock solution of $AuCl_3$ in CD_3CN (10 wt%, 40.8 mg, equivalent to 4.08 mg $AuCl_3$, 13.5 μmol) was added. The reaction was monitored by ^{1}H NMR spectroscopy:

Initially the cleavage of the ketal group furnished a small amount of **13** and small peaks of **15** became visible. After 10 min this came to an end and the formation of the arene oxide **16** was observed. Most of the conversion took place in the first 30 min, but then the reaction became very slow and even after 90 min there were still signals of the starting material visible. The solvent was removed under vacuum and the residue was purified by column chromatography. Under these work-up conditions **16** isomerized to **18**. The R_f values are quite similar, thus a complete separation was a significant problem. In particular, **16** was always contaminated with **15** and **18**, a clear evidence for the latter two compounds being formed from **16** on the column. Product **18** cannot be detected in the ^{1}H NMR spectra of the crude reaction mixture.

From the column the following amounts of pure compounds could be obtained in addition to some fractions which contained a mixture of two of the products: 8 mg (9%) of **13** as a yellow solid, 18 mg (18%) of **18** as a colourless solid, and 5 mg (6%) of **15** as a colourless solid. Also, 22 mg of **16** as a colourless solid were obtained, but it contained impurities of **15** and **18**. Single crystals for the crystal structure analysis of **18** were obtained from acetonitrile.

2-(4-Toluenesulfonyl)-2,3-dihydro-1*H*-isoindol-5-ol (**15**):[3a] ^{1}H NMR ($CDCl_3$, 300 MHz): $\delta = 2.40$ (s, 3H), 4.53 (m, 2H), 4.55 (m, 2H), 5.10 (s, 1H, OH), 6.63 (d, $J = 2.3$ Hz, 1H), 6.70 (dd, $J = 8.3$ Hz, 2.3 Hz, 1H), 7.00 (d, $J = 8.3$ Hz, 1H), 7.31 (d, $J = 8.3$ Hz, 2H), 7.75 (d, $J = 8.3$ Hz, 2H).

1a-(2-Methyl-[1,3]dioxolan-2-yl)-5-(toluen-4-sulfonyl)-4,5,6,6b-tetrahydro-1a*H*-1-oxa-5-aza-cyclopropa[*e*]indene (**16**): R_f (petrol ether:ethyl acetate:dichloromethane, 10:2:3) = 0.20; ^{1}H NMR (CD_3CN, 500 MHz): $\delta = 1.36$ (s, 3H), 2.43 (s, 3H), 3.86–3.94 (m, 4H), 4.10 (s, 1H), 4.25 (t, $J^* = 4.3$ Hz, 2H), 4.58 (t, $J^* = 4.3$ Hz, 2H), 6.30 (d, $J = 9.8$ Hz, 1H), 6.47 (d, $J = 9.8$ Hz, 1H), 7.42 (d, $J = 8.2$ Hz, 2H), 7.74 (d, $J = 8.2$ Hz, 2H).

5-(2-Methyl-[1,3]dioxolan-2-yl)-2-(toluen-4-sulfonyl)-2,3-dihydro-1*H*-oxepino[4,5-*c*]pyrrole (**18**): R_f (petrol ether:ethyl acetate:dichloromethane, 10:2:3) = 0.20; mp 92–93 °C; IR (film): $\nu = 2359$, 2184, 1642, 1342, 1163, 1103 cm^{-1}; ^{1}H NMR (CD_3CN, 300 MHz): $\delta = 1.46$ (s, 3H), 2.44 (s, 3H), 3.86–3.94 (m, 4H), 4.17 (s, 4H), 5.57 (d, $J = 5.0$ Hz, 1H), 5.78 (d, $J = 5.0$ Hz, 1H), 5.87 (s, 1H), 7.43 (d, $J = 8.3$ Hz, 2H), 7.73 (d, $J = 8.3$ Hz, 2H); ^{13}C NMR ($CDCl_3$, 300 MHz): $\delta = 20.19$ (q), 22.59 (q), 55.64 (t), 55.79 (t), 64.45 (t, 2C), 105.20 (s), 107.45 (d), 112.66 (d), 127.21 (d, 2C), 129.60 (d, 2C), 132.77 (s), 132.85 (d), 133.06 (s), 138.07 (s), 143.90 (s), 149.32 (s); MS (EI in CI-volume): *m/z* (%) = 375 (12) [M^+], 288 (22), 220 (15), 134 (100), 91 (38); HR-MS (EI positive ion in CI volume): *m/z* = 375.1124, calcd. for $C_{19}H_{21}NO_5S$: 375.1140.

5,7,8,9-Tetrahydro-13-(2-methyl-[1,3]dioxolan-2-yl)-8-[(4-methylphenyl)sulfonyl]-2-phenyl-5,9a-*endo*-oxirano-1*H*,9a*H*-pyrrolo[3,4-*c*][1,2,4]triazolo[1,2-*a*]pyridazine-1,3(2H)-dione (21)

The previous reaction was repeated on the same scale and when **16** had formed, at room temperature small portions of 4-phenyl-1,2,4-triazoline-3,5-dion were added until no decolourisation was observed any more. In all 26.2 mg (150 mmol) of the trapping reagent were needed, decolourisation took only seconds. The solvent was removed and the residue was purified by column chromatography on silica gel. Thus **21** were obtained as a colourless solid; yield 49.2 mg (33% over both steps). R_f (PE:EE, 1:1) = 0.28; mp 99–101 °C; IR (film): $\nu = 1770$, 1707, 1599, 1494, 1400, 1341, 1230, 1152, 1103, 950, 881, 810, 762 cm^{-1}; ^{1}H NMR ($CDCl_3$, 500 MHz): $\delta = 1.43$ (s, 3H), 2.43 (s, 3H), 3.61 (s, 1H), 3.75 (d, $J = 7.5$ Hz, 1H), 3.89 (dd, $J = 14.7$ Hz, 2.5 Hz, 1H), 3.94 (m, 5H), 4.89 (d, $J = 11.7$ Hz, 1H), 5.38 (d, $J = 6.1$ Hz, 1H), 6.05 (dt, $J = 6.1$ Hz, 2.1 Hz, 1H), 7.33–7.38 (m, 5H), 7.41–7.45 (m, 2H), 7.76 (d, $J = 8.4$ Hz, 1H, 2H); ^{13}C NMR ($CDCl_3$, 126 MHz): $\delta = 21.69$ (q), 22.00 (q), 48.52 (d), 48.67 (t), 51.21 (t), 54.58 (d), 56.52 (s), 65.62 (t), 66.39 (t), 70.44 (s), 107.01 (s), 116.56 (d), 125.61 (d, 2C), 128.22 (d, 2C), 128.52 (d), 129.16 (d, 2C), 129.98 (d, 2C), 131.18 (s), 132.61 (s), 138.96 (s), 144.44 (s), 154.05 (s), 154.18 (s). MS (FAB positive ion, matrix: 3-nitrobenzyl alcohol): *m/z* (%) = 551 (100) [MH^+], 374 (34); HR-MS (FAB positive ion, matrix: 3-nitrobenzyl alcohol): *m/z* = 551.1598, calcd. for $C_{27}H_{26}N_4O_7S + H^+$: 551.1600; anal. calcd. for $C_{27}H_{26}N_4O_7S$ (550.58): C 58.90, H 4.76, N 10.18; found: C 57.62, H 4.92, N 9.38.

From a mixture of petroleum ether, dichloromethane and diethyl ether suitable crystals for the X-ray crystal structure analysis could be obtained. **21**:

Reaction of 16 with D_2O

To **12** (101 mg, 269 μmol) in 0.5 mL CD_3CN in an NMR tube, a stock solution of $AuCl_3$ in CD_3CN (10 wt%, 40.8 mg, corresponiding to 4.08 mg $AuCl_3$, 13.5 μmol, 5 mol%) was added at room temperature. The reaction was monitored by ^{1}H NMR. After the conversion to **16** had stopped, D_2O (2 mL) was added. ^{1}H NMR showed that **16** was converted to **15** and the remaining starting material **12** was deprotected to **13**. Water (10 mL) was added, after three extractions with dichloromethane (10 mL each) the combined extracts were dried over $MgSO_4$, filtered and the solvent was removed under vacuum. Column chromatography on silica gel furnished **13** (12 mg, 13%) and **15** (49 mg, 63%).

6-(4-Bromphenyl)-1*H*,3*H*-furo[3,4-*c*]oxepine (24)

Substrate **23** (100 mg, 343 μmol) was dissolved in absolute chloroform (1.5 mL) and catalyst **7** (6.4 mg, 17 μmol) was added. After 10 min a layer of petroleum ether was added

and the solution was stored at −28 °C. After 5 days a brownish precipitate containing yellow-brown spherical particles had formed. The solvent was removed with a pipette and the spherical particles selected with a tweezers. Thus **24**, which slowly decomposed to the corresponding phenol, was obtained; yield: 37 mg (37 %). IR (film): ν = 3075, 2878, 2822, 1711, 1606, 1476, 1428, 1354, 1269, 1221, 1164, 1116, 1032, 831, 770, 700, 663, 606 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz): δ = 4.63 (s, 2H), 4.65 (s, 2H), 5.33 (s, 1H), 6.24 (d, J = 7.5 Hz, 1H), 6.34 (d, J = 7.5 Hz, 1H), 7.41–7.49 (m, 4H); ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ = 70.25 (t), 72.94 (t), 112.14 (s), 117.05 (d), 121.50 (d), 122.54 (s), 125.53 (s), 127.26 (d, 2 C), 131.81 (d, 2 C), 132.39 (d), 135.51 (s), 140.13 (s). $C_{14}H_{11}O_2Br$ (291.14).

Reaction of the Intermediate Oxepine Obtained from 23 with 4-Phenyl-1,2,4-triazoline-3,5-dione

To **23** (100 mg, 343 μmol) in absolute chloroform (5 mL) the catalyst **7** (6.5 mg, 17.2 μmol, 5 mol %) was added. After 90 min at room temperature, when in the ^1H NMR only signals of the oxepine **24** were visible, the reaction mixture was cooled to 0 °C. Then 4-phenyl-1,2,4-triazoline-3,5-dione (60.1 mg, 343 μmol) was added. The initially red solution quickly turned light brown. It was stored at −28 °C overnight. Column chromatograpy on silica gel (petroleum ether:acetone:dichloromethane, 10:1:1) furnished **26** as a yellow solid; yield: 75 mg (47 %). R_f (petrol ether:aceton:dichloromethane, 10:1:1) = 0.08; mp 78–80 °C; IR (film): ν = 2923, 2848, 1771, 1711, 1593, 1495, 1399, 1244, 1140, 1054, 1009, 908, 850, 823, 763, 721, 688, 649 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ = 3.85 (s, 1H), 4.35 (ddd, J = 14.3 Hz, 2.6 Hz, 0.7 Hz, 1H), 4.59 (ddd, J = 14.3 Hz, 1.8 Hz, 0.7 Hz, 1H), 5.28 (d, J = 11.1 Hz, 1H), 5.28 (d, J = 11.1 Hz, 1H), 5.58 (d, J = 5.9 Hz, 1H), 6.15 (dt*, J = 5.9 Hz, J = 2.1 Hz, 1H), 7.53–7.38 (m, 7H), 7.64–7.59 (m, 2H). (* expected: ddd, ^3J = 5.9 Hz, ^4J = 2.6 Hz, ^4J = 1.8 Hz); ^{13}C NMR ($CDCl_3$, 62.9 MHz): δ = 53.28 (d), 55.64 (s), 59.28 (d), 68.26 (t), 70.48 (t), 73.95 (s), 114.45 (d), 123.36 (s), 127.37 (d, 2 C), 129.07 (d, 2 C), 129.65 (d), 130.06 (d, 2 C), 132.30 (s), 132.83 (d, 2 C), 134.96 (s), 143.92 (s), 155.64 (s), 156.17 (s); MS (EI 70 eV): m/z (%) = 467 (1) [$^{81}Br-M^+$], 465 (1) [$^{79}Br-M^+$], 322 (9), 292 (60), 290 (63), 263 (41), 261 (39), 183 (36) , 182 (39), 181 (36), 119 (100); HR-MS (EI, 70 eV): m/z = 465.0324, calcd. for $C_{22}H_{16}BrN_3O_4$: 465.0324.

As a side-product the known aldehyde formed by the hydrolysis of the intermediate gold carbenoid species[3k] (4.1 mg, 4 %) was isolated.

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[6] CCDC 631909 (**11**), 631911 (**12**), 631912 (**18**) and 631913 (**21**) contain the supplementary crystallographic data for this paper. These data can be obtained online free of charge (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223–336–033; or mailto:deposit@ccdc.cam.ac.uk).

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