Cyclic Hypervalent Iodine Reagents for Azidation: Safer Reagents and Photoredox-Catalyzed Ring Expansion

Sebastien Alazet,†,⊥ Johannes Preindl,†,⊥ Raphael Simonet-Davin,† Stefano Nicolai,† Annik Nanchen,‡ Thierry Meyer,§ and Jerome Waser*†

†Laboratory of Catalysis and Organic Synthesis, Institute of Chemical Sciences and Engineering, Ecole Polytechnique Fédérale de Lausanne, EPFL SB ISIC LCSO, BCH 4306, CH-1015 Lausanne, Switzerland
‡Process Safety, TÜV SÜD Schweiz AG, CH-4002 Basel, Switzerland
§Group of Chemical and Physical Safety, Institute of Chemical Sciences and Engineering, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

ABSTRACT: Azides are building blocks of increasing importance in synthetic chemistry, chemical biology, and materials science. Azidobenziodoxolone (ABX, Zhdankin reagent) is a valuable azide source, but its safety profile has not been thoroughly established. Herein, we report a safety study of ABX, which shows its hazardous nature. We introduce two derivatives, tBu-ABX and ABZ (azidobenziodazolone), with a better safety profile, and use them in established photoredox- and metal-mediated azidations, and in a new ring-expansion of silylated cyclobutanols to give azidated cyclopentanones.

Organic azides are versatile building blocks in synthetic chemistry, chemical biology, and materials science. Therefore, the development of a new synthetic methodology to access them is an important field of research. In this context, azide-containing hypervalent iodine(III) reagents derived from iodobenzene have been known for a long time as sources of electrophilic azides or azido radicals. Nevertheless, these reagents are highly unstable at room temperature and need to be generated in situ.

In 1994, an important progress was realized by Zhdankin and co-workers, shortly followed by Kita and co-workers, with the isolation of the first cyclic hypervalent iodine reagents being stable up to 100 °C: the azidobenziodoxol(on)es (ABX) 1a−1c (Scheme 1A). Zhdankin demonstrated the functionalization of C−H bonds with azidobenziodoxolone 1a (Zhdankin reagent) under mild thermal activation with or without dibenzoyl peroxide as the initiator. Surprisingly, this result did not attract the attention it should have, and it was only in 2013 that our group, as well as Gade and co-workers, reported the excellent properties of ABX reagents as a source of electrophilic azides, whereas Studer and co-workers reported reductive conditions to generate azido radicals from 1a. Since then, the Zhdankin reagent 1a has established itself as an excellent azide source, either under thermal, or metal-mediated activation.

In 2017, our group reported the divergent reactivity of the Zhdankin reagent (1a) and azidobenziodoxole 1b in the azidolactonization of alkenes (Scheme 1B). Whereas 1a was ideally suited for 1,2-azidation under photoredox conditions, Lewis acid activation of 1b led to 1,1-azidolactonization via an 1,2-aryl shift. On the basis of these results, we wondered if we could also develop an azidative ring-expansion of alkene-substituted cyclobutanol derivatives via reaction with azido radicals (Scheme 1C). Such ring expansions are usually initiated by the addition of electrophilic or organometallic intermediates onto the olefin. More recently, the addition of a radical followed by oxidation and an 1,2-shift under photoredox conditions has emerged as a very efficient approach for ring

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expansion,\textsuperscript{14} but it has never been reported for the synthesis of organic azides.\textsuperscript{15} Preliminary results with the Zhdankin reagent (1\texttext{a}) using a copper photoredox catalyst were highly promising, but a spontaneous explosion of a pure sample of 1\texttext{a} in our laboratory made us aware of serious safety hazards.

Herein, we report safety studies of the Zhdankin reagent (1\texttext{a}), which highlighted a very high shock and friction sensitivity.\textsuperscript{16} The stability of two higher weight derivatives (tBu-ABX (1\texttext{c}) and ABZ (azidobenziodiazolone 2), Scheme 1\texttext{C}) was investigated, showing an enhanced safety profile. ABZ (2), in particular, was well suited for the generation of azido radicals under mild photoredox conditions, allowing us to develop the desired ring expansion in high yield and with a broad scope. Finally, we demonstrate that either tBu-ABX (1\texttext{d}) or ABZ (2) can be used as alternatives to the Zhdankin reagent in a broad range of transformations involving thermal, photoredox, or metal-mediated activation.

On the basis of our photocatalyzed azidolactonisation work,\textsuperscript{11} we started our investigations on the tandem azidation-ring expansion by reacting 1-(1-phenylvinyl)cyclobutanol (3\texttext{a}) with ABX (1\texttext{a}) (2.0 equiv) as an azide precursor in acetonitrile in the presence of Cu(dap)\texttext{2}Cl (5)\texttext{(0.5–1 mol %)} under blue LED irradiation (eq 1). The expected product 6\texttext{a} was obtained in 57\% yield as a mixture with 25\% of 1,2-azido-epoxide 7\texttext{a}. To avoid this oxyzidation process, the silyl-protected precursor 4\texttext{a} was used, and the ring-expansion product 6\texttext{a} could be obtained in an improved 79\% yield.

However, during further optimization studies, a freshly prepared batch of ABX reagent (1\texttext{a}) (500 mg) spontaneously exploded when the researcher was handling the reagent with a spatula in a glass flask, causing multiple serious cuts and burns.\textsuperscript{18} We therefore decided to stop experimentation with reagent 1\texttext{a} until its safety profile had been further evaluated. In addition, we synthesized the azidobenziodoxolone reagents tBu-ABX (1\texttext{d}) and ABZ (2) with higher molecular weight, hoping that the lower proportional azide content would diminish their explosion potential (Scheme 1\texttext{C}). Both reagents 1\texttext{d} and 2 are easy accessible on gram scale from 4-tert-butyl toluene (3.4 g in 5 steps and 31\% overall yield) and 2-iodobenzoic acid (5.4 g in 4 steps and 30\% overall yield), respectively.

The stability of the compounds was then determined by differential scanning calorimetry (DSC, Figure 1 and Table 1).\textsuperscript{19} According to Stoesszel,\textsuperscript{20} thermal risk is the combination of the severity (expressed by the average heat release) and the likelihood of occurrence (defined as TD\textsubscript{24} corresponding to the temperature at which the time to the maximum rate of the decomposition reaction is 24 h). Mage et al.\textsuperscript{21} defined a 3 \times 3 risk matrix using both the released energy and the TD\textsubscript{24}. Compounds with severity higher than 400 kJ/kg and TD\textsubscript{24} below 150 °C are classified in the most hazardous category. The DSC results (see Table 1) revealed a heat release of 1770 kJ/kg for the Zhdankin reagent (1\texttext{a}), 1440 kJ/kg for tBu-ABX (1\texttext{d}), and 965 kJ/kg (first peak, with a second peak of 380 kJ/kg) for ABZ (2). Onset temperatures were higher for 1\texttext{d} and 2. Estimated values\textsuperscript{22} for TD\textsubscript{24} are 45 °C for the Zhdankin reagent (1\texttext{a}), 52 °C for tBu-ABX (1\texttext{d}), and 88 °C for ABZ (2). Therefore, all three compounds have a high severity and likelihood of occurrence, with the Zhdankin reagent having the highest thermal potential hazard.

Another safety parameter for these compounds is related to impact sensitivity. A Fallhammer test showed limiting energies of 1, 2, and 5 J for reagents 1\texttext{a}, 1\texttext{d}, and 2 (Table 1). As a comparison, the energy released by the fall of a flask on the floor can be estimated to 3.4 J and of a spatula in a flask to 0.1 J.\textsuperscript{23} Both scenarios are hazardous for the Zhdankin reagent (1\texttext{a}), even if the lower limit for impact could not be determined experimentally. In addition, all three reagents were sensitive to a friction load of 360 N on a porcelain plate. The results for ABZ (2) and tBu-ABX (1\texttext{d}) were, however, most probably false positives as they showed no friction sensitivity on Alox plates.

In light of the preliminary safety studies, ABZ (2) is the most stable reagent to use as an azide source. Motivated by the better safety profiles of tBu-ABX (1\texttext{d}) and, especially, ABZ (2), we then investigated the use of these reagents in the ring expansion reaction. The best results were obtained with ABZ (2), and the desired product 6\texttext{a} was obtained in 90\% yield after a short optimization (Scheme 2).\textsuperscript{24} This is an important result, demonstrating that Zhdankin and ABZ reagents 1\texttext{a} and 2 have similar efficiency in the generation of azido radicals under photoredox conditions. The scope of the transformation was broad, and para-substituted styrenes with alkyl-, phenyl-, as well as methoxy-, and chlorine-groups gave the desired cyclopentanones 6\texttext{a–g} in excellent yields. Cyclopentanones 6\texttext{h–j} and 6\texttext{k} with either a meta or an ortho substituent on the arene ring were also obtained in very good yields. Meta, para-disubstituted derivatives 6\texttext{l–n} were as well isolated in very good yields. 1-Naphthyl substituted 6\texttext{o} was isolated in 95\% yield, whereas the more hindered 2-naphthyl derivative 6\texttext{p} was obtained in 79\% yield. Interestingly, oxetanes were suitable substrates for the ring expansion reaction, and 3-furanone 6\texttext{q} was obtained in 58\% yield. However, the corresponding Boc-protected acetidine did not react. Styrenes with 1,2 disubstituted olefins were also not suitable substrates, and the secondary azide 6\texttext{r} was not obtained. A surprising result was observed when the para-CF\textsubscript{3}-substituted styrene 4\texttext{t} was subjected to the optimized reaction conditions: epoxide 7\texttext{t} was isolated as the only product. Azides are versatile functional groups, and the obtained products were readily converted into useful structural motives, such as triazoles, protected amines, or isothiocyanates.

When considering the better safety profile of ABZ (2) and to a lesser extend tBu-ABX (1\texttext{d}), we decided to investigate their
use in other transformations recently discovered using ABX (1a). First, we examined the azidolactonisation previously reported in our group (eq 2). The reaction of alkene 8 gave 76% yield of azidolactone 9 with ABX (1a), 56% with tBu-ABX (1d), and 81% with ABZ (2). This result definitively confirmed that ABZ (2) is an excellent and safer substitute of ABX (1a) for the generation of azide radicals under photoredox conditions. Another azidative cyclization, but using thermal activation, was then investigated (eq 2). The cyclization of 10 to give azide 11 has been reported in 70% yield with ABX (1a) by the Nevado group. tBu-ABX (1d) gave 64% yield of 11, but ABZ did not show any reactivity at 60 °C. However, by heating at 100 °C, 11 could be obtained in 43% yield with ABZ (2). This is in good accordance with the higher thermal stability of ABZ (2), requiring higher temperature for activation. Next, metal-catalyzed azidation processes were examined, starting with the iron-catalyzed sp3 C−H azidation reported by Hartwig and co-workers (eq 4). The representative reaction selected was the azidation of cumene (12). Compared to ABX (1a) set at 1.00, relative yields of 1.81 and 0.06 were obtained for tBu-ABX (1d) and ABZ (2), respectively, by GC-MS. This result may be due to the relative solubility of the reagents in ethyl acetate: ABZ (2) was nearly insoluble, while tBu-ABX (1d) was more soluble than ABX (1a). As a next example, we examined the copper-catalyzed SP2 C−H bond azidation of anilines reported by Hao and co-workers (eq 5). Azide 15 was obtained in 63, 62, or 72% yields using reagents 1a, 1d, or 2, respectively, from p-toluidine (14). Finally, the copper-catalyzed aminoazidation of olefins developed by Wang and co-workers was examined on alkene 16 (eq 6). Again, no significant difference of reactivity between the reagents was observed, and the use of ABZ (2) should be favored.

In summary, we have reported the first in-depth safety studies of the hypervalent iodine azidation reagents ABX (Zhdankin reagent, 1a), tBu-ABX (1d), and ABZ (2), showing the better profile of the latest in particular. ABZ (2) was as efficient as the Zhdankin reagent (1a) in a new photoredox-mediated ring expansion process as well as in established radical- or metal-mediated transformations. When considering the growing importance of hypervalent iodine reagents for azide transfer in synthetic chemistry, we are convinced that our work will be highly useful for researchers to continue to exploit their amazing reactivity in safer settings.

Table 1. Safety Test Results

<table>
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<th>test data</th>
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<sup>a</sup>Large variation in onset temperature between two measurements. <sup>b</sup>First peak. <sup>c</sup>Second peak.

Scheme 2. Scope of the Ring Expansion Reaction

ABX (1a) set at 1.00, relative yields of 1.81 and 0.06 were obtained for tBu-ABX (1d) and ABZ (2), respectively, by GC-MS. This result may be due to the relative solubility of the reagents in ethyl acetate: ABX (2) was nearly insoluble, while tBu-ABX (1d) was more soluble than ABX (1a). As a next example, we examined the copper-catalyzed SP2 C−H bond azidation of anilines reported by Hao and co-workers (eq 5). Azide 15 was obtained in 63, 62, or 72% yields using reagents 1a, 1d, or 2, respectively, from p-toluidine (14). Finally, the copper-catalyzed aminoazidation of olefins developed by Wang and co-workers was examined on alkene 16 (eq 6). Again, no significant difference of reactivity between the reagents was observed, and the use of ABZ (2) should be favored.

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**EXPERIMENTAL SECTION**

**General Methods.** All reactions were carried out in oven- or flame-dried glassware under a nitrogen atmosphere, unless stated otherwise. For quantitative flash chromatography, distilled technical grade solvents were used. THF, Et2O, CH3CN, and CH2Cl2 were dried by passage over activated alumina under a nitrogen atmosphere (H2O content < 7 ppm, Karl Fischer titration). NEt3 was dried by distillation over CaH2 under a nitrogen atmosphere. All chemicals were purchased and used as received, unless stated otherwise.

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<sup>a</sup>Large variation in onset temperature between two measurements. <sup>b</sup>First peak. <sup>c</sup>Second peak.
Chromatographic purification was performed as flash chromatography using Macherey–Nagel silica 40–63, 60 Å, using the solvents indicated as the eluent with 0.1–0.5 bar pressure. TLC was performed on Merck silica gel 60 F254 TLC aluminum plates and visualized with UV-light, permanganate, CAM, or p-anisaldehyde stains. 1H NMR spectra were recorded at room temperature on a Bruker DPX-400 400 MHz spectrometer in chloroform-d or d6-DMSO; all signals are reported in ppm with the internal chloroform signal at 7.26 ppm or the internal d9-DMSO signal at 2.50 ppm as the standard. The data are being reported as (s = singlet, d = doublet, t = triplet, q = quartet, dq = doublet of quartets, m = multiplet or unresolved, br = broad signal, integration, coupling constant(s) in Hz, interpretation). 13C NMR spectra were recorded with 1H-decoupling on a Bruker DPX-400 101 MHz spectrometer in chloroform-d or d6-DMSO; all signals are reported in ppm with the internal chloroform signal at 77.00 ppm or the internal DMSO signal at 39.51 ppm as the standard. Infrared spectra were recorded on a JASCO FT-IR B4100 spectrophotometer with an ATR PRO4100-S and a ZnSe prism and are reported as cm⁻¹ (w = weak, m = medium, s = strong). High-resolution mass spectrometric measurements were performed by the mass spectrometry service of ISIC at the EPFL on a MICROMASS (ESI): Q-TOF Ultima API. Melting points were measured on a Buechi B-540 melting point apparatus and were not corrected. Reactions were performed in test tubes (1.0–0.0 mL), which were held using a rack for test tubes placed at the center of a crystallization flask. On this flask, were attached the LEDs (LED ribbon cable with open ends, Barthelme Y51515213 182007 12 V 502 cm green 1 pc(s), both purchased directly on www.conrad.ch/fr). The distance between the LEDs and the test tubes was approximately 3–4 cm. Long irradiation for more than 2 h resulted in the temperature increasing up to 34 °C. 3GC-MS analysis was performed on a TSQ 8000 EVO coupled with TRACE 1300 through a Sebron ZB-5 ms column. The injection volume was 1 μL at 250 °C, and the gradient started at 50 °C for 3 min, then 15 °C/mins up to 300 °C, and finally 300 °C for 10 min. Reactions under microwave irradiation were performed using a Biotage Initiator reactor in a sealed vial using external temperature control.

Synthesis of ABX (1a). Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a reported procedure, 2-iodobenzoic acid (18) (13.6 g, 54.8 mmol, 1.0 equiv) and NaOAc (17 g, 81 mmol, 1.0 equiv) were suspended in ac. AcOH (30% v/v, 83 mL). The mixture was stirred at reflux (120 °C) for 4 h. Past this time, ice-cold water (80 mL) was added under stirring, and the mixture was allowed to cool down to room temperature, while being protected from light with aluminum foil. It was then filtered, and the solid was washed with ice-cold water (3 × 70 mL) and cold acetone (3 × 70 mL). The resulting colorless solid (HO-BX, 13.4 g, 50.6 mmol, 92% yield) was allowed to dry in the air overnight and then directly used in the next step. 1H NMR (400 MHz, d6-DMSO, δ): 8.02 (dd, J = 7.7, 1.4 Hz, 1H), 7.97 (m, 1H), 7.85 (dd, J = 8.2, 0.7 Hz, 1H), 7.71 (td, J = 7.6, 1.2 Hz, 1H) ppm. 13C{1H} NMR (100 MHz, d6-DMSO, δ): 167.7, 134.5, 131.5, 131.1, 130.4, 126.3, 120.4 ppm. The signals of the NMR spectra were in accordance with the data reported in the literature. 7b Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a reported procedure, 2-AcO-BX (1.00 g, 3.28 mmol, 1.00 equiv, synthesized in our laboratory) was stirred in dry DCM (3 mL), and then TMSN3 (0.66 mL, 4.9 mmol, 1.5 equiv, 94% yield, catalogue number L00173-22) was cautiously added. A catalytic amount of TMSOTf (0.3 μL, 0.02 mmol, 0.005 equiv, Flurochem, catalogue number S20400-250g) was added last to the mixture, which was then stirred at room temperature for 30 min. The solvent was then removed under reduced pressure at room temperature, and the residue was dried under high vacuum for 1 h to give a yellow solid, which was washed with pentane (2 × 10 mL), cold acetone (2 × 5 mL), and pentane (2 × 10 mL) and dried 1 h under a high vacuum. ABX (1a) (0.711 g, 2.46 mmol, 75% yield) was obtained as a pale yellow solid.

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a modified reported procedure, AcO-BX (306 mg, 1.00 mmol, 1.0 equiv) was dissolved in dry DCM (2 mL). TMS-azide (0.21 mL, 1.5 mmol, 1.5 equiv) was cautiously added by syringe dropwise at 0 °C, leading to the conversion of the initial colorless mixture to a yellowish suspension. One drop of TMS-triflate (ca. 0.90 μL, 5.0 mmol, 5 mol %) was finally added, and the mixture was stirred at 0 °C for 30 min. The solids were then filtered under low pressure suction in two portions (for safety reasons), washed with pentane, and air-dried in the air for 15 min. ABX (1a) (0.246 g, 0.853 mmol, 85% yield) was obtained as a pale yellow solid. 1H NMR (400 MHz, CDCl3, δ): 8.19 (dd, J = 7.5, 1.4 Hz, 1H), 7.95 (dd, J = 8.4, 1.3 Hz, 1H), 7.91 (dd, J = 8.4, 7.0, 1.4 Hz, 1H), 7.70 (dd, J = 7.8, 6.8, 1.2 Hz, 1H) ppm. 13C{1H} NMR (100 MHz, CDCl3,CD3CN; 10:1, δ): 166.2, 134.8, 131.8, 130.4, 125.4, 116.6, 115.4 ppm. Synthesis of tBuABX (1d). Following a reported procedure, iodine (11.42 g, 45.00 mmol, 0.50 equiv) was dissolved in TFA (90 mL; some iodine remained undissolved) to give a violet solution. Under stirring, this mixture was treated with eq. HCl (37% w/w; 1.1 mL, 13 mmol, 0.15 equiv) and eq. NaNO2 (40% w/w; 0.776 g, 4.50 mmol, 0.05 equiv), which resulted in the rapid darkening of the solution to red-brown-black (1.0 mmol). 4-tert-Butyltoluene (19) (15.5 mL, 90.0 mmol, 1.0 equiv) was finally added. Using a balloon, oxygen was bubbled through the mixture. Stirring was then continued under oxygen for 4 h, after which the reaction was quenched by the addition of saturated sodium thiosulfate (200 mL) and sat. eq. NaHCO3 (200 mL). The mixture was partitioned between dichloro methane (400 mL) and deionized water (400 mL). The organic layer was collected, dried over MgSO4, filtered, and concentrated under vacuum to provide a red-brown crude oil. The latter was purified by flash chromatography (silica; pentane) to give 4-(tert-buty1)-2-iodo-1-methylbenzene (20) (24.6 g, 90.0 mmol, quantitative yield) as a bright yellow oil. 1H NMR (400 MHz, CDCl3, δ): 7.80 (d, J = 2.0 Hz, 1H), 7.27 (q, J = 2.4, 1.9 Hz, 1H), 7.16 (d, J = 7.7, 7.5 Hz, 1H), 2.39 (s, 4H), 1.29 (s, 9H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature. 28 Following a slightly modified reported procedure, 4-(tert-buty1)-2-iodo-1-methylbenzene (20) (15.0 g, 54.7 mmol, 1.0 equiv) was dissolved in a mixture of water (175 mL) and pyridine (220 mL). Potassium permanganate (34.6 g, 219 mmol, 4.0 equiv) was added to the mixture, followed by tetrabutylammonium iodide (0.303 g, 0.821 mmol, 15 mol %). The violet suspension was refluxed under vigorous stirring for 3 days. It was then allowed to cool down to room temperature, and the solids were filtered off through a plug of Celite, which was then washed with eq. NaOH (2.0 M; 300 mL). Most of the pyridine was removed from the filtrate by evaporation under reduced pressure. The aqueous residue was washed with diethyl ether (3 × 200 mL), and it was then acidified until pH < 2 by careful addition of eq. HCl (37% v/v). The aqueous layer was extracted with DCM (3 × 200 mL), and the combined organic extracts were dried over MgSO4, filtered, and concentrated under vacuum to furnish the desired product as a pale yellow solid. The latter was recrystallized from hexane and chloroform (30 mL + 8 mL) to furnish highly pure 4-(tert-buty1)-2-iodobenzoic acid (21) (8.10 g, 26.6 mmol, 48%) as a
sticky, pale yellow crystalline solid. 1H NMR (400 MHz, CDCl3, δ): 11.81 (br s, 1H), 8.05 (d, J = 1.9 Hz, 1H), 7.99 (dd, J = 8.3, 1.9 Hz, 1H), 7.46 (dd, J = 8.3, 2.0 Hz, 1H), 7.33 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 171.4, 157.6, 139.3, 132.0, 130.0, 125.2, 95.2, 34.8, 30.9 ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.28

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a slightly modified reported procedure,29 4-(tert-butyl)-2-iodobenzoic acid (21) (7.70 g, 25.3 mmol, 1.0 equiv) and NaOH (5.42 g, 25.3 mmol, 1.0 equiv) were suspended in a 7:3 mixture of water (34.4 mL) and AcOH (14.7 mL). The mixture was stirred at 110 °C for 4 h (behind a safety shield). Full dissolution of the solids was observed a few minutes after reaching the reflux temperature, to give a clear, pale yellow solution. Stirring was continued while protecting the mixture from light with aluminum foil. The resulting colorless solid (HO(Bu)BX) (10.1 g, 39.5 mmol, 98%) was filtered, and the solid was dried in the air overnight and then directly used in the next step.

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. The solid obtained from the previous step (7.07 g, 11.3 mmol, 1.0 equiv) was dissolved in Ac2O (160 mL, 1.68 mol, 42.4 equiv) in AcOH (158 mL, 0.10 M), and the resulting mixture was heated for 48 h to 80 °C. Thereafter, the mixture was cooled to room temperature, and diethyl ether (150 mL) was added. Compound 24 (7.13 g, 15.5 mmol, 39%) crystallized at 0 °C from the solution and was collected by filtration. mp 161 °C (decomposition). 1H NMR (400 MHz, d6-DMSO, δ): 8.05 (d, J = 8.0 Hz, 1H), 7.95 (dd, J = 1.5 Hz, 1H), 7.71 (dd, J = 8.0, 1.6 Hz, 1H), 2.27 (s, 3H), 1.41 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 176.2, 168.3, 161.0, 132.8, 128.9, 126.2, 125.6, 119.0, 36.2, 31.1, 20.3 ppm. The signals of the NMR spectra were in accordance with the data reported in the literature.29

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a slightly modified reported procedure,29 4-(tert-butyl)-2-iodobenzoic acid (21) (7.70 g, 25.3 mmol, 1.0 equiv) and NaOH (5.42 g, 25.3 mmol, 1.0 equiv) were suspended in a 7:3 mixture of water (34.4 mL) and AcOH (14.7 mL). The mixture was stirred at 110 °C for 4 h (behind a safety shield). Full dissolution of the solids was observed a few minutes after reaching the reflux temperature, to give a clear, pale yellow solution. Stirring was continued while protecting the mixture from light with aluminum foil. The resulting colorless solid (HO(Bu)BX) (10.1 g, 39.5 mmol, 98%) was filtered, and the solid was dried in the air overnight and then directly used in the next step.

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. The solid obtained from the previous step (7.07 g, 11.3 mmol, 1.0 equiv) was dissolved in Ac2O (160 mL, 1.68 mol, 42.4 equiv) in AcOH (158 mL, 0.10 M), and the resulting mixture was heated for 48 h to 80 °C. Thereafter, the mixture was cooled to room temperature, and diethyl ether (150 mL) was added. Compound 24 (7.13 g, 15.5 mmol, 39%) crystallized at 0 °C from the solution and was collected by filtration. mp 161 °C (decomposition). 1H NMR (400 MHz, d6-DMSO, δ): 8.05 (d, J = 8.0 Hz, 1H), 7.95 (dd, J = 1.5 Hz, 1H), 7.71 (dd, J = 8.0, 1.6 Hz, 1H), 2.27 (s, 3H), 1.41 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 176.2, 168.3, 161.0, 132.8, 128.9, 126.2, 125.6, 119.0, 36.2, 31.1, 20.3 ppm. The signals of the NMR spectra were in accordance with the data reported in the literature.29

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a slightly modified reported procedure,29 4-(tert-butyl)-2-iodobenzoic acid (21) (7.70 g, 25.3 mmol, 1.0 equiv) and NaOH (5.42 g, 25.3 mmol, 1.0 equiv) were suspended in a 7:3 mixture of water (34.4 mL) and AcOH (14.7 mL). The mixture was stirred at 110 °C for 4 h (behind a safety shield). Full dissolution of the solids was observed a few minutes after reaching the reflux temperature, to give a clear, pale yellow solution. Stirring was continued while protecting the mixture from light with aluminum foil. The resulting colorless solid (HO(Bu)BX) (10.1 g, 39.5 mmol, 98%) was filtered, and the solid was dried in the air overnight and then directly used in the next step.

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a slightly modified reported procedure,29 4-(tert-butyl)-2-iodobenzoic acid (21) (7.70 g, 25.3 mmol, 1.0 equiv) and NaOH (5.42 g, 25.3 mmol, 1.0 equiv) were suspended in a 7:3 mixture of water (34.4 mL) and AcOH (14.7 mL). The mixture was stirred at 110 °C for 4 h (behind a safety shield). Full dissolution of the solids was observed a few minutes after reaching the reflux temperature, to give a clear, pale yellow solution. Stirring was continued while protecting the mixture from light with aluminum foil. The resulting colorless solid (HO(Bu)BX) (10.1 g, 39.5 mmol, 98%) was filtered, and the solid was dried in the air overnight and then directly used in the next step.

Caution: For safety reasons, the reaction was carried out behind an antiblast shield. Following a slightly modified reported procedure,29 4-(tert-butyl)-2-iodobenzoic acid (21) (7.70 g, 25.3 mmol, 1.0 equiv) and NaOH (5.42 g, 25.3 mmol, 1.0 equiv) were suspended in a 7:3 mixture of water (34.4 mL) and AcOH (14.7 mL). The mixture was stirred at 110 °C for 4 h (behind a safety shield). Full dissolution of the solids was observed a few minutes after reaching the reflu
at 0 °C. Thereafter, the reaction mixture was stirred for 15 min at 0 °C and then quenched with sat. aq. Na2S2O3. The mixture was extracted with CH2Cl2 (3 × 30 mL), and the combined organic extracts were washed with brine and dried over Na2SO4. The drying agent was filtered off, and the solvent was evaporated. The residue was dissolved in THF/CH3OH 1:1 (0.5 m), K2CO3 (2.0 equiv) was added, and the mixture was stirred for 3 h at room temperature. Thereafter, the solvent was evaporated, and the residue was suspended in water (50 mL) and then extracted with pentane (3 × 50 mL). The combined organic extracts were washed with brine (150 mL) and dried over Na2SO4. The residue was purified by column chromatography (silica, pentane), affording the desired 1-(1-bromovinyl)-arene 25, which, due to low stability, was used immediately in the next step.

1-(1-Bromovinyl)-4-methylbenzene (25b).

Compound 25b was prepared according to the general method A, starting with 1-(p-tolyl)ethanone (1.1 mL, 9.3 mmol, 1.0 equiv), Br2 (0.60 mL, 12 mmol, 1.2 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et3N (1.7 mL, 13 mmol, 1.35 equiv). The title compound 25b was obtained as a colorless liquid (1.2 g, 61% yield). 1H NMR (400 MHz, CDCl3, δ): 7.60–7.44 (m, 2H), 7.24–7.07 (m, 2H), 6.10 (s, 1H), 5.75 (s, 1H2), 3.8 (s, 3H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.31

1-(1-Bromovinyl)-4-(tert-butyl)benzene (25c).

Compound 25c was prepared according to the general method B, starting with 1-(tert-butyl)-4-vinylbenzene (1.9 mL, 10 mmol, 1.0 equiv), Br2 (0.60 mL, 12 mmol, 1.2 equiv), and K2CO3 (2.8 g, 20 mmol, 2.0 equiv). The title compound 25c was obtained as a colorless liquid (2.0 g, 84 mmol, 84% yield). 1H NMR (400 MHz, CDCl3, δ): 7.58–7.49 (m, 2H), 7.42–7.34 (m, 2H), 6.10 (d, J = 2.0 Hz, 1H), 5.74 (d, J = 2.0 Hz, 1H), 1.33 (s, 9H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.30

4-(1-Bromovinyl)-1,1′-biphenyl (25d).

Compound 25d was prepared according to the general method A, starting with 1-[1-(1′-biphenyl)-4-yl]ethanone (2.1 g, 11 mmol, 1.0 equiv), Br2 (0.62 mL, 12 mmol, 1.2 equiv), triphenyl phosphite (3.1 mL, 12 mmol, 1.10 equiv), and Et3N (2.0 mL, 14 mmol, 1.35 equiv). The title compound 25d was obtained as a colorless oil (1.6 g, 62 mmol, 58% yield). 1H NMR (400 MHz, CDCl3, δ): 7.70–7.65 (m, 2H), 7.63–7.56 (m, 4H), 7.50–7.42 (m, 2H), 7.40–7.33 (m, 1H), 6.18 (d, J = 2.0 Hz, 1H), 5.81 (d, J = 2.0 Hz, 1H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.32

1-(1-Bromovinyl)-4-methoxybenzene (25e).

Compound 25e was prepared according to general method A, starting with 1-(4-methoxyphenyl)ethanone (1.4 g, 9.3 mmol, 1.0 equiv), Br2 (0.62 mL, 12 mmol, 1.25 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et3N (1.8 mL, 13 mmol, 1.35 equiv). The title compound 25e was obtained as a colorless liquid (1.5 g, 70 mmol, 76% yield). 1H NMR (400 MHz, CDCl3, δ): 7.64–7.51 (m, 2H), 6.90–6.76 (m, 2H), 6.02 (d, J = 2.0 Hz, 1H), 5.68 (d, J = 2.0 Hz, 1H), 3.83 (s, 3H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.31

1-(1-Bromovinyl)-4-fluorobenzene (25f).

Compound 25f was prepared according to general method B, starting with 1-fluoro-4-vinylbenzene (1.2 mL, 10 mmol, 1.0 equiv), Br2 (0.62 mL, 12 mmol, 1.2 equiv), and K2CO3 (2.8 g, 20 mmol, 2.0 equiv). The title compound 25f was obtained as a colorless liquid (1.6 g, 8.0 mmol, 80% yield). 1H NMR (400 MHz, CDCl3, δ): 7.61–7.53 (m, 2H), 7.12–6.97 (m, 2H), 6.06 (d, J = 2.1 Hz, 1H), 5.76 (d, J = 2.1 Hz, 1H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.34

1-(1-Bromovinyl)-4-chlorobenzene (25g).

Compound 25g was prepared according to general method B, starting with 1-chloro-4-vinylbenzene (1.3 mL, 10 mmol, 1.0 equiv), Br2 (0.62 mL, 12 mmol, 1.2 equiv), and K2CO3 (2.8 g, 20 mmol, 2.0 equiv). The title compound 25g was obtained as a colorless liquid (1.0 g, 4.6 mmol, 46% yield). 1H NMR (400 MHz, CDCl3, δ): 7.59–7.48 (m, 2H), 7.36–7.29 (m, 2H), 6.11 (d, J = 2.2 Hz, 1H), 5.79 (d, J = 2.2 Hz, 1H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.31

1-(1-Bromovinyl)-3-methylbenzene (25h).

Compound 25h was prepared according to general method B, starting with 1-methyl-3-vinylbenzene (1.3 mL, 10 mmol, 1.0 equiv), Br2 (0.62 mL, 12 mmol, 1.2 equiv), and K2CO3 (2.8 g, 20 mmol, 2.0 equiv). The title compound 25h was obtained as a colorless liquid (1.0 g, 5.1 mmol, 51% yield). 1H NMR (400 MHz, CDCl3, δ): 7.67–7.57 (m, 2H), 7.53–7.30 (m, 1H), 7.18–7.14 (m, 1H), 6.11 (d, J = 2.0 Hz, 1H), 5.77 (d, J = 2.0 Hz, 1H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.30

1-(1-Bromovinyl)-3-methoxybenzene (25i).

Compound 25i was prepared according to general method A, starting with 1-(3-methoxyphenyl)ethanone (1.3 mL, 9.3 mmol, 1.0 equiv), Br2 (0.62 mL, 12 mmol, 1.25 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et3N (1.8 mL, 13 mmol, 1.35 equiv). The title compound 25i was obtained as a colorless liquid (2.5 g, 13 mmol, 132% yield). 1H NMR (400 MHz, CDCl3, δ): 7.56–7.42 (m, 2H), 7.14 (m, 1H), 6.11 (d, J = 2.0 Hz, 1H), 6.02 (d, J = 2.0 Hz, 1H), 5.77 (d, J = 2.0 Hz, 1H), 3.83 (s, 3H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.31
13 mmol, 1.35 equiv). The title compound 25j was obtained as a colorless oil (0.50 g, 2.3 mmol, 25% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 7.03–7.04 (m, 3H), 6.15 (d, $J = 2.1$ Hz, 1H), 5.82 (d, $J = 2.2$ Hz, 1H) ppm. The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{36}$

**1-(1-Bromovinyl)-3-fluorobenzene (25j).**

Compound 25j was prepared according to general method B, starting with 1-fluoro-3-vinylbenzene (1.2 mL, 10 mmol, 1.0 equiv), Br$_2$ (0.62 mL, 12 mmol, 1.2 equiv), and K$_2$CO$_3$ (2.8 g, 20 mmol, 2.0 equiv). The title compound 25j was obtained as a colorless liquid (1.6 g, 7.9 mmol, 79% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 7.42–7.43 (m, 1H), 7.34–7.35 (m, 1H), 7.05 (m, 1H), 6.10 (d, $J = 2.6$ Hz, 1H), 5.99 (d, $J = 2.1$ Hz, 1H), 3.86 (s, 3H) ppm. The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{35}$

**1-(1-Bromovinyl)-2-methylbenzene (25k).**

Compound 25k was prepared according to general method A, starting with 1-(o-tolyl)ethanone (1.3 mL, 10 mmol, 1.0 equiv), Br$_2$ (64 $\mu$L, 13 mmol, 1.25 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et$_3$N (1.9 mL, 13 mmol, 1.35 equiv). The title compound 25k was obtained as a colorless oil (1.2 g, 6.2 mmol, 62% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 7.34–7.41 (m, 4H), 6.26 (d, $J = 8.1$ Hz, 1H), 5.77 (d, $J = 1.6$ Hz, 1H), 2.44 (s, 3H) ppm. The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{38}$

**4-(1-Bromovinyl)-1,2-dimethylbenzene (25l).**

Compound 25l was prepared according to general method A, starting with 1-(naphthalen-2-yl)ethanone (1.6 g, 9.3 mmol, 1.0 equiv), Br$_2$ (0.62 mL, 12 mmol, 1.25 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et$_3$N (1.9 mL, 13 mmol, 1.35 equiv). The title compound 25l was obtained as a colorless oil (1.5 g, 6.6 mmol, 71% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 8.23 (dq, $J = 8.5, 0.9$ Hz, 1H), 7.93–7.78 (m, 3H), 7.69 (dd, $J = 8.7, 1.9$ Hz, 1H), 7.56–7.43 (m, 2H), 6.27 (d, $J = 2.1$ Hz, 1H), 5.88 (d, $J = 2.1$ Hz, 1H). The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{38}$

**2-(1-Bromovinyl)naphthalene (25o).**

Compound 25o was prepared according to the general method A, starting with 1-(naphthalen-2-yl)ethanone (1.6 g, 9.3 mmol, 1.0 equiv), Br$_2$ (0.62 mL, 12 mmol, 1.25 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et$_3$N (1.9 mL, 13 mmol, 1.35 equiv). The title compound 25o was obtained as a colorless oil (1.0 g, 4.3 mmol, 46% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 8.09 (d, $J = 1.8$ Hz, 1H), 7.90–7.78 (m, 3H), 7.69 (dd, $J = 8.7, 1.9$ Hz, 1H), 7.56–7.43 (m, 2H), 6.27 (d, $J = 2.1$ Hz, 1H), 5.88 (d, $J = 2.1$ Hz, 1H). The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{38}$

**1-(1-Bromovinyl)naphthalene (25p).**

Compound 25p was prepared according to general method B, starting with 1-vinylnaphthalene (1.95 g, 12.7 mmol, 1.0 equiv), Br$_2$ (78 $\mu$L, 15 mmol, 1.20 equiv), and K$_2$CO$_3$ (3.49 g, 25.3 mmol, 2.0 equiv). The title compound 25p was obtained as a colorless liquid (2.48 g, 10.6 mmol, 84% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 8.23 (dq, $J = 8.5, 0.9$ Hz, 1H), 7.93–7.77 (m, 2H), 7.65–7.39 (m, 4H), 6.10 (d, $J = 1.5$ Hz, 1H), 5.97 (d, $J = 1.5$ Hz, 1H). The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{39}$

**5-(1-Bromovinyl)benzo[d][1,3]dioxole (25n).**

Compound 25n was prepared according to general method A, starting with 1-(benzo[d][1,3]dioxol-5-yl)ethanone (1.5 g, 9.3 mmol, 1.0 equiv), Br$_2$ (0.62 mL, 12 mmol, 1.25 equiv), triphenyl phosphite (2.7 mL, 10 mmol, 1.1 equiv), and Et$_3$N (1.8 mL, 13 mmol, 1.35 equiv). The title compound 25n was obtained as a colorless oil (0.50 g, 2.3 mmol, 27% yield.). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 7.17 (dd, $J = 8.4, 2.3$ Hz, 1H), 7.10 (d, $J = 2.2$ Hz, 1H), 6.82 (d, $J = 8.4$ Hz, 1H), 6.02 (d, $J = 2.0$ Hz, 1H), 5.69 (d, $J = 2.0$ Hz, 1H), 3.91 (s, 3H), 3.89 (s, 3H) ppm. The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.$^{37}$

**5-(1-Bromovinyl)benzo[d][1,3]dioxole (25n).**
Compound 25t was prepared according to general method B, starting with 4-(trifluoromethyl)-styrene (3.4 g, 20 mmol, 1.0 equiv), Br₂ (1.3 mL, 24 mmol, 1.2 equiv), and K₂CO₃ (5.5 g, 40 mmol, 2.0 equiv). The title compound 25t was obtained as a colorless liquid (2.2 g, 8.7 mmol, 43% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.77–7.68 (m, 2H), 7.61 (d, J = 8.2 Hz, 2H), 6.21 (d, J = 2.2 Hz, 1H), 5.90 (d, J = 2.2 Hz, 1H) ppm. ¹³C{¹H} NMR (101 MHz, CDCl₃; the multiplet peak corresponding to the CF₃ was not resolved, δ: 141.9, 131.4, 131.0 (q, J = 32.7 Hz), 127.6, 125.3 (q, J = 3.9 Hz), 122.5, 119.7 ppm. HRMS (ESI): [M+] calcd for C₁₉H₁₅F₃, 249.9541; found, 249.9541. IR (cm⁻¹): 2950 (s), 1720 (s), 1230 (s), 1150 (s), 750 (s).

Synthesis of 1-(1-(Arene)vinyl)cyclobutanols. General Method C. One crystal of iodine and 1,2-dibromoethane (0.4 equiv) were added to a suspension of magnesium (4.0 equiv) in THF (0.2 M). After being cooled to room temperature, the reaction mixture was stirred for 1 h at 60 °C. Then, the corresponding cyclobutanone (1.0 equiv) was added dropwise, and stirring was continued at 60 °C for 5 h. After being cooled to room temperature, the reaction was quenched with water and extracted with ethyl acetate (3 × 40 mL). The combined organic extracts were washed with water (50 mL) and brine (50 M) and then dried over Na₂SO₄. The residue was purified by column chromatography (silica; pentane:EtOAc 100:0 to 95:5 to 80:20 to 70:30), affording the title compound 3.

1-(1-Phenylvinyl)cyclobutanol (3a).

Compound 3a was prepared according to general method C using magnesium (0.40 g, 16 mmol, 4.0 equiv), 1,2-dibromoethane (0.14 mL, 1.6 mmol, 0.4 equiv), (1-bromovinyl)benzene (0.70 mL, 5.2 mmol, 1.3 equiv, 90% purity), and cyclobutanone (0.30 mL, 4.0 mmol, 1.0 equiv). The title compound 3a was obtained as a colorless oil (0.65 g, 3.7 mmol, 93% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.52–7.45 (m, 2H), 7.38–7.27 (m, 3H), 5.38 (s, 1H), 5.36 (d, J = 0.9 Hz, 1H), 2.54–2.42 (m, 2H), 2.25 (m, 2H), 1.99 (m, 2H), 1.63 (m, 1H) ppm. The signals of the ¹H NMR spectra were in accordance with the data reported in the literature.

1-(1-(p-Tolyl)vinyl)cyclobutanol (3b).

Compound 3b was prepared according to general method C using magnesium (0.30 g, 13 mmol, 4.0 equiv), 1,2-dibromoethane (0.10 mL, 1.3 mmol, 0.4 equiv), 1-(1-bromovinyl)-4-methylbenzene (25b, 1.0 g, 4.1 mmol, 1.3 equiv), and cyclobutanone (0.25 mL, 3.4 mmol, 1.0 equiv). The title compound 3b was obtained as a colorless oil (0.48 g, 2.5 mmol, 75% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.44–7.38 (m, 2H), 7.16 (d, J = 7.9 Hz, 2H), 5.34 (m, 2H), 2.53–2.43 (m, 2H), 2.37 (s, 3H), 2.26 (m, 3H), 2.01 (m, 1H), 1.64 (m, 1H) ppm. The signals of the ¹H NMR spectra were in accordance with the data reported in the literature.

1-(1-(4-(tert-Butyl)phenyl)vinyl)cyclobutanols (3c).

Compound 3c was prepared according to general method C using magnesium (0.30 g, 13 mmol, 4.0 equiv), 1,2-dibromoethane (0.10 mL, 1.3 mmol, 0.4 equiv), 1-(1-bromovinyl)-4-(tert-butyl)benzene (25c, 1.0 g, 4.2 mmol, 1.3 equiv), and cyclobutanone (0.26 mL, 3.4 mmol, 1.00 equiv). The title compound 3c was obtained as a colorless oil (0.46 g, 2.0 mmol, 53% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.44–7.40 (m, 2H), 7.37–7.34 (m, 2H), 5.37 (d, J = 0.9 Hz, 1H), 5.34 (d, J = 1.0 Hz, 1H), 2.50 (m, 2H), 2.27 (m, 2H), 1.98 (m, 2H), 1.64 (m, 1H), 1.32 (s, 9H) ppm. The signals of the ¹H NMR spectra were in accordance with the data reported in the literature.

1-(1-(1,1′-Biphenyl)-4-y)vinyl)cyclobutanols (3d).

Compound 3d was prepared according to general method C using magnesium (0.25 g, 11 mmol, 4.00 equiv), 1,2-dibromoethane (0.10 mL, 1.1 mmol, 0.4 equiv), 4-(1-bromovinyl)-1,1′-biphenyl (25d, 0.85 g, 3.3 mmol, 1.3 equiv), and cyclobutanone (0.21 mL, 2.7 mmol, 1.0 equiv). The title compound 3d was obtained as a colorless oil (0.56 g, 2.7 mmol, 53% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.64–7.53 (m, 5H), 7.45 (m, 2H), 7.35 (m, 1H), 5.45 (d, J = 0.8 Hz, 1H), 5.41 (d, J = 0.8 Hz, 1H), 2.52 (m, 2H), 2.29 (m, 2H), 2.02 (m, 2H), 1.67 (m, 1H) ppm. The signals of the ¹H NMR spectra were in accordance with the data reported in the literature.

1-(1-(4-Methoxyphenyl)vinyl)cyclobutanols (3e).

Compound 3e was prepared according to general method C using magnesium (0.380 g, 15.6 mmol, 4.00 equiv), 1,2-dibromoethane (0.13 mL, 1.6 mmol, 0.40 equiv), 1-(1-bromovinyl)-4-methoxybenzene (25e, 1.0 g, 4.7 mmol, 1.3 equiv), and cyclobutanone (0.29 mL, 3.9 mmol, 1.00 equiv). The title compound 3e was obtained as a colorless oil (0.560 g, 2.74 mmol, 70% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.44 (m, 2H), 6.86 (m, 2H), 5.31 (d, J = 0.9 Hz, 1H), 5.30 (d, J = 0.9 Hz, 1H), 3.81 (s, 3H), 2.47 (m, 2H), 2.25 (m, 2H), 1.98 (m, 2H), 1.63 (m, 1H) ppm. The signals of the ¹H NMR spectra were in accordance with the data reported in the literature.

1-(1-(4-Fluorophenyl)vinyl)cyclobutanols (3f).

Compound 3f was prepared according to general method C using magnesium (0.40 g, 16 mmol, 4.0 equiv), 1,2-dibromoethane (0.20 mL, 2.6 mmol, 0.4 equiv), 1-(1-bromovinyl)-4-fluorobenzene (25f, 1.6 g, 8.0 mmol, 1.3 equiv), and cyclobutanone (0.50 mL, 6.6 mmol, 1.0 equiv). The title compound 3f was obtained as a colorless oil (0.95 g, 4.9 mmol, 74% yield). ¹H NMR (400 MHz, CDCl₃, δ): 7.52–7.41 (m, 2H), 7.13–6.91 (m, 2H), 5.36 (d, J = 0.8 Hz, 1H), 5.32 (d, J = 0.7 Hz, 1H), 2.44 (m, 2H), 2.22 (m, 2H), 1.99 (m, 1H), 1.90 (m, 1H), 1.62 (m, 1H) ppm. The signals of the ¹H NMR spectra were in accordance with the data reported in the literature.
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1-(1-(4-Chlorophenyl)vinyl)cyclobutanols (3g).

Compound 3g was prepared according to general method C using magnesium (0.30 g, 12 mmol, 4.0 equiv), 1,2-dibromoethane (0.11 mL, 1.3 mmol, 0.4 equiv), 1-(1-bromovinyl)-4-chlorobenzene (25g, 0.83 g, 3.8 mmol, 1.3 equiv), and cyclobutanone (0.24 mL, 3.2 mmol, 1.0 equiv). The title compound 3g was obtained as a colorless oil (0.42 g, 64% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 7.39 (m, 2H), 7.31–7.39 (m, 2H), 5.38 (s, 1H), 5.36 (d, $J = 0.7$ Hz, 1H), 2.44 (m, 2H), 2.22 (m, 2H), 1.99 (m, 1H), 1.86 (brs, 1H), 1.62 (m, 1H) ppm. The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.13c

1-(1-(m-Toly1)vinyl)cyclobutanol (3h).

Compound 3h was prepared according to general method C using magnesium (0.140 g, 5.63 mmol, 4.00 equiv), 1,2-dibromoethane (0.16 mL, 1.8 mmol, 0.400 equiv), 4-(1-bromovinyl)-1,2-dimethylbenzene (25h, 1.26 g, 5.97 mmol, 1.3 equiv), and cyclobutanone (0.32 mL, 4.23 mmol, 1.0 equiv). The title compound 3h was obtained as a colorless oil (0.680 g, 85% yield). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$): 7.27 (m, 2H), 7.22 (td, $J = 7.3$, 1.3 Hz, 1H), 7.12 (m, 1H), 5.36 (d, $J = 0.9$ Hz, 1H), 5.34 (d, $J = 0.9$ Hz, 1H), 2.48 (m, 2H), 2.36 (s, 3H), 2.25 (m, 2H), 1.99 (m, 1H), 1.63 (m, 1H) ppm. The signals of the $^1$H NMR spectra were in accordance with the data reported in the literature.13c

1-(1-(3-Methoxyphenyl)vinyl)cyclobutanols (3i).

Compound 3i was prepared according to the general method C using magnesium (0.140 g, 5.63 mmol, 4.00 equiv), 1,2-dibromoethane (0.140 g, 5.63 mmol, 4.00 equiv), 1-(1-bromovinyl)-3-methylbenzene (25i, 0.36 g, 1.67 mmol, 1.3 equiv), and cyclobutanone (0.11 mL, 1.4 mmol, 1.0 equiv). The title compound 3i was prepared according to the general method C using magnesium (0.410 g, 16.5 mmol, 4.00 equiv), 1,2-dibromoethane (0.16 mL, 1.8 mmol, 0.400 equiv), 4-(1-bromovinyl)-1,2-dimethylbenzene (25i, 0.36 g, 1.67 mmol, 1.3 equiv), and cyclobutanone (0.11 mL, 1.4 mmol, 1.0 equiv). The title

1-(1-(3-Fluorophenyl)vinyl)cyclobutanols (3j).

Compound 3j was prepared according to general method C using magnesium (0.190 g, 7.95 mmol, 4.00 equiv), 1,2-dibromoethane (0.23 mL, 2.7 mmol, 0.40 equiv), 1-(1-bromovinyl)-3-fluorobenzene (25j, 1.6 g, 8.0 mmol, 1.3 equiv), and cyclobutanone (0.50 mL, 6.6 mmol, 1.0 equiv). The title
The title compound 3m was obtained as a colorless oil (0.20 g, 0.85 mmol, 62% yield). Rf (silica, pentane:EtOAc 4:1): 0.2. 1H NMR (400 MHz, CDCl3, δ): 7.02 (m, 2H), 6.78 (d, J = 8.1 Hz, 1H), 5.28 (d, J = 0.9 Hz, 1H), 5.26 (d, J = 0.9 Hz, 1H), 3.84 (s, 6H), 2.43 (m, 2H), 2.35 – 2.16 (m, 3H), 1.95 (m, 1H), 1.59 (m, 1H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 151.1, 148.5, 148.4, 131.7, 119.9, 111.7, 110.9, 110.7, 78.2, 55.8, 35.6, 13.4 ppm. One alkyl signal was not resolved. HRMS (ESI): [M + H]+ calcd for C16H15O2, 253.1144; found, 253.1144.

1-(1-(Benzo[d][1,3]dioxol-5-yl)vinyl)cyclobutanol (3n).

Compound 3n was prepared according to general method C using magnesium (0.530 g, 22.0 mmol, 4.00 equiv), 1,2-dibromoethane (0.19 mL, 2.0 mmol, 0.40 equiv), 5-(1-bromovinyl)benzo[d][1,3]dioxole (25n, 1.5 g, 6.6 mmol, 1.3 equiv), and cyclobutanone (0.41 mL, 5.5 mmol, 1.00 equiv). The title compound 3n was obtained as a colorless oil (0.560 g, 2.57 mmol, 47% yield). 1H NMR (400 MHz, CDCl3, δ): 7.01 (d, J = 1.8 Hz, 1H), 6.97 (dd, J = 8.1, 1.7 Hz, 1H), 6.77 (dt, J = 8.1, 0.9 Hz, 1H), 5.95 (m, 2H, OCH2O), 5.29 (m, 2H), 2.45 (m, 2H), 2.22 (m, 2H), 1.97 (m, 2H), 1.61 (m, 1H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.14 1H NMR (101 MHz, CDCl3, δ): 7.38 (m, 3H), 7.36 (m, 3H), 5.46 (s, 1H), 5.42 (s, 1H), 2.82 (s, 1H), 2.31 (m, 2H), 2.02 (m, 2H), 1.67 (m, 1H) ppm. 13C{1H} NMR data correspond to the reported values, apart from the peak at δ = 1.67 ppm, which corresponds better to the attributed 1H nuclei than the signal in the reference article.11

1-(1-(Naphthalen-2-yl)vinyl)cyclobutanol (3o).

Compound 3o was prepared according to general method C using magnesium (0.35 g, 14.3 mmol, 4.00 equiv), 1,2-dibromoethane (0.12 mL, 1.4 mmol, 0.40 equiv), 2-(1-bromovinyl)naphthalene (25o, 1.0 g, 4.3 mmol, 1.3 equiv), and cyclobutanone (0.27 mL, 3.6 mmol, 1.0 equiv). The title compound 3o was obtained as a colorless oil (0.50 g, 2.2 mmol, 62% yield). 1H NMR (400 MHz, CDCl3, δ): 7.96 (m, 1H), 7.87 – 7.76 (m, 3H), 7.63 (dd, J = 8.5, 1.8 Hz, 1H), 7.47 (m, 2H), 5.50 (d, J = 0.8 Hz, 1H), 5.48 (d, J = 0.8 Hz, 1H), 2.53 (m, 2H), 2.31 (m, 2H), 2.02 (m, 2H), 1.67 (m, 1H) ppm. 1H NMR data correspond to the reported values, apart from the peak at δ = 1.67 ppm, which corresponds better to the attributed 1H nuclei than the signal in the reference article.11 1H NMR (101 MHz, CDCl3, δ): 7.73 – 7.52 (m, 4H), 6.30 (d, J = 8.5 Hz, 1H), 5.46 (s, 1H), 5.42 (s, 1H), 2.99 – 2.78 (m, 2H), 2.29 – 2.18 (m, 2H), 2.08 – 1.94 (m, 2H), 1.70 – 1.55 (m, 1H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 156.4, 149.5, 137.7, 128.5, 128.0, 126.9, 114.8, 79.7, 72.5, 69.9, 61.9, 28.3 ppm. HRMS (ESI): [M + Na]+ calcd for C18H15NaO2, 298.1414; found, 298.1413.

1-(1-(4-(Trifluoromethyl)phenyl)vinyl)cyclobutanols (3t).

Compound 3t was prepared according to general method C using magnesium (843 mg, 34.7 mmol, 4.00 equiv), 1,2-dibromoethane (0.30 mL, 3.5 mmol, 0.40 equiv), 25t (2.83 g, 11.3 mmol, 1.30 equiv), and cyclobutanone (0.64 mL, 8.7 mmol, 1.00 equiv). The title compound 3t was obtained as a colorless oil (1.01 g, 4.16 mmol, 48% yield). Rf (silica, pentane:EtOAc 10:1): 0.5. 1H NMR (400 MHz, CDCl3, δ): 7.72 – 7.44 (m, 4H), 5.46 (s, 1H), 5.42 (s, 1H), 2.49 – 2.39 (m, 2H), 2.29 – 2.18 (m, 2H), 2.08 – 1.94 (m, 2H), 1.70 – 1.55 (m, 1H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 151.4, 142.8, 129.4 (q, J = 32.4 Hz), 127.9, 125.0 (q, J = 3.7 Hz), 124.2 (q, J = 271.4 Hz), 114.5, 77.9, 35.6, 13.3 ppm. HRMS (ESI): [M]+ calcd for C11H13F3O2, 242.0913; found, 242.0917.
IR (film): 3381 (w), 2991 (w), 2953 (w), 1619 (w), 1573 (w), 1407 (w), 1326 (s), 1251 (w), 1166 (m), 1122 (s), 1067 (m), 1018 (m), 912 (m), 850 (m) cm⁻¹.

**Synthesis of (1-(Arene)vinyl)cyclobutoxytrimethylsilanes.** General Procedure D. TMSCl (1.2 equiv) was added dropwise to a solution of (1-(arene)vinyl)cyclobutanol (3.0 equiv) and triethylamine (1.5 equiv) in DCM (0.2 M) at 0 °C. The reaction mixture was stirred until full conversion on TLC, then it was quenched with sat. aq. NH₄Cl (10 mL), and extracted with CH₂Cl₂ (3 × 30 mL). The combined organic extracts were washed with brine and dried over MgSO₄. The drying agent was filtered off, and the solvent was evaporated. Purification of the residue by column chromatography (silica, pentane:EtOAc 1:0 to 9:1) afforded the title product 4.

Trimethyl(1-(phenylvinyl)cyclobutoxy)silane (4a).

Compound 4a was prepared according to general method D using 1-(phenylvinyl)cyclobutanol (3a, 1.58 g, 9.07 mmol, 1.00 equiv), Et₃N (0.90 mL, 6.3 mmol, 1.1 equiv), and TMSCl (1.4 mL, 11 mmol, 1.3 equiv). The title compound 4a was obtained as a colorless oil (2.0 g, 81% yield).

Trimethyl(1-(p-tolyvinyl)cyclobutoxy)silane (4b).

Compound 4b was prepared according to general method D using 1-(p-tolyl)vinyl)cyclobutanol (3b, 0.45 g, 2.4 mmol, 1.0 equiv), Et₃N (0.50 mL, 3.6 mmol, 1.5 equiv), and TMSCl (0.37 mL, 2.9 mmol, 1.3 equiv). The title compound 4b was obtained as a colorless oil (0.56 g, 2.1 mmol, 90% yield).

Trimethyl(1-(4-Butylphenyl)vinyl)cyclobutoxy)trimethylsilane (4c).

Compound 4c was prepared according to general method D using 1-(4-(tert-butyl)phenyl)vinyl)cyclobutanol (3c, 0.45 g, 2.0 mmol, 1.0 equiv), Et₃N (0.40 mL, 2.9 mmol, 1.5 equiv), and TMSCl (0.30 mL, 2.3 mmol, 1.3 equiv). The title compound 4c was obtained as a pale yellow oil (0.47 g, 1.6 mmol, 90% yield).

**Note**

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Compound 4f was prepared according to general method D using 1-(1-(4-fluorophenyl)vinyl)cyclobutanol (3g, 0.40 g, 1.9 mmol, 1.0 equiv), Et3N (0.40 mL, 2.9 mmol, 1.5 equiv), and TMSCl (0.30 mL, 2.3 mmol, 1.3 equiv). The title compound 4g was obtained as a colorless oil (0.43 g, 1.5 mmol, 80% yield). 

Rf (silica, pentane): 0.7. 1H NMR (400 MHz, CDCl3, δ): 7.48 (m, 2H), 7.26 (m, 2H), 5.45 (d, J = 0.6 Hz, 1H), 5.39 (d, J = 0.6 Hz, 1H), 2.45–2.21 (m, 4H), 1.82 (m, 1H), 1.53 (m, 1H), 0.00 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 130.7, 137.9, 133.1, 129.4, 128.0, 112.7, 78.8, 37.1, 13.7, 1.8 ppm. HRMS (ESI): [M+Na]+ calcd. for C15H21FOSiNa, 286.1574; found, 286.1574. IR (film): 3095 (w), 3092 (w), 3041 (w), 3034 (w), 2988 (w), 2954 (w), 2953 (w), 2901 (w), 2874 (w), 1250 (s), 1124 (m), 1122 (m), 912 (s), 840 (s) cm⁻¹.

Trimethyl(1-(1-m-tolylic)cyclobutaxy)trimethylsilane (4h).

Compound 4h was prepared according to the general method D using 1-(1-(m-tolyl)cyclobutanol (3h, 0.68 g, 3.6 mmol, 1.0 equiv), Et3N (0.75 mL, 5.4 mmol, 1.5 equiv), and TMSCl (0.55 mL, 4.3 mmol, 1.3 equiv). The title compound 4h was obtained as a colorless oil (0.76 g, 2.9 mmol, 81% yield). 

Rf (silica, pentane): 0.8. 1H NMR (400 MHz, CDCl3, δ): 7.55 (m, 2H), 7.19 (m, 1H), 7.08 (m, 1H), 5.42 (m, 1H), 5.37 (m, 1H), 2.43 (m, 2H), 2.34 (m, 5H), 1.81 (m, 1H), 1.53 (m, 1H), 0.01 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 152.0, 139.7, 137.2, 128.8, 128.0, 127.7, 125.3, 112.3, 79.0, 37.2, 21.7, 13.7, 1.8 ppm. HRMS (ESI): [M+Na]+ calcd. for C16H14NaOSi, 283.1489; found, 283.1485. IR (film): 3095 (w), 3092 (w), 3041 (w), 3034 (w), 3026 (w), 2988 (w), 2954 (w), 2953 (w), 2901 (w), 2874 (w), 1250 (s), 1158 (m), 1124 (m), 912 (s), 840 (s) cm⁻¹.

Trimethyl(1-(1-o-tolylic)cyclobutoxy)silane (4i).

Compound 4i was prepared according to general method D using 1-(1-(3-methoxyphenyl)vinyl)cyclobutanol (3i, 0.15 g, 0.73 mmol, 1.0 equiv), Et3N (0.15 mL, 1.1 mmol, 1.5 equiv), and TMSCl (0.11 mL, 0.88 mmol, 1.3 equiv). The title compound 4i was obtained as a colorless oil (0.15 g, 0.54 mmol, 74% yield). 

Rf (silica, pentane): 0.6. 1H NMR (400 MHz, CDCl3, δ): 7.22 (m, 1H), 7.13 (m, 2H), 6.82 (dd, J = 8.1, 2.6, 1.1 Hz, 1H), 5.46 (d, J = 0.9 Hz, 1H), 5.39 (d, J = 0.8 Hz, 1H), 3.81 (s, 3H), 2.43 (m, 2H), 2.31 (m, 2H), 1.82 (m, 1H), 1.54 (m, 1H), 0.04 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 151.7, 140.6, 136.2, 129.8, 129.5, 126.7, 124.7, 113.6, 79.5, 36.1, 20.5, 13.6, 1.9 ppm. HRMS (ESI): [M]+ calcd. for C16H14OSi, 260.1596; found, 260.1586. IR (film): 2978 (m), 2958 (m), 1489 (w), 1381 (w), 1250 (s), 1167 (w), 1079 (w), 995 (m), 926 (m), 841 (s), 760 (m), 732 (m) cm⁻¹.
Compound 4f was prepared according to the general method D using 1-(3-phenylprop-1-en-2-yl)cyclobutanol (3f, 0.680 g, 3.61 mmol, 1.00 equiv), Et3N (0.75 mL, 5.4 mmol, 1.5 equiv), and TMSCl (0.55 mL, 4.3 mmol, 1.3 equiv). The title compound 4f was obtained as a colorless oil (0.610 g, 2.34 mmol, 65% yield). Rf (silica, pentane:EtOAc = 0.9). 1H NMR (400 MHz, CDCl3, δ): 7.32 (d, J = 2.0 Hz, 1H), 7.29 (dd, J = 7.8, 2.0 Hz, 1H), 7.07 (d, J = 7.8 Hz, 1H), 5.42 (d, J = 1.0 Hz, 1H), 5.34 (d, J = 1.0 Hz, 1H), 2.49–2.38 (m, 2H), 2.36–2.29 (m, 2H), 2.28 (s, 3H), 2.27 (s, 3H), 1.90–1.76 (m, 1H), 1.64–1.44 (m, 1H), 0.04 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 151.6, 137.0, 135.6, 135.4, 129.1, 128.9, 125.5, 111.6, 79.0, 37.9, 19.9, 19.4, 13.6, 1.7 ppm. HRMS (ESI): [M+H] calcd. for C20H24O3Si, 326.1591; found, 326.1594.

Compound 4m was prepared according to general method D using 1-(1-(3,4-dimethylphenyl)vinyl)cyclobutanol (3m, 0.20 g, 0.85 mmol, 1.0 equiv), Et3N (0.18 mL, 1.33 mmol, 1.5 equiv), and TMSCl (0.35 mL, 2.8 mmol, 1.3 equiv). The title compound 4m was obtained as a colorless oil (0.13 g, 0.42 mmol, 50% yield). Rf (silica, pentane): 0.4. 1H NMR (400 MHz, CDCl3, δ): 7.17 (d, J = 2.1 Hz, 1H), 7.11 (dd, J = 8.4, 2.1 Hz, 1H), 6.80 (d, J = 8.4 Hz, 1H), 5.42 (d, J = 0.8 Hz, 1H), 5.31 (d, J = 0.8 Hz, 1H), 3.88 (s, 3H), 3.88 (s, 3H), 2.40 (m, 2H), 2.29 (m, 2H), 1.82 (m, 1H), 1.52 (m, 1H), 0.02 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 151.0, 148.4, 148.1, 132.3, 120.5, 111.6, 111.3, 110.5, 79.2, 55.9, 37.1, 13.7, 1.8 ppm. HRMS (ESI): [M+H] calcd. for C19H24OSi, 296.1591; found, 296.1594.

Compound 4n was prepared according to general method D using 1-(1-(benzo[d][1,3]dioxol-5-yl)vinyl)cyclobutanol (3n, 0.55 g, 2.5 mmol, 1.0 equiv), Et3N (0.53 mL, 3.8 mmol, 1.5 equiv), and TMSCl (0.39 mL, 3.0 mmol, 1.3 equiv). The title compound 4n was obtained as a colorless oil (0.610 g, 2.10 mmol, 83% yield). Rf (silica, pentane): 0.4. 1H NMR (400 MHz, CDCl3, δ): 7.07 (d, J = 1.8 Hz, 1H), 7.03 (dd, J = 8.1, 1.8 Hz, 1H), 6.75 (d, J = 8.1 Hz, 1H), 5.94 (s, 2H), 5.37 (d, J = 0.7 Hz, 1H), 5.31 (d, J = 0.7 Hz, 1H), 2.40 (m, 2H), 2.29 (m, 2H), 1.81 (m, 1H), 1.51 (m, 1H), 0.02 (s, 9H) ppm.

Compound 4p was prepared according to the general method D using 1-(1-(naphthalen-2-yl)vinyl)cyclobutanol (3o, 0.50 g, 2.2 mmol, 1.0 equiv), Et3N (0.47 mL, 3.3 mmol, 1.5 equiv), and TMSCl (0.34 mL, 2.7 mmol, 1.3 equiv). The title compound 4p was obtained as a colorless oil (0.43 g, 1.4 mmol, 65% yield). Rf (silica, pentane): 0.1. 1H NMR (400 MHz, CDCl3, δ): 8.03 (s, 1H), 7.84 (m, 2H), 7.78 (d, J = 8.6 Hz, 1H), 7.70 (d, J = 8.7, 1.6 Hz, 1H), 7.50–7.42 (m, 2H), 5.62 (d, J = 0.9 Hz, 1H), 5.50 (s, 1H), 2.51 (m, 2H), 2.40 (m, 2H), 1.87 (m, 1H), 1.57 (m, 1H), 0.03 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 151.7, 137.0, 133.3, 132.7, 128.4, 127.5, 127.1, 127.0, 126.4, 125.9, 125.8, 112.9, 79.1, 37.3, 13.7, 1.8 ppm. HRMS (ESI): [M+H] calcd. for C24H19OSi, 306.1591; found, 306.1594.

Compound 4q was prepared according to the general procedure, 3-(1-phenylvinyl)oxetan-3-yl)trimethylsilane (3q, 0.400 g, 2.27 mmol, 1.00 equiv), Et3N (0.48 mL, 3.4 mmol, 1.5 equiv), and TMSCl (0.35 mL, 2.8 mmol, 1.3 equiv). The title compound 4q was obtained as a pale yellow oil (0.440 g, 1.77 mmol, 78% yield).
Compound 4r was prepared according to the general method D using 3r (0.44 g, 1.6 mmol, 1.0 equiv), Et3N (0.33 mL, 2.4 mmol, 1.5 equiv), and TMSCl (0.24 mL, 1.9 mmol, 1.2 equiv). The title compound 4r was obtained as a colorless oil (0.410 g, 1.18 mmol, 74% yield). 1H NMR (400 MHz, CDCl3, δ): 7.45 (dd, J = 8.2, 1.5 Hz, 2H), 7.36–7.27 (m, 3H), 5.61 (s, 1H), 5.41 (s, 1H), 4.18 (s, 2H), 4.06 (dd, J = 9.0, 0.9 Hz, 2H), 1.42 (s, 9H), 0.04 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3): 156.3, 149.4, 137.9, 128.2, 127.8, 127.1, 114.2, 29.8, 63.4, 62.0, 28.3, 1.3 ppm. HRMS (ESI): [M + H]+ calcd for C17H24OSi, 272.1591; found, 272.1589.

1-(3,4-Dihydronaphthalen-1-yl)cyclobutanol (4s). Following a reported procedure,4r Br2 (0.60 mL, 12 mmol, 1.2 equiv), and Cu(dap)2Cl (4.4 mg, 5.0 mol %), and the mixture was degassed (three pump and freeze cycles) and stirred for 16 h at room temperature, while being irradiated with green LEDs. Thereafter, the mixture was filtered through a plug of Celite and concentrated. The residue was purified by column chromatography (silica, pentane) to afford 2-(Azidomethyl)-2-phenylcyclopentanone (6a).

Compound 4s was prepared according to the general method D using 3s (0.750 g, 3.74 mmol, 1.0 equiv), Et3N (0.78 mL, 5.6 mmol, 1.5 equiv), and TMSCl (0.57 mL, 4.5 mmol, 1.2 equiv). The title compound 4s was obtained as a colorless oil (810 mg, 2.97 mmol, 79% yield). 1H NMR (400 MHz, CDCl3, δ): 7.57 (dt, J = 6.1, 1.8, 1H), 7.20–7.06 (m, 3H), 6.18 (t, J = 4.6, 1H), 2.79–2.68 (m, 2H), 2.54–2.41 (m, 2H), 2.40–2.25 (m, 4H), 1.88–1.73 (m, 1H), 1.56–1.40 (m, 1H), −0.08 (s, 9H) ppm. 13C{1H} NMR (101 MHz, CDCl3): 139.2, 137.1, 132.8, 127.3, 126.6, 126.3, 125.4, 77.8, 37.0, 28.2, 23.3, 14.0, 1.5 ppm. HRMS (ESI): [M+] calcd for C17H15NO3Si, 272.1591; found, 272.1589.

Ring Expansion Reactions. General Procedure E. Freshly dried CH3CN (2.5 mL, 0.20 M) was added to a mixture of (1-(1-arenyl)cyclobutyl)trimethylsilane 4 (0.5 mmol, 1 equiv), Cu(dap)Cl (2.2 mg, 2.5 μmol, 5 mol %), and the mixture was degassed (three pump and freeze cycles) and stirred for 16 h at room temperature, while being irradiated with green LEDs. Thereafter, the mixture was filtered through a plug of Celite and concentrated. The residue was purified by column chromatography (silica, pentane:EtOAc 30:1), affording the title compounds 6.

2-(Azidomethyl)-2-phenylcyclopentanone (6a).

Compound 6a was prepared according to general method E using 4a (246 mg, 1.00 mmol, 1.0 equiv), 2 (531 mg, 2.12 mmol, 1.2 equiv), and Cu(dap)Cl (4.4 mg, 5.0 μmol, 0.5 mol %) in CH3CN (5.0 mL, 0.2 m). The title compound 6a was obtained as a colorless oil (193 mg, 0.897 mmol, 90%). Rf 0.7 (silica, pentane:EtOAc: 10:1). 1H NMR (400 MHz, CDCl3, δ): 7.37 (m, 4H), 7.30 (m, 1H), 3.72 (d, J = 12.2 Hz, 1H), 3.49 (d, J = 12.2 Hz, 1H), 2.60 (m, 1H), 2.41–2.19 (m, 3H), 2.00 (m, 1H), 1.78 (m, 1H) ppm. 13C{1H} NMR (101 MHz, CDCl3): 217.5, 136.9, 129.8, 122.8, 126.8, 57.9, 57.8, 37.5, 31.7, 18.5 ppm. HRMS (ESI): [M + Na]+ calcd for C21H14NaO5, 328.0953; found, 328.0952. IR (film): 2967 (w), 2925 (w), 2917 (w), 2890 (w), 2140 (w), 1738 (s), 1497 (w), 1448 (w), 1301 (w), 12347 (v), 11247 (m), 1056 (w), 911 (m), 795 (s), 748 (w), 634 (s), 580 (w).
1300 (w), 1288 (w), 1253 (w), 1160 (w) cm⁻¹. NMR data correspond to the reported values.²⁷

Characterization of 2-(Azidomethyl)-2-phenyl-1-oxaspiro[2.3]-hexane (7a).

\[ \text{Compound } 6b \text{ was prepared according to general method E using } 4b \text{ (130 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH}_2\text{CN (2.5 mL, 0.2 m). The title compound } 6b \text{ was obtained as a colorless oil (98 mg, 0.42 mmol, 84%).} \]

\[ \text{Compound } 6c \text{ was prepared according to general method E using } 4c \text{ (151 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH}_2\text{CN (2.5 mL, 0.2 m). The title compound } 6c \text{ was obtained as a colorless oil (115 mg, 0.457 mmol, 91%).} \]

\[ \text{Compound } 6d \text{ was prepared according to general method E using } 4d \text{ (161 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH}_2\text{CN (2.5 mL, 0.2 m). The title compound } 6d \text{ was obtained as a colorless oil (130 mg, 0.446 mmol, 89%).} \]
Compound 6g was prepared according to general method E using 4g (140 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap),Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH3CN (2.5 mL, 0.2 m). The title compound 6g was obtained as a colorless oil (120 mg, 0.481 mmol, 96%). Rf 0.7 (silica, pentane:EtOAc 10:1). 1H NMR (400 MHz, CDCl3, δ): 7.37−7.28 (m, 4H), 3.66 (d, J = 12.3 Hz, 1H), 1.70−1.62 (m, 1H). 13C{1H} NMR (101 MHz, CDCl3, δ): 216.9, 135.3, 133.7, 128.9, 128.1, 57.6, 57.0, 37.4, 31.6, 18.4 ppm. HRMS (ESI): [M + Na]+ calcd for C13H15N3NaO+, 252.1107; found, 252.1111. IR (film): 2971 (w), 2837 (w), 2102 (s), 1736 (s), 1605 (w), 1456 (w), 1300 (w), 1272 (w), 1178 (w), 1105 (w), 1016 (w), 908 (s), 837 (w) cm⁻¹.

2-(Azidomethyl)-2-(4-chlorophenyl)cyclopentanone (6j).

Compound 6j was prepared according to general method E using 4j (132 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap),Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH3CN (2.5 mL, 0.2 m). The title compound 6j was obtained as a colorless oil (96 mg, 0.41 mmol, 82%). Rf 0.6 (silica, pentane:EtOAc 1:1). 1H NMR (400 MHz, CDCl3, δ): 7.33 (td, J = 8.0, 6.1 Hz, 1H), 7.17 (dt, J = 8.0, 1.2 Hz, 1H), 7.12 (dt, J = 10.5, 2.2 Hz, 1H), 7.03−6.95 (m, 1H), 3.69 (d, J = 12.3 Hz, 1H), 3.48 (d, J = 12.3 Hz, 1H), 2.62−2.52 (m, 1H), 2.43−2.23 (m, 3H), 2.09−1.96 (m, 1H), 1.87−1.70 (m, 1H). 13C{1H} NMR (101 MHz, CDCl3, δ): 216.9, 163.0 (d, J = 246.8 Hz), 139.5 (d, J = 7.0 Hz), 130.4 (d, J = 8.3 Hz), 122.4 (d, J = 2.9 Hz), 114.8 (d, J = 21.1 Hz), 114.0 (d, J = 22.6 Hz), 57.7, 57.5 (d, J = 1.7 Hz), 37.5, 31.8, 18.5 ppm. 19F NMR (376 MHz, CDCl3, δ): −111.5 (d, J = 7.7, 7.7, 6.1 Hz) ppm. HRMS (ESI): [M + H]+ calcd for C13H14FNO+, 206.0976; found, 206.0973 (loss of N2). IR (film): 2972 (w), 2105 (s), 1738 (m), 1614 (w), 1588 (w), 1490 (w), 1439 (w), 1274 (w), 1161 (w), 875 (w), 789 (w) cm⁻¹.

2-(Azidomethyl)-2-(4-fluorophenyl)cyclopentanone (6i).

Compound 6i was prepared according to general method E using 4i (138 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap),Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH3CN (2.5 mL, 0.2 m). The title compound 6i was obtained as a colorless oil (105 mg, 0.428 mmol, 86%). Rf 0.6 (silica, pentane:EtOAc 10:1). 1H NMR (400 MHz, CDCl3, δ): 7.27−7.21 (m, 1H, ArH), 7.20−7.15 (m, 2H, ArH), 7.10 (d, J = 7.5 Hz, 1H, ArH), 3.72 (d, J = 12.3 Hz, 1H, CH2-N3), 3.47 (d, J = 12.3 Hz, 1H, CH2-N3), 2.60 (m, 1H, CH2), 2.44−2.17 (m, 6H, CH2, CH3), 1.99 (m, 1H, CH3), 1.86−1.69 (m, 1H, CH3) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 217.4, 138.5, 136.7, 128.7, 128.4, 123.5, 123.5, 57.7, 57.6, 37.3, 31.6, 21.4, 18.3 ppm. HRMS (ESI): [M + Na]+ calcd for C13H14N3NaO+, 252.1107; found, 252.1111. IR (film): 3458 (w), 3027 (w), 2968 (w), 2886 (w), 2253 (w), 2101 (s), 1736 (s), 1605 (w), 1456 (w), 1300 (w), 1272 (w), 1158 (w), 909 (m) cm⁻¹.

2-(Azidomethyl)-2-(3-methoxyphenyl)cyclopentanone (6i).

Compound 6i was prepared according to general method E using 4i (138 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap),Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH3CN (2.5 mL, 0.2 m). The title compound 6i was obtained as a colorless oil (105 mg, 0.428 mmol, 86%). Rf 0.6 (silica, pentane:EtOAc 10:1). 1H NMR (400 MHz, CDCl3, δ): 7.27 (t, J = 8.0 Hz, 1H), 6.95 (ddd, J = 8.0, 2.2, 0.9 Hz, 1H), 6.92 (t, J = 2.2 Hz, 1H), 6.83 (ddd, J = 8.0, 2.2, 0.9 Hz, 1H), 3.80 (s, 3H), 3.71 (d, J = 12.2 Hz, 1H), 3.48 (d, J = 12.2 Hz, 1H), 2.64−2.52 (m, 1H), 2.41−2.16 (m, 3H), 2.07−1.93 (m, 1H), 1.87−1.71 (m, 1H) ppm. 13C{1H} NMR (101 MHz, CDCl3, δ): 217.3, 159.9, 138.4, 129.9, 118.9, 113.0, 112.7, 57.7, 55.2, 37.4, 31.7, 18.4 ppm. HRMS (ESI): [M + Na]+ calcd for C13H14N3O+, 217.1097; found, 217.1101 (loss of N2). IR (film): 2968 (w), 2837 (w), 2102 (s), 1736 (s), 1599 (m), 1582 (m), 1435 (w), 1292 (m), 1263 (m), 1242 (m), 1157 (w), 1053 (m), 883 (w), 781 (w) cm⁻¹.

2-(Azidomethyl)-2-(3-fluorophenyl)cyclopentanone (6i).
Compound 6l was prepared according to general method E using 4l (0.13 g, 0.50 mmol, 1 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH_2CN (2.5 mL, 0.2 mL). The title compound 6l was obtained as a colorless oil (89 mg, 0.39 mmol, 78%). Rf 0.7 (silica, pentane:EtOAc 10:1). ^1H NMR (400 MHz, CDCl_3, δ): 7.20–6.94 (m, 3H), 3.72 (d, J = 12.3 Hz, 1H), 3.46 (d, J = 12.3 Hz, 1H), 2.70–2.54 (m, 1H), 2.46–2.16 (m, 9H), 2.06–1.91 (m, 1H), 1.84–1.72 (m, 1H) ppm. ^13C(^1H) NMR (101 MHz, CDCl_3, δ): 217.6, 137.2, 136.2, 134.0, 130.1, 127.8, 123.9, 57.8, 57.4, 37.3, 31.5, 19.9, 19.3, 18.4 ppm. HRMS (ESI): [M + Na]^+ calcd. for C_16H_15N_3NaO_3^+, 382.0849. IR (v): 3061 (w), 2972 (w), 2105 (s), 1738 (m), 1598 (w), 1437 (w), 1343 (w), 1275 (w), 1160 (w), 1036 (w), 968 (w), 863 (w), 821 (w) cm\(^{-1}\).

2-(Azidomethyl)-2-(3,4-dimethoxyphenyl)cyclooctanone (6m).

Compound 6m was prepared according to general method E using 4m (153 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.2 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH_2CN (2.5 mL, 0.2 mL). The title compound 6m was obtained as a colorless oil (120 mg, 0.436 mmol, 87%). Rf 0.2 (silica, pentane:EtOAc 10:1). ^1H NMR (400 MHz, CDCl_3, δ): 7.01–6.78 (m, 3H), 3.88 (s, 3H), 3.87 (s, 3H), 3.70 (d, J = 12.2 Hz, 1H), 3.46 (d, J = 12.2 Hz, 1H), 2.63–2.53 (m, 1H), 2.41–2.20 (m, 3H), 2.06–1.94 (m, 1H), 1.87–1.73 (m, 1H) ppm. ^13C(^1H) NMR (101 MHz, CDCl_3, δ): 217.5, 149.2, 148.7, 128.8, 119.1, 111.2, 110.0, 58.0, 57.3, 56.0, 55.8, 37.4, 31.7, 18.5 ppm. HRMS (ESI): [M + Na]^+ calcd. for C_16H_17N_3NaO_3^+, 288.1107; found, 288.1118. IR (v): 3061 (w), 2972 (w), 1738 (m), 1598 (w), 1437 (w), 1343 (w), 1275 (w), 1160 (w), 1036 (w), 968 (w), 863 (w), 821 (w) cm\(^{-1}\).

2-(Azidomethyl)-2-(naphthalen-1-yl)cyclooctanone (6p).

Compound 6p was prepared according to general method E using 4p (0.15 g, 0.50 mmol, 1 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH_2CN (2.5 mL, 0.2 mL). The title compound 6p was obtained as a colorless oil (105 mg, 0.396 mmol, 79%). Rf 0.7 (silica, pentane:EtOAc 10:1). ^1H NMR (400 MHz, CDCl_3, δ): 8.16–8.09 (m, 1H), 7.89 (dd, J = 7.9, 1.7 Hz, 1H), 7.79 (dt, J = 8.2, 1.1 Hz, 1H), 7.59–7.46 (m, 2H), 7.35 (dd, J = 8.2, 7.4 Hz, 1H), 7.22 (dd, J = 7.4, 1.1 Hz, 1H), 4.21 (d, J = 12.5 Hz, 1H), 4.00 (d, J = 12.5 Hz, 1H), 2.89 (ddd, J = 13.0, 7.2, 3.9, 1.5 Hz, 1H), 2.66 (ddd, J = 13.0, 9.5, 7.2 Hz, 1H), 2.56 (ddd, J = 18.8, 9.5, 4.8, 1.5 Hz, 1H), 2.38 (dd, J = 18.8, 8.6 Hz, 1H), 2.08–1.92 (m), 1.82–1.68 (m, 1H) ppm. ^13C(^1H) NMR (101 MHz, CDCl_3, δ): 219.3, 153.5, 153.4, 153.0, 129.9, 129.1, 125.8, 125.7, 125.4, 125.0, 58.7, 55.4, 37.6, 33.0, 18.9 ppm. HRMS (ESI): [M^+] calcd. for C_33H_23NO_4, 537.1148; found, 537.1156 (loss of N2). IR (v): 3454 (w), 2972 (w), 2890 (w), 2780 (w), 2102 (s), 1734 (s), 1611 (w), 1505 (s), 1488 (s), 1437 (m), 1297 (w), 1237 (s), 1157 (w), 1115 (w), 1039 (s), 911 (s) cm\(^{-1}\).

4-(Azidomethyl)-4-phenylidihydrofuran-3(2H)-one (6q).

Compound 6q was prepared according to general method E using 4q (157 mg, 0.500 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv), and Cu(dap)_2Cl (2.2 mg, 2.5 μmol, 0.5 mol %) in CH_2CN (2.5 mL, 0.2 mL). The title compound 6q was obtained as a colorless oil (82 mg, 0.29 mmol, 58%). Rf 0.6 (silica, pentane:EtOAc 10:1). ^1H NMR (400 MHz, CDCl_3, 3:1 mixture of keto/enol tautomers, δ): 7.47–7.28 (m, 5H), 6.10–5.50 (m, 4H), 4.61–4.41 (m, 1H), 4.00–3.75 (m, 1H), 3.05–2.57 (m, 2H), 2.57–2.25 (m, 2H), 2.08–1.92 (m), 1.82–1.68 (m, 1H) ppm. HRMS (ESI): [M^+] calcd. for C_18H_17NO_2^+, 277.1156; found, 277.1166. IR (v): 3454 (w), 2972 (w), 2890 (w), 2780 (w), 2102 (s), 1734 (s), 1611 (w), 1505 (s), 1488 (s), 1437 (m), 1297 (w), 1237 (s), 1157 (w), 1115 (w), 1039 (s), 911 (s) cm\(^{-1}\).
Compound 7t was prepared according to general method E using 4 (124 mg, 0.50 mmol, 1.00 equiv), 2 (265 mg, 0.600 mmol, 1.20 equiv) and Cu(dap)Cl (2.2 mg, 0.004 mmol, 0.10 mol %) in THF (415 μL, 0.20 M). The title compound 7t was obtained as a colorless oil (72 mg, 0.35 mmol, 1.00 equiv) and CuI (6 mg, 0.04 mmol, 10 mol %) in THF (1.62 mL). The resulting colorless solution was cooled to 0 °C for 30 min, and a solution of 4-oxo-4-phenylbutanoic acid (30) (3.00 g, 16.8 mmol, 1.00 equiv) in dry THF (1 M) was added dropwise. The reaction was stirred at 0 °C for 1 h and at room temperature overnight. The solvent was removed in vacuo, and the residue was diluted with DCM and aqueous NaOH (1 M). The aqeous layer was separated, washed with DCM, and acidified to pH 1 with concentrated HCl (35%). DCM was added, and the organic compound was extracted twice with DCM. The organic layer was washed with water, dried over MgSO₄, and concentrated in vacuo. The crude product was purified by flash column chromatography (SiO₂, DCM/MeOH: 100:1 then 95:5 and 90:10) to give 4-phenyl-4-enolic acid (8) (2.38 g, 13.5 mmol, 80%). Rf 0.3 (silica, DCM/MeOH 9:1) 0.70. 1H NMR (400 MHz, CDCl₃, δ): 7.49–7.26 (m, 1H), 7.24–7.12 (m, 1H), 7.09–7.00 (m, 1H), 6.92–6.84 (m, 1H), 6.73–6.65 (m, 1H), 6.62–6.55 (m, 1H), 5.86–5.79 (m, 1H), 5.34 (s, 2H), 2.87 (t, J = 7.8 Hz, 2H), 2.56 (dd, J = 8.9, 6.7 Hz, 2H, ppm). The signals of the 1H NMR spectra were in accordance with the data reported in the literature.¹³

-established Azidation Reactions Performed with BuABX (1d) and ABZ (2). 4-Phenylpent-4-enolic Acid (8). Following a reported procedure,¹¹ a solution of BuABX (4.91 g, 43.8 mmol, 2.6 equiv) in dry THF (0.5 M) was added under nitrogen to a bromo(methyl)triphenylphosphonane (7.82 g, 21.9 mmol, 1.3 equiv) in portions at 0 °C. The mixture was stirred at 0 °C for 30 min, and a solution of 4-oxo-4-phenylbutanoic acid (30) (3.00 g, 16.8 mmol, 1.00 equiv) in dry THF (1 M) was added dropwise. The reaction was stirred at 0 °C for 1 h and at room temperature overnight. The solvent was removed in vacuo, and the residue was diluted with DCM and aqueous NaOH (1 M). The aqeous layer was separated, washed with DCM, and acidified to pH 1 with concentrated HCl (35%). DCM was added, and the organic compound was extracted twice with DCM. The organic layer was washed with water, dried over MgSO₄, and concentrated in vacuo. The crude product was purified by flash column chromatography (SiO₂, DCM/MeOH: 100:1 then 95:5 and 90:10) to give 4-phenyl-4-enolic acid (8) (2.38 g, 13.5 mmol, 80%). Rf 0.3 (silica, DCM/MeOH 9:1) 0.70. 1H NMR (400 MHz, CDCl₃, δ): 7.49–7.26 (m, 1H), 7.24–7.12 (m, 1H), 7.09–7.00 (m, 1H), 6.92–6.84 (m, 1H), 6.73–6.65 (m, 1H), 6.62–6.55 (m, 1H), 5.86–5.79 (m, 1H), 5.34 (s, 2H), 2.87 (t, J = 7.8 Hz, 2H), 2.56 (dd, J = 8.9, 6.7 Hz, 2H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.¹¹

-N-Phenyl-(2-vinylphenyl)sulfonil)methacrylamide (10). Following a reported procedure,¹² 2-bromobenzene-1-sulfonyl chloride (31) (1.34 g, 5.24 mmol, 1.0 equiv) was dissolved in DMF (52 mL). The resulting colorless solution was cooled to 0 °C (ice-water bath), and aniline (32) (1.9 mL, 21 mmol, 4.0 equiv) was added dropwise via syringe. The cooling bath was removed, and the mixture was stirred at room temperature for 1.5 h. During this time, it became pale yellow. The reaction was then quenched by the addition of water (50 mL). The aqueous layer was extracted with EtOAc (4 × 50 mL). The organic extracts were washed withaq. HCl (3 × 50 mL) and twice with brine, dried over MgSO₄, filtered, and concentrated under vacuum. The resulting yellow, crude oil was submitted to flash column chromatography (SiO₂ pentane/ EtOAc in pentane 19:1 to 6:4) to provide 2-bromo-N-phenylbenzenesulfonamide (33) (0.819 g, 2.62 mmol, 50%) as a pale yellow, crystalline solid. Rf 0.3 (silica, pentane/EtOAc 4:1) 0.39. 1H NMR

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**Note**

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(400 MHz, CDCl₃, δ): 8.02 (m, 1H), 7.70 (m, 1H), 7.36 (m, 2H), 7.25–7.18 (m, 2H), 7.18–7.06 (m, 4H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.45

Following a reported procedure,44 a 25 mL round-bottom test tube was charged with 2-bromo-N-phenylbenzenesulfonylamide (33) (0.600 g, 1.92 mmol, 1.0 equiv), PdCl₂(PPh₃)₂ (67 mg, 0.096 mmol, 5 mol %), potassium (vinyl)triﬂuoroborate (0.283 g, 2.11 mmol, 1.1 equiv), and cesium carbonate (1.88 g, 5.77 mmol, 3.0 equiv). The tube was sealed, evacuated, and backﬁlled with nitrogen (3 times). A 9:1 mixture of THF and water (30 mL) was added via syringe. The resulting mixture then was heated to 85–90 °C under stirring, turning from a clear, pale brown solution into a dark brown suspension. After 16 h, the mixture was diluted with water (30 mL), and most of the volatile solvents were removed by evaporation under reduced pressure. The aqueous residue was washed with diethyl ether (3 × 20 mL) and acidiﬁed by cautious addition of conc. HCl (32% v/v) until pH < 3. It was then extracted with DCM (3 × 30 mL). The combined organic extracts were dried over MgSO₄, and concentrated under vacuum to afford 2-allylbenezonic acid (37) (0.500 g, 3.08 mmol, 83%) as a colorless solid, which did not require any further puriﬁcation. 1H NMR (400 MHz, δ, DMSO) the signal corresponding to the CO₂H was not resolved, δ: 7.80 (dd, J = 7.5, 1.5 Hz, 1H), 7.48 (td, J = 7.5, 1.5 Hz, 1H), 7.35–7.26 (m, 2H), 5.96 (ddt, J = 18.5, 9.4, 6.5 Hz, 1H), 5.01 (dd, J = 3.7, 1.8 Hz, 1H), 4.97 (d, J = 1.6 Hz, 1H), 3.71 (d, J = 6.6 Hz, 2H) ppm. 13C{1H} NMR (101 MHz, CDCl₃, δ): 173.6, 142.8, 137.3, 133.1, 131.7, 131.1, 128.2, 126.3, 115.7, 38.6. The signals of the NMR spectra were in accordance with the data reported in the literature.11

Following a reported procedure,100 a 50 mL round-bottom test tube was charged with 2-allylbenezonic acid (37) (0.400 g, 2.47 mmol, 1.0 equiv) and DCM (dry; 12.3 mL). O-Methylhydroxylamine hydrochloride (0.309 g, 3.70 mmol, 1.5 equiv), DMAP (0.603 g, 4.93 mmol, 2.0 equiv), and EDCI (0.946 g, 4.93 mmol, 2.0 equiv) were added to provide a pale yellow-pink solution, which was stirred at room temperature for 20 h. The organic solution was then treated with aq. HCl (1.0 M; 15 mL). The aqueous layer was extracted with DCM (3 × 15 mL). The combined organic extracts were washed with brine, dried over MgSO₄, and concentrated under vacuum to furnish a pale yellow crude solid. The latter was submitted to column chromatography (silica; pentane:EtOAc; pentane 19:1 to 6:4) to obtain a colorless solid. 1H NMR spectra were in accordance with the data reported in the literature.13

Cul-Catalyzed Intramolecular Oxydation of Alkenes: Synthesis of 5-(Azidomethyl)-5-phenyldihydrofuran-2(3H)-one 9 Experiment with ABX (General Method F). Following a slightly modiﬁed procedure,45 distilled dry acetonitrile (preliminarily purged with Ar for 5 min; 10 mL) was added in a ﬂame-dried 4 mL round bottom test tube containing 4-phenylpent-4-enic acid (8) (35.0 mg, 0.200 mmol, 1.0 equiv), ABX (1a) (116 mg, 0.400 mmol, 2.0 equiv), and Cu(dap)Cl (0.90 mg, 0.10 mg, 0.50 mol %). The resulting solution was irradiated with blue light LEDs under stirring at room temperature for 18 h. The reaction mixture was then concentrated, diluted with EtO (10 mL), ﬁltered through a plug of Celite, and again concentrated under reduced pressure. The residue was submitted to ﬂash column chromatography (SiO₂; pentane:EtOAc 50:50 to 30:70) to afford pure 5-allyl-5-nitrobenzofuran-2(3H)-one (16) (0.380 g, 2.00 mmol, 81%) as a colorless solid. Rf (silica; pentane:EtOAc 5:4) 0.37. 1H NMR (400 MHz, CDCl₃, δ): 8.42 (br s, 1H), 7.37–7.29 (m, 2H), 7.30–7.22 (m, 2H), 6.00 (ddt, J = 16.6, 10.1, 6.3 Hz, 1H), 5.09 (dd, J = 10.2, 1.6 Hz, 1H), 5.02 (dd, J = 17.1, 1.8 Hz, 1H), 3.88 (s, 3H), 3.57 (d, J = 6.3 Hz, 2H) ppm. The signals of the 1H NMR spectra were in accordance with the data reported in the literature.46

Experiment with tBuABX (1d). The reaction was performed following the general method F, starting from the same amounts of 4-phenylpent-4-enic acid (8) and Cu(dap)Cl, but using tBuABX (1d) (138 mg, 0.400 mmol, 2.0 equiv) instead of ABX (1a). 5-(Azidomethyl)-5-phenyldihydrofuran-2(3H)-one (9) was obtained in 56% yield (24.0 mg, 0.112 mmol).56

Experiment with ABZ (2). The reaction was performed following the general method F, starting from the same amounts of

1H NMR spectra were in accordance with the data reported in the literature.45

Following a reported procedure,47 methyl 2-allylbenzoate (36) (0.650 g, 3.69 mmol, 1.0 equiv) was dissolved in a mixture of THF (13.3 mL), MeOH (3.1 mL), and water (3.1 mL). LiOH (0.883 g, 36.9 mmol, 10 equiv) was added, and the resulting suspension was vigorously stirred overnight at room temperature. After 16 h, the mixture was diluted with water (30 mL), and most of the volatile solvents were removed by evaporation under reduced pressure. The aqueous residue was washed with diethyl ether (3 × 20 mL) and acidiﬁed by cautious addition of conc. HCl (32% v/v) until pH < 3. It was then extracted with DCM (3 × 30 mL). The combined organic extracts were dried over MgSO₄, and concentrated under vacuum to afford 2-allylbenezonic acid (37) (0.500 g, 3.08 mmol, 83%) as a colorless solid, which did not require any further puriﬁcation. 1H NMR (400 MHz, δ, DMSO) the signal corresponding to the CO₂H was not resolved, δ: 7.80 (dd, J = 7.5, 1.5 Hz, 1H), 7.48 (td, J = 7.5, 1.5 Hz, 1H), 7.35–7.26 (m, 2H), 5.96 (ddt, J = 18.5, 9.4, 6.5 Hz, 1H), 5.01 (dd, J = 3.7, 1.8 Hz, 1H), 4.97 (d, J = 1.6 Hz, 1H), 3.71 (d, J = 6.6 Hz, 2H) ppm. 13C{1H} NMR (101 MHz, CDCl₃, δ): 173.6, 142.8, 137.3, 133.1, 131.7, 131.1, 128.2, 126.3, 115.7, 38.6. The signals of the NMR spectra were in accordance with the data reported in the literature.11
4-phenylpent-4-enoic acid (8) and Cu(dap)Cl, but using ABZ (2) (177 mg, 0.400 mmol, 2.0 equiv) instead of ABX (1a). 5-(Azidomethyl)-5-phenyl-2,3-dihydro-1H-indene-1-carboxamide (11) was obtained in 81% (35.0 mg, 0.162 mmol).

**Generation of Functionalized Indanes through a Complex Radical Cascade Reaction: Synthesis of 3-(Azidomethyl)-1-methyl-N-phenyl-2,3-dihydro-1H-indene-1-carboxamide (11).** Following a reported procedure, a 25 mL round-bottom test tube was charged with N-phenyl-N-(2-vinylphenyl)sulfonyl)methacrylamide (10) (98 mg, 0.30 mmol, 1.0 equiv) and tBuABX (1d) (0.207 g, 0.600 mmol, 2.0 equiv). The tube was sealed, evacuated, and backfilled with nitrogen three times. DCM (dry and freshly degassed by the freeze-pump-thaw method; 6.0 mL) was then added via syringe. The mixture was stirred at room temperature for 10 s, resulting in the immediate dissolution of the solids, and then heated at 60 °C overnight (14 h). The mixture was then concentrated under vacuum in the presence of silica gel. The crude product, adsorbed on silica gel, was then submitted to column chromatography (SiO2; pentane:EtOAc 19:1 to 9:1) to afford a mixture of the desired product with tert-butyl iodobenzoic acid. To remove the latter, this mixture was diluted with DCM (10 mL) and washed twice withaq. K2CO3 (2.0 M; 15 mL). The aqueous layer was extracted with DCM (3 × 15 mL), and the organic extracts were dried over MgSO4, filtered, and concentrated under reduced pressure. 3-(Azidomethyl)-1-methyl-N-phenyl-2,3-dihydro-1H-indene-1-carboxamide (11) (finally obtained as a pale yellow viscous oil (mixture of diastereoisomers, dr 9:1; 65 mg, 0.19 mmol, 64%) (6.4 Hz, 1H), 3.00 (dd, J = 8.1, 7.2 Hz, 2H), 7.07 (dd, J = 8.6, 7.1, 1.2 Hz, 1H), 6.99 (br s, 1H), 3.70–3.95 (m, 2H), 3.51 (s, J = 9.3, 6.4 Hz, 1H), 3.00 (dd, J = 13.1, 7.3 Hz, 1H), 1.87 (dd, J = 13.1, 9.5 Hz, 1H), 1.73 (s, 3H) ppm. 13C NMR spectra below for more clarity). Then, a ratio was done between the area of the dodecane peak as an internal standard (not shown on the spectra below for more clarity). Then, a ratio was done between the area of the peaks with 1a, 1d, or 2 as the reagent using 1a as the reference (ratio of 1.00).

**Experiment with tBuABX (1d).** The reaction was performed following the general method G, starting from the same amounts of cumene (12), Fe(OAc)2, and 2,6-bis-(5)-4-isopropyl-4,5-dihydrooxazol-2-yl)pyridine, but using tBuABX (1d) (207 mg, 0.600 mmol, 3.0 equiv) instead of ABX (1a). The reaction was monitored by GC-MS (the chromatogram showing the reaction progress after 22 h is shown in Figure S2).

**Experiment with ABZ (2).** The reaction was performed following the general method G, starting from the same amounts of cumene (12), Fe(OAc)2, and 2,6-bis-(5)-4-isopropyl-4,5-dihydrooxazol-2-yl)pyridine, but using ABZ (2) (265 mg, 0.600 mmol, 3.0 equiv) instead of ABX (1a). The reaction was monitored by GC-MS (the chromatogram showing the reaction progress after 22 h is shown in Figure S3).

**Cu(II)-Catalyzed Azidation of Anilines: Synthesis of 2-Azido-4-methylaniline (15).** Experiment with ABX (1a) (General Method H). Following a slightly modified procedure, a 20 mL round-bottom test tube was charged with ABX (1a) (116 mg, 0.400 mmol, 1.0 equiv), Cu(OAc)2 (15 mg, 0.080 mmol, 10 mol %), and THF (2.7 mL) under air, t-BuOH (14) (86 mg, 0.80 mmol, 2.0 equiv) was then added, and the resulting dark mixture was stirred at room temperature under air for 12 h. The solution was then diluted with ethyl acetate (27 mL), washed with saturated aqueous NaHCO3, and the two layers were separated. The organic layer was then dried over MgSO4, filtered, and concentrated in vacuo to afford a brown crude oil (14% NMR yield; based on 1H NMR and using CH2Br2 (20 μL, 0.28 mmol) as an internal standard: 63%). The latter was adsorbed on silica gel and submitted to chromatography (silica; petroleum ether:EtOAc 100:0 to 95:5) to afford pure 2-azido-4-methylaniline (15) as a brown oil (14 mg, 0.10 mmol, 24% yield; the volatility of the compound accounts for the low isolated yield). Rf (silica, pentane:EtOAc 8:2) 0.45. 1H NMR (400 MHz, CDCl3, δ) 5.34 (d, J = 1.9 Hz, 1H), 1.61 (d, J = 8.0 Hz, 1H), 1.37 (s, 2H), 2.27 (s, 3H). The signals of the 1H NMR spectra were in accordance with the data reported in the literature.

**Experiment with ABX (1d).** The reaction was performed following the general method H, starting from the same amounts of p-toluidine (14) and Cu(OAc)2, but using ABX (1d) (138 mg, 0.400 mmol, 1.0 equiv) instead of ABX (1a), 2-Azido-4-methylaniline (15) was generated in 62% yield (based on 1H NMR and using CH2Br2 (20 μL, 0.28 mmol) as an internal standard). Upon column chromatography, it was isolated as a brown oil (15 mg, 0.10 mmol, 25% yield; the volatility of the compound accounts for the low isolated yield).

**Experiment with ABZ (2).** The reaction was performed following the general method H, starting from the same amounts of p-toluidine (14) and Cu(OAc)2, but using ABZ (2) (177 mg, 0.400 mmol, 1.0 equiv) instead of ABX (1a). 2-Azido-4-methylaniline (15) was generated in 72% yield (based on 1H NMR and using CH2Br2 (20 μL, 0.28 mmol) as an internal standard). Upon column chromatography, it was isolated as a brown oil (16 mg, 0.10 mmol, 26% yield; the volatility of the compound accounts for the low isolated yield).

**Cu(II)-Catalyzed Intramolecular Alkene Aminoazidation: Synthesis of 3-(Azidomethyl)-2-methoxy-3,4-dihydroisoquinolin-1(2H)-one (17).** Experiment with tBuABX (1d) (General Method H). Following a reported procedure, a 25 mL round-bottom test tube was charged with 2-allyl-N-methoxybenzamide (16) (57 mg, 0.30 mmol, 1.0 equiv), tBuABX (1d) (0.124 g, 0.360 mmol, 1.2 equiv), and CuOAc (3.7 mg, 0.030 mmol, 10 mol %). The vessel was sealed, evacuated, and backfilled with nitrogen (3 times). Acetoneitrile (dry and degassed by purging it with Ar for 15 min; 30 mL) was added via syringe, giving initially a pale blue suspension. The latter was heated at 60 °C under stirring for 2 h. After 5 min at this temperature, the suspension had turned into a clear blue-green solution; a precipitate was formed after 1.5 h. After 2 h, TLC analysis (pentane:EtOAc 3:1) showed the complete consumption of the starting material. The reaction mixture was poured into sat. aq. NaHCO3 (15 mL), and the aqueous layer was extracted with EtOAc (3 × 15 mL). The combined organic extracts were washed with brine, dried over MgSO4, filtered, and concentrated under vacuum to afford a pale yellow crude solid.
The impact energy is varied by the selection of drop height and weight. The test was performed with 1 J steps. In the second experiment with ABZ (2), the reaction was performed following the general method I, starting from the same amounts of 2-allyl-N\textsubscript{2}methoxybenzamide (16) and CuOTAC, but using ABZ (2) (159 mg, 0.360 mmol, 2.0 equiv) instead of BuABX (1d). The crude product was purified by column chromatography (SiO\textsubscript{2}; pentane:EtOAc 94:6 to 50:50), followed by preparative TLC (SiO\textsubscript{2}, 20 × 20 sq. cm; hexane:EtOAc 50:50), to afford 3-(azidomethyl)-2-methoxy-3,4-dihydroisoquinolin-1(2H)-one (17) (0.060 g, 0.26 mmol, 86\% yield) as a colorless oil.

**METHODS FOR SAFETY STUDIES**

The stability of the compounds was determined by DSC. A few milligrams of the compounds were sealed in gold plated pressure resistant crucibles. The crucibles were heated in an oven from 30 to 400 °C at a rate of 4 °C/min. The T\textsubscript{onset} (temperature at which an exothermic signal is detected), the decomposition energy, and the peak temperature were recorded and compared. The provided data are the average of six measurements is obtained. Here a microphone was used for the detection. The limiting impact energy is the lowest energy at which a signal is detected, the decomposition energy, and the peak temperature were recorded and compared. The provided data are the average of six measurements. In the H\textsuperscript{1}NMR spectrum, all peaks were shifted +0.17 ppm with respect to the ones in the literature.

**EXPERIMENT WITH ABZ (2).** The reaction was performed following the general method I, starting from the same amounts of 2-allyl-N\textsubscript{2}methoxybenzamide (16) and CuOTAC, but using ABZ (2) (159 mg, 0.360 mmol, 2.0 equiv) instead of BuABX (1d). The crude product was purified by column chromatography (SiO\textsubscript{2}; pentane:EtOAc 94:6 to 50:50), followed by preparative TLC (SiO\textsubscript{2}, 20 × 20 sq. cm; hexane:EtOAc 50:50), to afford 3-(azidomethyl)-2-methoxy-3,4-dihydroisoquinolin-1(2H)-one (17) (0.060 g, 0.26 mmol, 86\% yield) as a colorless oil.

**ASSOCIATED CONTENT**

* Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.8b02068.

Reactions schemes for the synthesis of starting materials and reagents, reaction optimization details, accident report, and chromatogram and NMR spectra of new compounds or reported compounds synthesized using modified methods (PDF)

**AUTHOR INFORMATION**

* Corresponding Author
  jerome.waser@epfl.ch

Thierry Meyer: 0000-0003-2546-9107
Jerome Was er: 0000-0002-4570-914X

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(4) (a) The reaction was performed following the general method I, starting from the same amounts of 2-allyl-N\textsubscript{2}methoxybenzamide (16) and CuOTAC, but using ABZ (2) (159 mg, 0.360 mmol, 2.0 equiv) instead of BuABX (1d).

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S.A. and J.P. contributed equally to this work.
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1. Synthesis of the azidation hypervalent iodine reagents

Synthesis of ABX (1a)

\[ \text{HO}_2C \quad \xrightarrow{\text{1. NaNO}_2, \text{AcOH}, 120 \degree C} \quad \xrightarrow{\text{2. Ac}_2O, 140 \degree C} \quad \xrightarrow{\text{3. TMSN}_3, \text{TMSOTf, DCM, 0 \degree C}} \quad \text{O} \quad \text{I} \quad \text{N}_3 \]

Synthesis of tBuABX (1d)

\[ \begin{array}{c}
\text{Me} \quad \text{Me} \\
\text{I} \\
\text{TFA, 25 \degree C, under O}_2 \\
\text{Me} \quad \text{Me} \\
\text{I} \quad \text{OAc} \\
\text{H}_2\text{OBF}_4, 90 \degree C \\
\text{Me} \quad \text{Me} \\
\text{I} \quad \text{N}_3 \\
\text{DCM, 0 \degree C}
\end{array} \]

Synthesis of ABZ (2)

\[ \begin{array}{c}
\text{OH} \\
\text{O} \quad \text{I} \\
\text{18} \xrightarrow{\text{1. SOCl}_2, \text{DMF, CH}_2\text{Cl}_2, \text{RT}} \\
\text{NHTs} \quad \text{N} \\
\text{23} \xrightarrow{\text{2. TsNH} \_2, \text{NEt}_3, \text{DMAP, toluene/EtOAc, 60 \degree C}} \\
\text{Ts} \quad \text{O} \quad \text{OAc} \\
\text{24} \xrightarrow{\text{TMSN}_3, \text{TMSOTf, CH}_2\text{Cl}_2, 0 \degree C} \\
\text{Ts} \quad \text{O} \quad \text{OAc} \\
\text{25} \xrightarrow{\text{TMSN}_3, \text{TMSOTf, CH}_2\text{Cl}_2, 0 \degree C} \\
\text{O} \quad \text{OAc} \\
\text{26} \xrightarrow{\text{TMSN}_3, \text{TMSOTf, CH}_2\text{Cl}_2, 0 \degree C}
\end{array} \]

2. Synthesis of 1-(1-bromovinyl)-arenes

General method A:

\[ \begin{array}{c}
\text{Br} \quad \text{P(OPh}_3\text{)} \_3, \text{NEt}_3 \\
\text{25} \xrightarrow{\text{CH}_2\text{Cl}_2, -60 \text{ to } 4 \degree C}
\end{array} \]

General method B:

\[ \begin{array}{c}
\text{Br} \quad \text{Br} \\
\text{25} \xrightarrow{1. \text{Br}_2, \text{CH}_2\text{Cl}_2, 0 \degree C} \\
\text{25} \xrightarrow{2. \text{K}_2\text{CO}_3, \text{THF}/\text{EtOH, RT}}
\end{array} \]

3. Synthesis of 1-(1-(arene)vinyl)cyclobutanols

General method C:
1-(3,4-dihyronaphthalen-1-yl)cyclobutanols (3s)

4. Synthesis of (1-(1-(arene)vinyl)cyclobutoxy)trimethylsilanes

General procedure D:

5. Optimization of the reaction

<table>
<thead>
<tr>
<th>Entry</th>
<th>ABZ (XX)</th>
<th>Catalyst</th>
<th>LED</th>
<th>Solvent</th>
<th>Resulta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>DMF</td>
<td>56% (6a)</td>
</tr>
<tr>
<td>2</td>
<td>2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>CH₃OH</td>
<td>70% (6a)</td>
</tr>
<tr>
<td>3</td>
<td>2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>DMA</td>
<td>65% (6a)</td>
</tr>
<tr>
<td>4</td>
<td>2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>CH₂Cl₂</td>
<td>56% (6a)</td>
</tr>
<tr>
<td>5</td>
<td>2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>DMSO</td>
<td>74% (6a:7a=1:3)</td>
</tr>
<tr>
<td>6</td>
<td>2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>CH₃CN</td>
<td>85% (6a)</td>
</tr>
<tr>
<td>7</td>
<td>1.2 equiv.</td>
<td>Cu(dap)₂Cl (0.5 mol%)</td>
<td>green</td>
<td>CH₃CN</td>
<td>88% (90%)b (6a)</td>
</tr>
<tr>
<td>8</td>
<td>1.2 equiv.</td>
<td>Ru(bpy)₃Cl₂ (1 mol%)</td>
<td>green</td>
<td>CH₃CN</td>
<td>74% (6a)</td>
</tr>
<tr>
<td>9</td>
<td>1.2 equiv.</td>
<td>Ru(bpy)₃Cl₂ (1 mol%)</td>
<td>blue</td>
<td>CH₃CN</td>
<td>79% (6a)</td>
</tr>
<tr>
<td></td>
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<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>10</td>
<td>1.2 equiv.</td>
<td>(Ir[dF(CF&lt;sub&gt;3&lt;/sub&gt;)ppy]&lt;sub&gt;2&lt;/sub&gt;(dtbpy))PF&lt;sub&gt;6&lt;/sub&gt; (1 mol%)</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>70% (6a)</td>
</tr>
<tr>
<td>11</td>
<td>1.2 equiv.</td>
<td>Eosin Y (5 mol%)</td>
<td>green</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>23% (6a)</td>
</tr>
<tr>
<td>12</td>
<td>1.2 equiv.</td>
<td>4CzIPN (5 mol%)</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>60% (6a)</td>
</tr>
<tr>
<td>13</td>
<td>1.6 equiv.</td>
<td>4CzIPN (5 mol%)</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>77% (74%)&lt;sup&gt;e&lt;/sup&gt; (6a)</td>
</tr>
<tr>
<td>14</td>
<td>2 equiv.</td>
<td>4CzIPN (5 mol%)</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>79% (6a)</td>
</tr>
<tr>
<td>15</td>
<td>2.5 equiv.</td>
<td>4CzIPN (5 mol%)</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>84% (6a)</td>
</tr>
<tr>
<td>16</td>
<td>1.6 equiv.</td>
<td>4CzIPN (2.5 mol%)</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>47% (6a)</td>
</tr>
<tr>
<td>17</td>
<td>1.2 equiv.</td>
<td>–</td>
<td>green</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>no conversion&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>18</td>
<td>1.2 equiv.</td>
<td>Cu(dap)&lt;sub&gt;2&lt;/sub&gt;Cl (0.5 mol%)</td>
<td>–</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>no conversion</td>
</tr>
<tr>
<td>19</td>
<td>1.6 equiv.</td>
<td>–</td>
<td>blue</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>no conversion</td>
</tr>
<tr>
<td>20</td>
<td>1.6 equiv.</td>
<td>4CzIPN (5 mol%)</td>
<td>–</td>
<td>CH&lt;sub&gt;3&lt;/sub&gt;CN</td>
<td>no conversion</td>
</tr>
</tbody>
</table>

<sup>a</sup> Reactions carried out on 0.1 mmol scale. <sup>b</sup> Isolated yield. <sup>c</sup> Reaction carried out on 1 mmol scale, 16 hours reaction time. <sup>d</sup> Partial cleavage of TMS group. <sup>e</sup> Reaction carried out on 1 mmol scale; 24 hours reaction time.

**General procedure for the optimization:**

The solvent (0.5 mL, 0.2 M) was added to a mixture of 4a (0.1 mmol), ABZ (2, 1.2 – 2.5 equiv.) and the catalyst (0.5 – 5 mol%). The mixture was degassed (3 pump and freeze cycles) and then stirred for 16 hours at room temperature with irradiation of the indicated LED source. Thereafter the solvent was evaporated and the residue was purified by column chromatography (silica, pentane:EtOAc 30:1) affording 6a as a colorless oil.
6. Ring expansion reactions

General Procedure E:

7. Product functionalization

2-Phenyl-2-((4-phenyl-1H,1,2,3-triazol-1-yl)methyl)cyclopentanone (27).

Benzyl ((2-oxo-1-phenylcyclopentyl)methyl)carbamate (28).

2-(Isothiocyanatomethyl)-2-phenylcyclopentanone (29).

9. Established azidation reactions performed with tBuABX (1d) and ABZ (2)

9.1 Preparation of starting material for the azidation reactions

4-phenylpent-4-enoic acid (8)

N-Phenyl-N-((2-vinylphenyl)sulfonyl)methacrylamide (10)
2-Allyl-N-methoxybenzamide (16)

![Chemical structure and reaction pathway](image)

9.2 Azidation experiments

Cu(I)-Catalyzed intramolecular oxyazidation of alkenes: Synthesis of 5-(azidomethyl)-5-phenylidihydrofuran-2(3H)-one (9)

Experiment with ABX (1a)

![Reaction scheme](image)

Experiment with tBuABX (1d)

![Reaction scheme](image)

Experiment with ABZ (2)

![Reaction scheme](image)

Generation of functionalized indanes through a complex radical cascade reaction: Synthesis of 3-(azidomethyl)-1-methyl-N-phenyl-2,3-dihydro-1H-indene-1-carboxamide (11)

Experiment with tBuABX (1d)

![Reaction scheme](image)

Experiment with ABZ (2)

![Reaction scheme](image)
Metal-catalysed azidation of tertiary C-H bonds: Synthesis of (2-azidopropan-2-yl)benzene (23)

Experiment with ABX (1a)

Figure S1: GC-MS chromatogram showing the conversion of cumene (12) into (2-azidopropan-2-yl)benzene (13) after 22 hours when ABX (1a) was used.

Experiment with tBuABX (1d)

Figure S2: GC-MS chromatogram showing the conversion of cumene (12) into (2-azidopropan-2-yl)benzene (13) after 22 hours when tBuABX (1d) was used.

Experiment with ABZ (2)
Figure S3: GC-MS chromatogram showing the conversion of cumene (12) into (2-azidopropan-2-yl)benzene (13) after 22 hours when ABZ (2) was used.

Cu(II)-Catalyzed azidation of anilines: Synthesis of 2-azido-4-methylaniline (15)

Experiment with ABX (1a)

Experiment with tBuABX (1d)

Experiment with ABZ (2)

Cu(I)-Catalyzed intramolecular alkene aminoazidation: Synthesis of 3-(azidomethyl)-2-methoxy-3,4-dihydroisoquinolin-1(2H)-one (17)

Experiment with tBuABX (1d)

Experiment with ABZ (2)
10. Accident report and safety studies

Before the accident: two detonations on small scale (20-30 mg) were observed when adding the compound to a flask containing an organocatalyst and a substrate (both solids). The compound is shock sensitive as demonstrated by hammer test.

Accident report

Followed experimental protocol

Caution: reaction carried out behind a safety shield! Following a reported procedure, the starting material (1.00 g, 3.28 mmol, 1.00 equiv, synthesized in our laboratory) was stirred in dry DCM (3 mL, dried by passage over activated alumina under nitrogen atmosphere) in a thoroughly washed round-bottom glass flask, then TMSN$_3$ (0.66 mL, 4.9 mmol, 1.5 equiv, 94% from Alfa Aesar, catalogue number L00173-22) was cautiously added. A catalytic amount of TMSOTf (3 μL, 0.02 mmol, 0.005 equiv, Fluorochem, catalogue number S20400-250g) was added last to the mixture which was then stirred for 30 minutes. The solvent was then removed under reduced pressure at room temperature and the residue was dried in vacuo for one hour to give a yellow solid, which was washed with pentane (2x10 mL), cold acetone (2x5 mL) and pentane (2x 10 mL) and dried one hour in high vacuo. For each wash, the following procedure was followed: add solvent, stir 5 min, filtered on a frit, breaking larger pieces with metal spatula, and remove solvent during one minute on the frit. Usual yield around 70% (not determined on this batch due to the accident, see below).

Note: this is the reported method 2 in EROS:
http://onlinelibrary.wiley.com/doi/10.1002/047084289X.rn02053/abstract?selectedXmlId=rn02053-eo-c00022&userIsAuthenticated=false&deniedAccessCustomisedMessage= With the difference of smaller reaction scale and the solvent used for washing (hexane was used in EROS). Acetone was found to be more efficient for removing yellow impurity in the compound.

Accident:

On the day of the experiment, the researcher (experienced postdoc having done already 200 experiments with the compound without any accident) wanted to use the batch immediately after preparing it to have the best quality possible. In the previous experiments, he had just filled the flask with nitrogen and stored the compound in the fridge for several weeks. This time, after drying 1 h in vacuum, he filled the flask with air and remove it from the vacuum line to weight it on the balance. The compound was first scratched from the wall of the flask with the spatula and then he slightly shook the flask (with the spatula in) to collect the solid at the bottom. At this point, it detonated. The flask was pulverized. As it was open, most of the energy went fortunately upwards.
Consequences:
The left hand had multiple bleeding small cuts and burns (1. Degree and 2. Degree on the thumb). Minor cuts also on the face and between face and chest (areas not protected by the lab coat). The safety glasses protected the eyes. Hearing was imparted through the detonation.
Immediate treatment at the emergency room of the local hospital followed. It was decided not to remove the glass fragments, as they were very small and should be resorbed naturally. If not the case, an operation may be needed later. Hearing problems, high noise sensitivity and headaches slowly decreased over two weeks. Work incapacity for two weeks. At this point, no long-term damage expected.

Analysis:
The cause of explosion could not be identified. Ongoing hypotheses:
- Remaining impurities: HN3? (but the wash was very thorough and careful)
- Explosive impurities formed with acetone (but intensive wash afterwards and no volatile should be left).
- Initiating non-volatile impurities, such as traces of metal
- The compound was pure, but the explosion was initiated by shock (very small one!) or electrostatic charging (via friction? indeed method of work not optimal in this case)

Proposed measures:
- Whenever possible, avoid using this compound!
- Diminish batch quantities (< 500 mg starting material)
- All actions behind safety shield (including weighting) with enhanced protection (explosion resistant mask and gloves)
- Action against electrostatic and shock (in particular no metal spatula, possibly avoid glass?)
- Diminish explosion potential of reagent by structure or formulation modification.

It seems very difficult to identify surely the cause(s) of explosion, exactly the same steps having been done several times in the lab, therefore the way to go is probably to envisage chemical modifications by adding stabilizing additive or changing the structure of the reagent (diminish nitrogen to carbon ratio) to decrease its explosion potential.

Safety Studies
The stability of the compounds was determined by differential scanning calorimetry (DSC). A few mg of samples were sealed in gold plated pressure resistant crucibles. The crucibles were heated in an oven from 30°C to 400°C at a rate of 4°C/min. The Tonset (temperature at which an exothermic signal is detected), the decomposition energy and the peak temperature were recorded and compared. The provided data are the mean of two measurements.
The sensitivity to friction and impact as well as the energy of decomposition measured by DSC were determined for the Zhdankin reactive (1a) as well as for tBu-ABX (1d) and ABZ (2).

The sensitivity to impact or shock (Fallhammer test) consists of subjecting 40 g of substance to different drop-weight impact. The impact energy is varied by the selection of drop height and weight. A drop-weight of 1 kg was used for this study. The test is positive if at least one positive result (detonation, fume, fire or sparks) in a series of six measurement is obtained. Here a microphone was used for the detection. The limiting impact energy is the lowest energy at which there is still a positive result. The tests were performed with 1 J steps.

The sensitivity to friction was measured with a BAM friction apparatus. A porcelain plate with 10 ul of test substance was moved by an electric motor against a stationary porcelain peg. The load corresponded to a friction force of 360 N. The test was then repeated on Alox (aluminium oxide) plates as many false positive are measured with porcelain plates.

11 Spectra of compounds synthesized by modified methods and of new compounds
ABX (1a)

\[
\text{O} \rightarrow \text{N}_2
\]

5-(Azidomethyl)-5-phenyldihydrofuran-2(3H)-one (9)

\[
\text{N}_2 \rightarrow \text{O}
\]
3-(Azidomethyl)-1-methyl-N-phenyl-2,3-dihydro-1H-indene-1-carboxamide (11)

2-Azido-4-methylaniline (15)
3-(Azidomethyl)-2-methoxy-3,4-dihydroisoquinolin-1(2H)-one (17)
2-iodo-N-tosyl benzamide (31)
Acetato (N-tosyl)benziodazole (32).
Azido \((N\text{-tosyl})\text{benzoiodazole}\ (2)\).
4-(1-Bromovinyl)-1,2-dimethylbenzene [33I].
1-(1-Bromovinyl)-4-(trifluoromethyl)benzene (33t).
1-(1-(3,4-Dimethylphenyl)vinyl)cyclobutanol (3l)
1-(1-(3,4-dimethoxyphenyl)vinyl)cyclobutanol (3m)
1-(1-(Naphthalen-1-yl)vinyl)cyclobutanol (3p).
**tert-Butyl 3-hydroxy-3-(1-phenylvinyl)azetidine-1-carboxylate (3r)**
1-(1-(4-(Trifluoromethyl)phenylvinyl)cyclobutanol (3t).
Trimethyl(1-(1-phenylvinyl)cyclobutoxy)silane (4a)

$\text{H NMR}$
$400 \text{ MHz}$
$\text{CDCl}_3$

$\text{C NMR}$
$400 \text{ MHz}$
$\text{CDCl}_3$
Trimethyl(1-(1-(p-tolyl)vinyl)cyclobutoxy)silane (4b)
(1-{4-(tert-Butyl)phenylvinyl)cyclobutoxy}trimethylsilane (4c)
(1-1-{[1,1'-Biphenyl]-4-yl}vinyl)cyclobutoxy)trimethylsilane (4d)
(1-(1-(4-methoxyphenyl)vinyl)cyclobutoxy)trimethylsilane (4e)
(1-(1-(4-Fluorophenyl)vinyl)cyclobutoxy)trimethylsilane (4f)
(1-(1-(4-Chlorophenyl)vinyl)cyclobutoxy)trimethylsilane (4g)
Trimethyl(1-(1-(m-tolyl)vinyl)cyclobutoxy)silane (4h)
(1-(1-(3-Methoxyphenyl)vinyl)cyclobutoxy)trimethylsilane (4i)
(1-(1-(3-Fluorophenyl)vinyl)cyclobutoxy)trimethylsilane (4j)
Trimethyl(1-(1-(o-tolyl)vinyl)cyclobutoxy)silane (4k).
(1-(1-(3,4-Dimethylphenyl)vinyl)cyclobutoxy)trimethylsilane (4l)
(1-(1-(3,4-Dimethoxyphenyl)vinyl)cyclobutoxy)trimethylsilane (4m)

$^{1}H$ NMR
400 MHz
CDCl$_3$

$^{13}$C NMR
125 MHz
CDCl$_3$
(1-1-\{Benzo[d][1,3]dioxol-5-yl\}vinyl)cyclobutoxy)trimethylsilane (4n)
Trimethyl(1-(1-(naphthalen-2-yl)vinyl)cyclobutoxy)silane (4o)
Trimethyl(1-(1-(naphthalen-1-yl)vinyl)cyclobutoxy)silane (4p).
Trimethyl(3-(1-phenylvinyl)oxetan-3-yl)oxy)silane (4q)
*tert*-Butyl 3-(1-phenylvinyl)-3-((trimethylsilyl)oxy)azetidine-1-carboxylate (4r)
(1-(3,4-Dihyronaphthalen-1-yl)cyclobutoxy)trimethylsilane (4s)
Trimethyl(1-(4-(trifluoromethyl)phenyl)vinyl)cyclobutoxy)silane (4t).
\[ ^{19}F \text{ NMR} \]
\[ 376 \text{ MHz} \]
\[ CDCl_3 \]
2-(Azidomethyl)-2-phenylcyclopentanone (6a)

$^1$H NMR
400 MHz
CDCl$_3$

$^{13}$C NMR
101 MHz
CDCl$_3$
2-(Azidomethyl)-2-(4-(tert-butyl)phenyl)cyclopentanone (6c).
2-[(1,1'-Biphenyl)-4-yl]-2-(azidomethyl)cyclopentanone (6d).
2-(Azidomethyl)-2-(4-methoxyphenyl)cyclopentanone (6e).
2-(Azidomethyl)-2-(4-fluorophenyl)cyclopentanone (6f)

\[ \text{NMR Data:} \]
- **\(^1H\)-NMR**: 400 MHz
- \( \text{CDCl}_3 \)

\[ \text{\( ^1H \)-NMR Data:} \]
- Chemical Shifts: [Insert specific chemical shifts]

\[ \text{\( ^1H \)-NMR Data:} \]
- [Insert specific chemical shifts]

\[ \text{\( ^13C \)-NMR**: 101 MHz}
- \( \text{CDCl}_3 \)

\[ \text{\( ^13C \)-NMR Data:} \]
- Chemical Shifts: [Insert specific chemical shifts]
$^{19}$F-NMR
376 MHz
CDCl$_3$
2-(Azidomethyl)-2-(4-chlorophenyl)cyclopentanone (6g).
2-(Azidomethyl)-2-(m-tolyl)cyclopentanone (6h).
2-(Azidomethyl)-2-(3-methoxyphenyl)cyclopentanone (6i).
2-(Azidomethyl)-2-(3-fluorophenyl)cyclopentanone (6).
2-(Azidomethyl)-2-(o-tolyl)cyclopentanone (6k).
2-(Azidomethyl)-2-(3,4-dimethylphenyl)cyclopentanone (6l).
2-(Azidomethyl)-2-(3,4-dimethoxyphenyl)cyclopentanone (6m).
2-(Azidomethyl)-2-(benzo[d][1,3]dioxol-5-yl)cyclopentanone (6n).
2-(Azidomethyl)-2-(naphthalen-2-yl)cyclopentanone (6o).
2-(Azidomethyl)-2-(naphthalen-1-yl)cyclopentanone (6p).
4-(Azidomethyl)-4-phenylidihydrofuran-3(2H)-one (6q).
2-(Azidomethyl)-2-(4-(trifluoromethyl)phenyl)-1-oxaspiro[2.3]hexane (7t).
2-Phenyl-2-((4-phenyl-1H-1,2,3-triazol-1-yl)methyl)cyclopentanone (14).
Benzyl ((2-oxo-1-phenylcyclopentyl)methyl)carbamate (15).
2-(Isothiocyanatomethyl)-2-phenylcyclopentanone (16).