Electronic Supplementary Material (ESI) for ChemComm.

Alkyne Mechanochemistry: Putative Activation by Transoidal Bending

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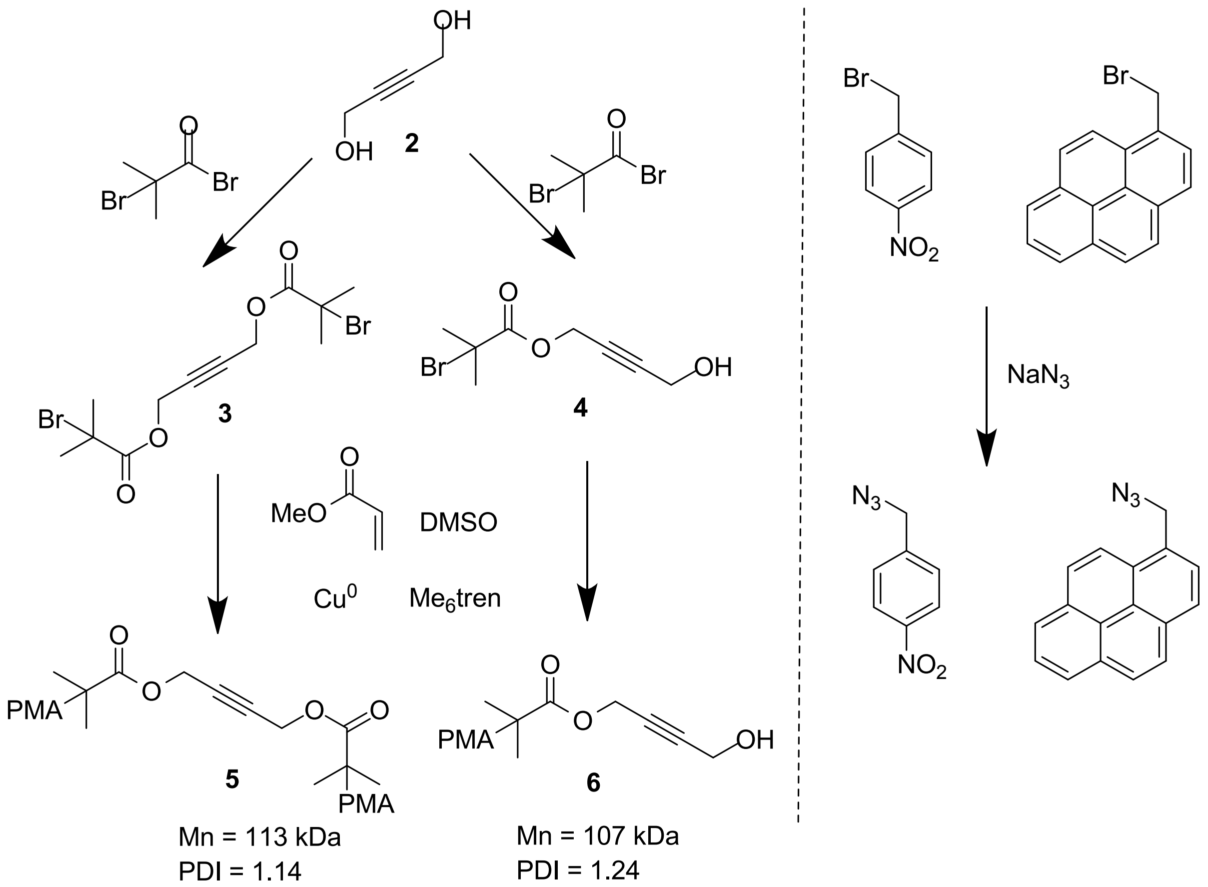
Table of Contents

I. Experimental

General. Unless otherwise stated, all chemical reagents were obtained from Sigma-Aldrich and used without purification. Column chromatography was conducted with silica gel 60 (230-400 mesh) obtained from Silicycle. ^{1}H and ^{13}C NMR spectra were collected on a Varian 500 MHz spectrometer and ^{15}N NMR were collected on a Varian 600 MHz spectrometer in the School of Chemical Sciences NMR laboratory at the University of Illinois; the residual solvent proton and carbon were used to reference the ^{1}H and ^{13}C chemical shifts,[1] and ^{15}N chemical shift was referenced to CH_3NO_2 at 0 ppm. Coupling constants (J) are reported in Hertz (Hz) and splitting patterns are designated as s (singlet) and d (doublet). High resolution EI and ESI mass spectra were obtained through the Mass Spectrometry Facility, SCS, University of Illinois. Gel permeation chromatography (GPC) analyses were carried out in Waters 1515 Isocratic HPLC pump, with a Waters (2707) 96-well autosampler and a series of 4 Waters HR Styragel columns (7.8 X 300mm, HR1, HR3, HR4, and HR5) in THF at 30 °C, coupled to a Waters (2998) Photodiode Array Detector and a Waters (2414) Refractive Index Detector. Polystyrene standard samples (Showa Denko K.K.) were used for molecular weight standard calibration. Ultrasound sonication experiments were performed on a Vibra Cell 505 liquid processor with a ½” diameter solid probe from Sonics and Materials. CoGEF calculations were conducted in Spartan’10 at the B3LYP/6-31G* level of theory.



but-2-yne-1,4-diyl-bis(2-bromo-2-methylpropanoate) (3). α-bromoisobutyryl bromide (3.5 mL, 28.3 mmol) and CH_2Cl_2 (50 mL) were added to a round bottom flask. 2-butyne-1,4-diol (recrystallized from ethyl acetate, 1.22 g, 14.2 mmol) and triethylamine (8 mL, 57.4 mmol) in CH_2Cl_2 (20 mL) were then added dropwise while cooling with an ice-water bath. After the end of addition, the mixture was stirred at room temperature overnight. The mixture was transferred to a separatory funnel, and the organic phase washed with saturated $NaHCO_3$, H_2O, 1% H_2SO_4 (twice), $NaHCO_3$ and H_2O (50 mL each). The organic phase was then dried over $MgSO_4$, filtered through a silica plug and evaporated, to provide pure **3** as a yellow solid (5.45g, yield >99%) ^1H NMR (500 MHz, $CDCl_3$): δ (ppm) 4.80 (s, 4H), 1.94 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$): δ (ppm) 171.0, 80.7, 55.1, 53.7, 30.8. HRMS (ESI) (m/z): calculated for $C_{12}H_{16}Br_2O_4$ $[M+H]^+$: 382.9494; found: 382.9502.

4-hydroxybut-2-yn-1-yl-2-bromo-2-methylpropanoate (4). 2-butyne-1,4-diol (recrystallized from ethyl acetate, 1.7023 g, 0.8 mmol) is dissolved in pyridine (50 mL). α-bromoisobutyryl bromide (0.1 mL, 0.8 mmol) was added dropwise. The pyridine was evaporated and the remainder taken in diethyl ether and ethyl acetate (10:1, 50 mL). The organic phase is washed with 0.1 M HCl (3 times), 1 M $NaHCO_3$ and water (50 mL each). The organic phase was then dried over $MgSO_4$, filtered through a silica plug and evaporated, to provide pure **4** as a yellow solid (134.7 mg, yield 70.2%) ^{1}H NMR (500 MHz, $CDCl_3$): δ (ppm) 4.79 (s, 2H), 4.30 (s, 2H), 1.93 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$): δ (ppm) 171.2, 85.7, 79.0, 55.2, 53.9, 51.0 30.7. HRMS (ESI) (m/z): calculated for $C_8H_{11}BrO_3$ $[M+Na]^+$: 256.9789; found: 256.9793.

General polymerization procedure. DMSO was degassed by freeze-pump-thaw and sparged with argon for 30 min prior to use. Methyl acrylate was filtered through basic alumina to remove inhibitor. Initiator (0.00643 mmol), Cu(0) (1.76 mg, 0.0277 mmol), and Me_6TREN (7.23 mg, 0.0319 mmol) were weighed on a microbalance and transferred to a 10 mL Schlenk flask equipped with a Teflon stir bar. Methyl acrylate (1.00 mL, 11.1 mmol) and DMSO (1 mL) were added. The flask was immediately sealed and three freeze-pump-thaw cycles were applied to remove dissolved oxygen. The flask was backfilled with argon and allowed to stir in a water bath for 2 h at room temperature. The polymerization was opened to air and 10 mL of THF was added. The mixture was filtered through a pad of silica gel. After solvent removal in vacuo, the polymer was precipitated by dropwise addition to stirring cold methanol. The resulting polymer was collected and dried under vacuum at room temperature.

General procedure for the preparation of azide traps. 4-nitrobenzyl bromide (2.1654 g, 10 mmol) and NaN_3 (2.4244 g, 37.3 mmol) are weighted in a vial. Acetone/water (3:1 10 mL) is added and the mixture stirred at room temperature for 6 h. The mixture is then transferred to a separatory funnel and water and ethyl acetate (50 mL each) are added. The aqueous phase is extracted with ethyl acetate 2 additional times (50 mL each) and the combined organic phases are washed with brine (100 mL). The organic phase is dried over $MgSO_4$ and evaporated to give the pure azide.

4-nitrobenzyl azide (yield >99%). NMR in accordance to literature.[2]

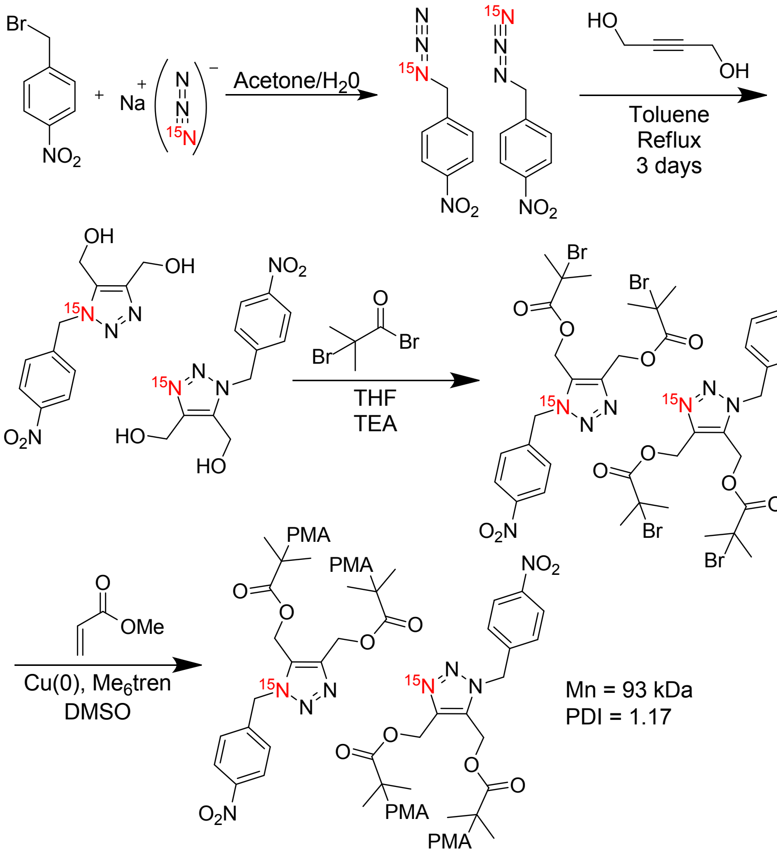
1-(azidomethyl)pyrene (yield >99%) was prepared by the same method, using THF/water as solvent (9:1). NMR in accordance to literature.[3]

General procedure for sonication experiment. Polymer (10 mg) was dissolved in acetonitrile (10 mL). Trapping agent (1200 eq. to triple bond) was added to the dissolved polymer, and the solution transferred to an oven-dried Suslick cell, which was placed into the collar and screwed onto the probe. An argon line and thermocouple were introduced into the cell and argon was sparged through the system for 30 min prior to any sonication runs, as well as during the run itself. A plastic cap was used to seal off the third arm of the Suslick cell. The Suslick cell was cooled with an ice bath throughout the entire sonication in order to maintain a constant temperature of 6-9° C. Pulsed ultrasound (0.5 s on, 1.0 s off, 8.7 W/cm^2) was then applied to the system for 3 hours. The sample was transferred to a scintillation vial and the solvent was removed via N_2 stream. The resulting solid was dissolved into 1 mL THF and filtered through a syringe filter (PTFE, 0.45 μm pore size). The resulting solution was analyzed by GPC. For ^{15}N gel-phase NMR analysis, 20 sonications were done in sequence, combined, and the polymer separated from the trapping agent by size exclusion chromatography (SX-3, THF).

Sonication experiment without bond scission. Polymer (10 mg) was dissolved in a 0.57 M solution of 4-nitrobenzyl azide in acetonitrile (11 mL). The solution transferred to an oven-dried Suslick cell, which was placed into the collar and screwed onto the probe. An argon line and thermocouple were introduced into the cell and argon was sparged through the system for 30 min prior to any sonication runs, as well as during the run itself. A plastic cap was used to seal off the third arm of the Suslick cell. The Suslick cell was cooled with a cooling probe in acetone, throughout the entire sonication in order to maintain a constant temperature of 2-6º C. Pulsed ultrasound (0.5 s on, 1.0 s off, 8.7 W/cm^2) was then applied to the system for 23 hours. The sample was transferred to a scintillation vial and the solvent was evaporated. The resulting solution was added to MeOH and filtered with a 0.45 μm Iso-Disc™ syringe tip filter. The filter was washed twice with MeOH to remove most of the excess trap, and finally the polymer was obtained by washing the filter with CH_2Cl_2. The polymer solution was evaporated, dissolved into 0.5 mL THF and filtered through a syringe filter (PTFE, 0.45 μm pore size). The resulting solution was analyzed by GPC.

Molecular weights of polymers before and after sonication calculated by standard calibration:

Polymer	Initial Mn (PDI)	Final Mn (PDI)
5 + 4-nitrobenzyl azide	113 kDa (1.14)	68 kDa (1.30)
5 + 1-(azidomethyl)pyrene	113 kDa (1.14)	70 kDa (1.25)
5 + 1-(azidomethyl)pyrene + 2	113 kDa (1.14)	75 kDa (1.25)
6 + 1-(azidomethyl)pyrene	107 kDa (1.24)	64 kDa (1.31)
Model polymer (chain-centered triazole)	93 kDa (1.17)	51 kDa (1.33)
5_{small} + 4-nitrobenzyl azide	30 kDa (1.18)	30 kDa (1.22)
6_{small} + 4-nitrobenzyl azide	14 kDa (1.21)	15 kDa (1.18)



Mixture of 4-nitrobenzyl-1'-^{15}N-azide and 4-nitrobenzyl-3'-^{15}N-azide (yield >99%). ^{1}H NMR (500 MHz, CDCl$_3$): δ (ppm) 8.23 (d, J = 8.2 Hz, 2H), 7.50 (d, J = 8.2 Hz, 2H), 4.50 (s, 2H). ^{13}C NMR (125 MHz, CDCl$_3$): δ (ppm) 147.8, 142.8, 128.6, 124.1, 53.8 (d+s). ^{15}N NMR (60 MHz, CDCl$_3$): δ (ppm) -165.3, -307.3. HRMS-EI (m/z): calculated for $C_7H_6N_3{}^{15}NO_2$ $[M]^+$: 179.0461; found: 179.0459.

Mixture of (1-(4-nitrobenzyl)-1H-1-^{15}N-1,2,3-triazole-4,5-diyl)dimethanol and (1-(4-nitrobenzyl)-1H-3-^{15}N-1,2,3-triazole-4,5-diyl)dimethanol. To a 50 mL round bottom flask, added 2-butyne-1,4-diol (85.0 mg, 0.99 mmol), labeled 4-nitrobenzyl-azide (171.6 mg, 0.96 mmol) and toluene (6 mL). The mixture was refluxed for 24 h. After solvent evaporation, the remainder was taken with ethyl acetate and washed with water (3 x 50 mL). The organic phase was dried over $MgSO_4$ and evaporated. The product was recrystallized from $CHCl_3$ to give a light yellow solid (162.9 mg, yield 62%). ^{1}H NMR (600 MHz, Acetone-d_6): δ (ppm) 8.12 (d, J = 8.1 Hz, 2H), 7.43 (d, J = 8.1 Hz, 2H), 5.77 (s, 2H), 4.85 (s, 2H), 4.69 (s, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): δ (ppm) 148.4, 146.0 (d+s), 144.2, 135.4 (d+s), 129.5, 124.4, 55.8, 52.5, 51.6 (d+s). ^{15}N NMR (60 MHz, $CDCl_3$): δ (ppm) -38.3, -135.7. HRMS-ESI (m/z): calculated for $C_{11}H_{12}N_3{}^{15}NO_4$ $[M+H]^+$: 266.0907; found: 266.09011.

Mixture of (1-(4-nitrobenzyl)-1H-1-^{15}N-1,2,3-triazole-4,5-diyl)bis(methylene)bis(2-bromo-2-methylpropanoate) and (1-(4-nitrobenzyl)-1H-3-^{15}N-1,2,3-triazole-4,5-diyl)bis(methylene)bis(2-bromo-2-methylpropanoate). Was prepared by the same method described for **3**, but purification was done by flash column chromatography (hexane/ethyl acetate 8:2) to provide a light yellow solid (184.7 mg, yield >99%). ^{1}H NMR (500 MHz, $CDCl_3$): δ (ppm) 8.23 (d, J = 8.2 Hz, 2H), 7.38 (d, J = 8.2 Hz, 2H), 5,79 (s, 2H), 5.39 (s, 2H), 5.23 (s, 2H), 1.91 (s, 3H), 1.85 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$): δ (ppm) 171.4, 171.0, 148.2, 141.3, 135.3, 130.7, 128.3, 124.5, 55.7, 55.0, 54.3, 51.8 (d+s), 30.7, 30.6. ^{15}N NMR (60 MHz, $CDCl_3$): δ (ppm) -26.5, -135.6. HRMS-ESI (m/z): calculated for $C_{19}H_{22}Br_2N_3{}^{15}NO_6$ $[M+H]^+$: 561.9955; found: 561.9963.

II. NMR Spectra

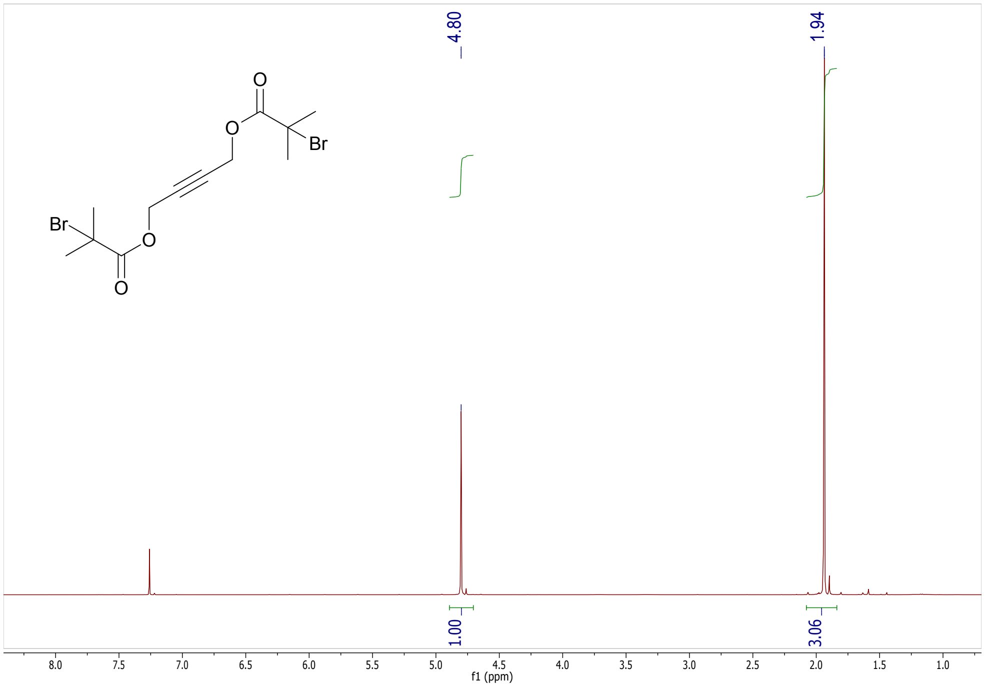


Figure S1. ^{1}H NMR spectra of **3** in $CDCl_3$.

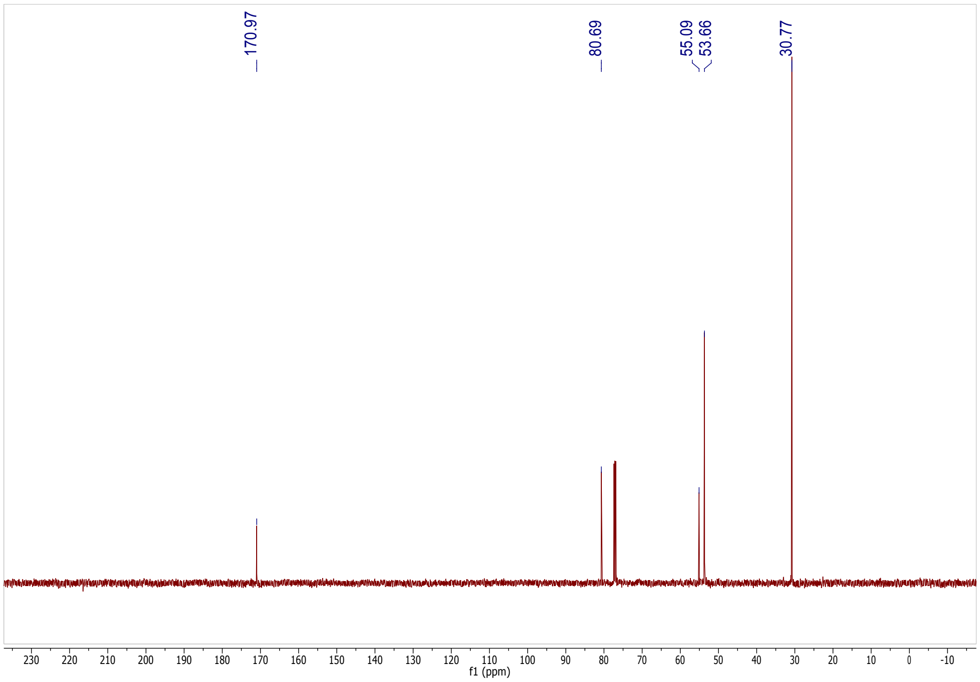


Figure S2. ^{13}C NMR spectra of **3** in $CDCl_3$.

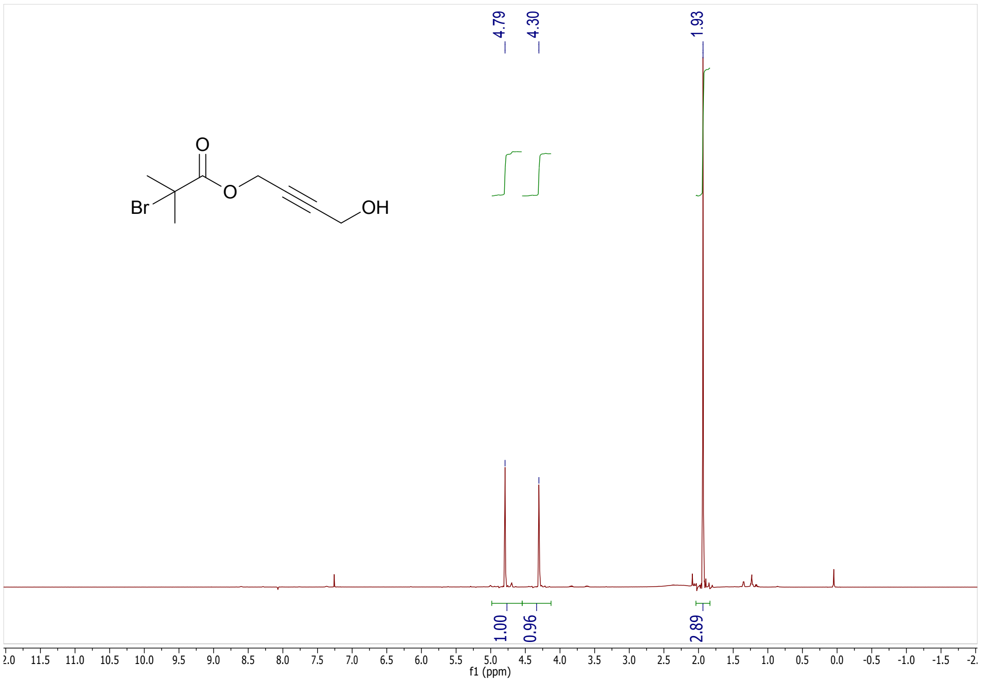


Figure S3. ^{1}H NMR spectra of **4** in $CDCl_3$.

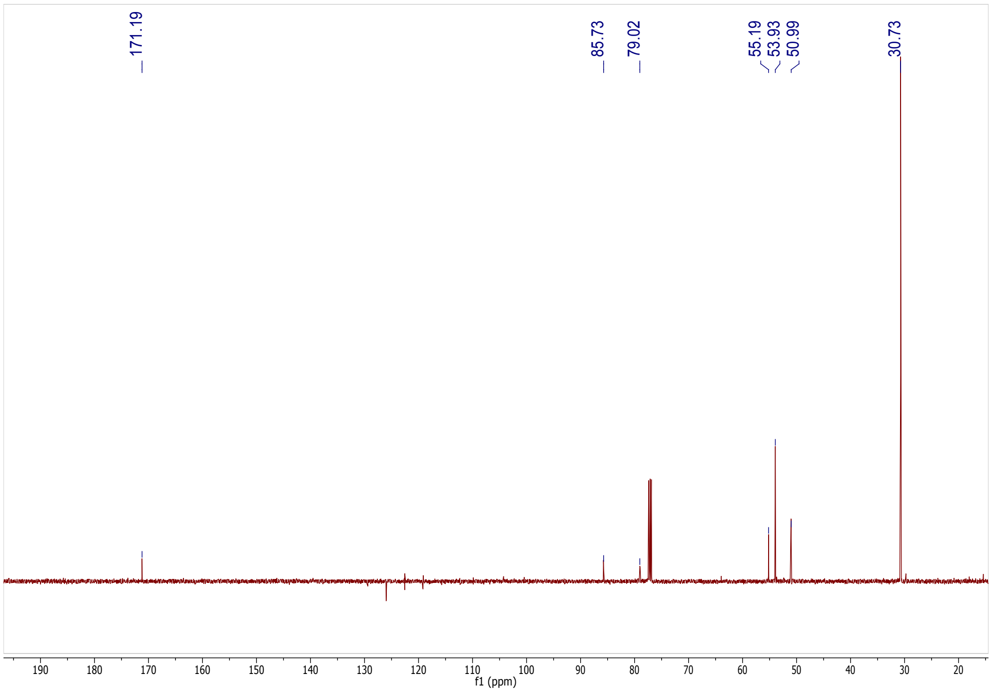


Figure S4. ^{13}C NMR spectra of **4** in $CDCl_3$.

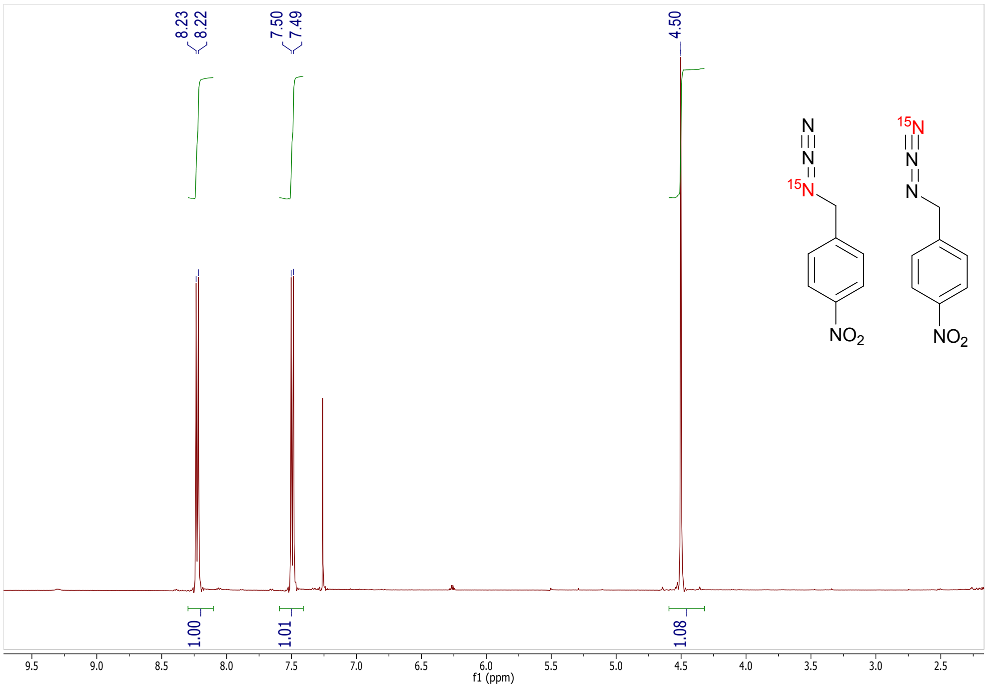


Figure S5. ^{1}H NMR spectra of ^{15}N labelled 4-nitrobenzyl azide in CDCl$_3$.

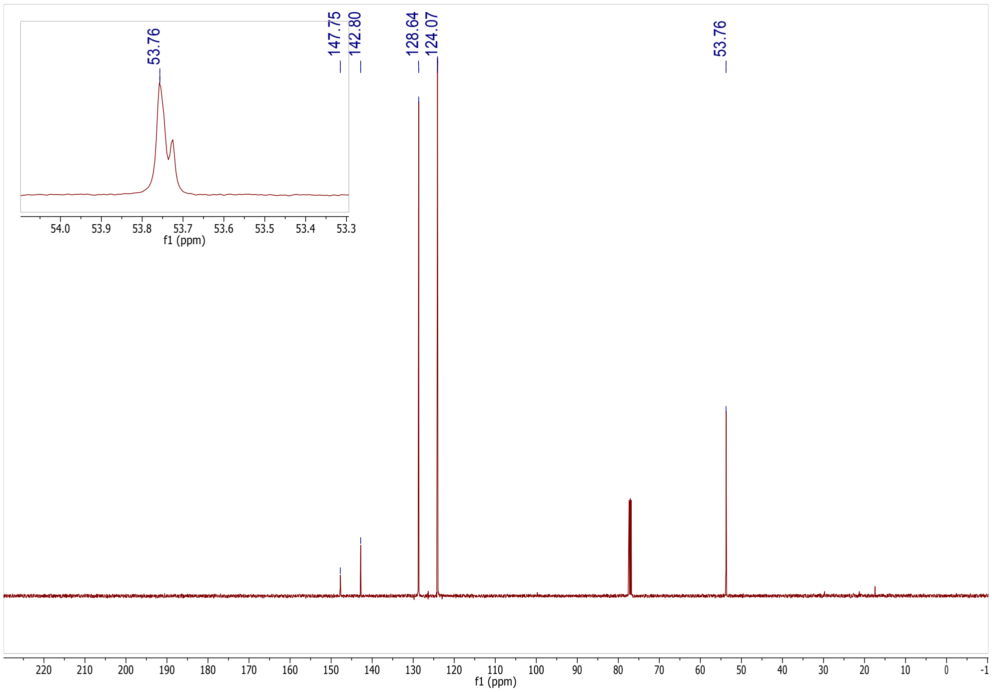


Figure S6. ^{13}C NMR spectra of ^{15}N labelled 4-nitrobenzyl azide in CDCl$_3$.

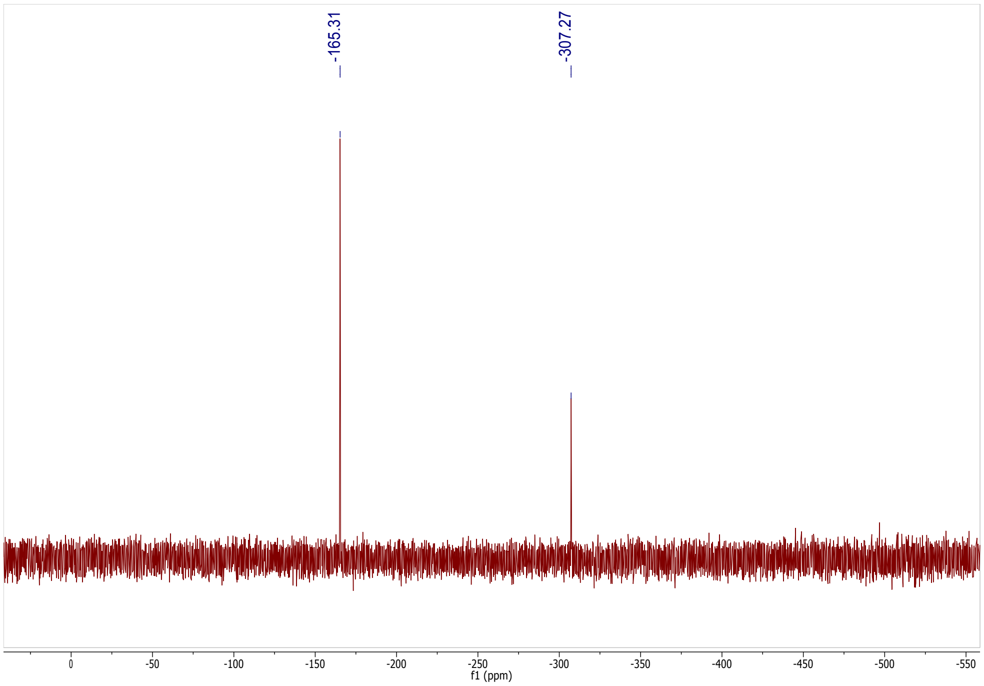


Figure S6. ^{15}N NMR spectra of ^{15}N labelled 4-nitrobenzyl azide in $CDCl_3$.

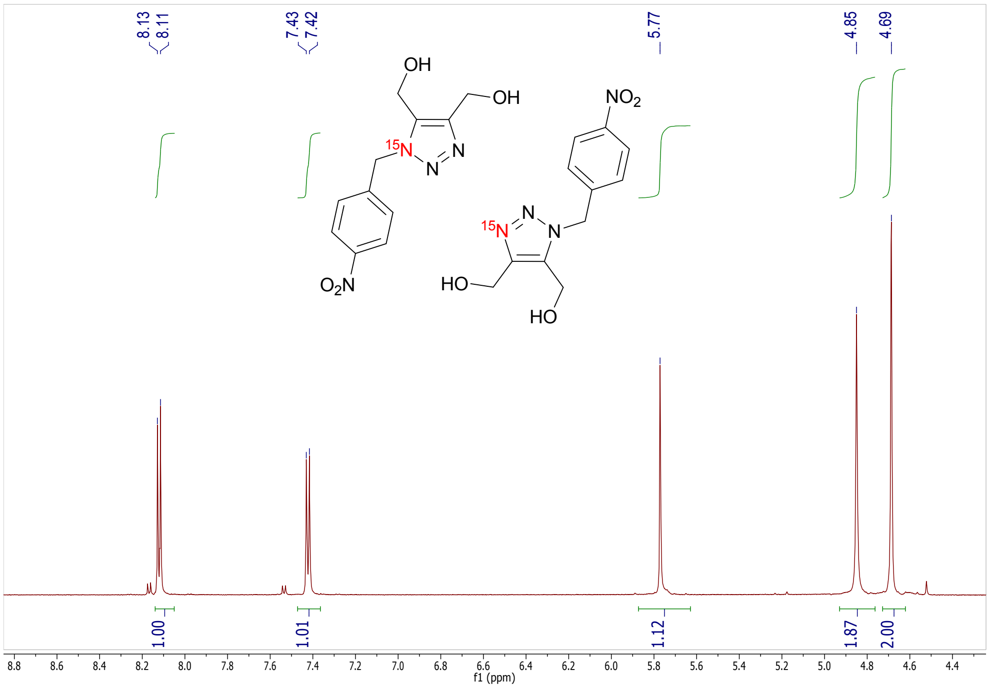


Figure S7. ^{1}H NMR spectra of ^{15}N labelled (1-(4-nitrobenzyl)-1H-1-15N-1,2,3-triazole-4,5-diyl)dimethanol in acetone-d_6.

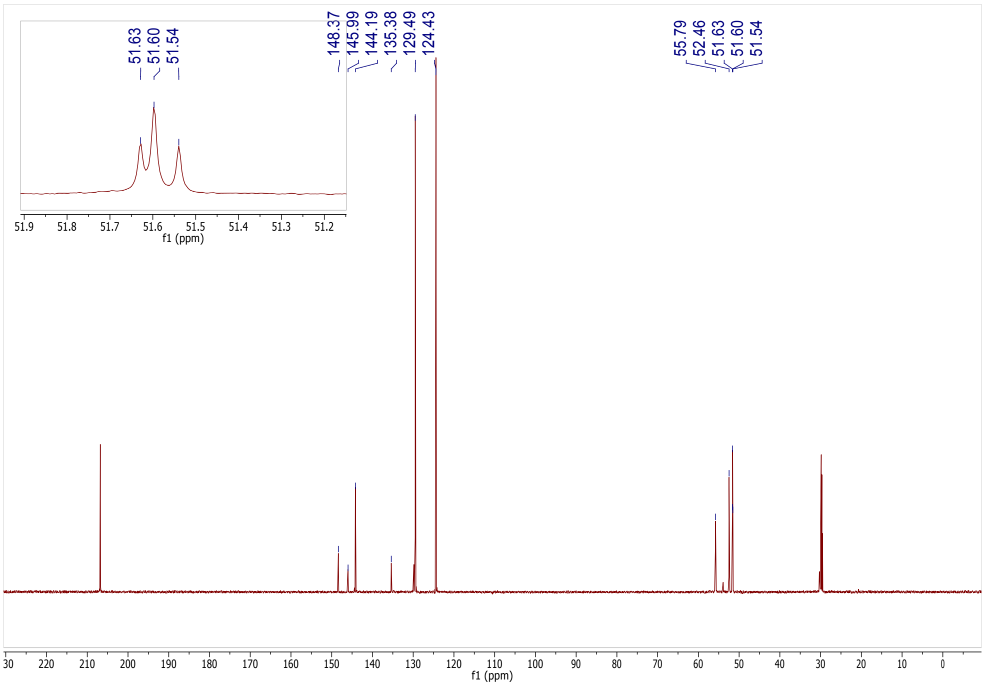


Figure S8. ^{13}C NMR spectra of ^{15}N labelled (1-(4-nitrobenzyl)-1H-1-15N-1,2,3-triazole-4,5-diyl)dimethanol in acetone-d$_6$.

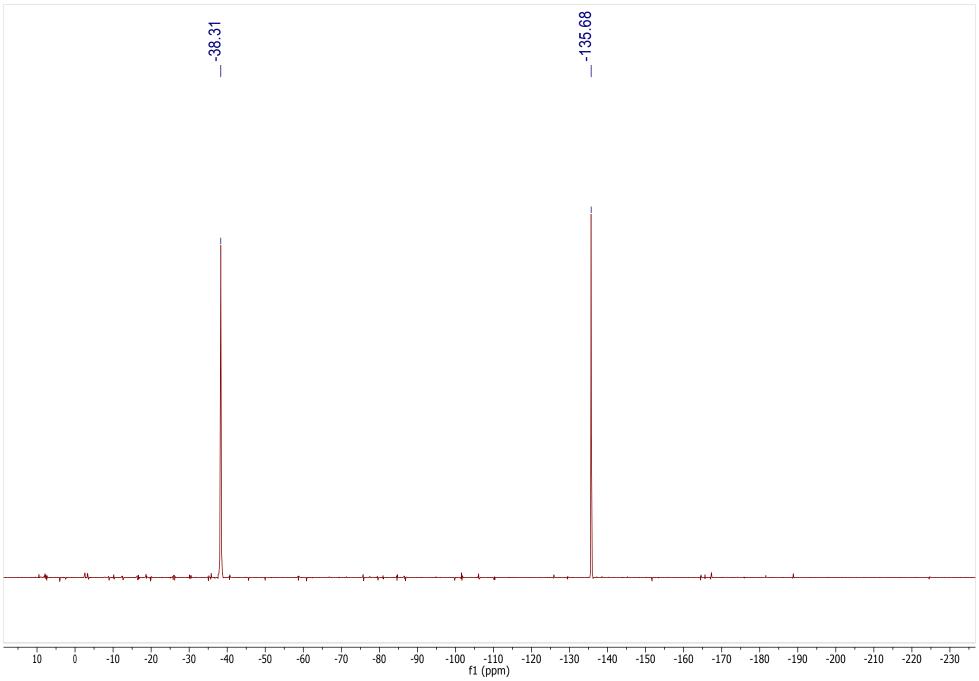


Figure S9. ^{15}N NMR spectra of ^{15}N labelled (1-(4-nitrobenzyl)-1H-1-15N-1,2,3-triazole-4,5-diyl)dimethanol in acetone-d$_6$.

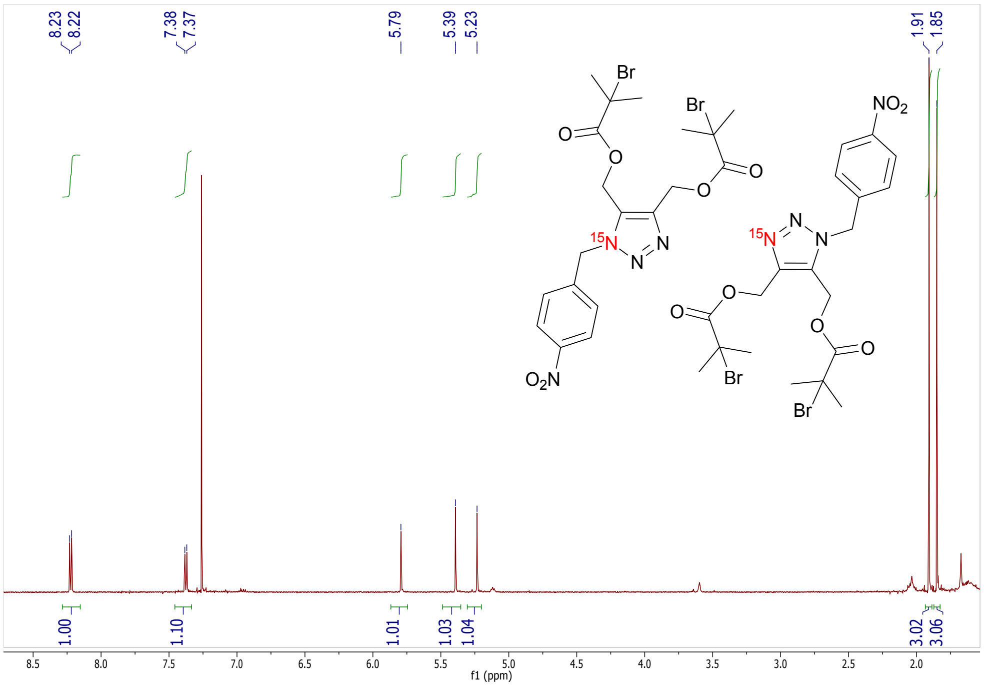


Figure S10. ^{1}H NMR spectra of ^{15}N labelled (1-(4-nitrobenzyl)-1H-1,2,3-triazole-4,5-diyl)bis(methylene)bis(2-bromo-2-methylpropanoate) in $CDCl_3$.

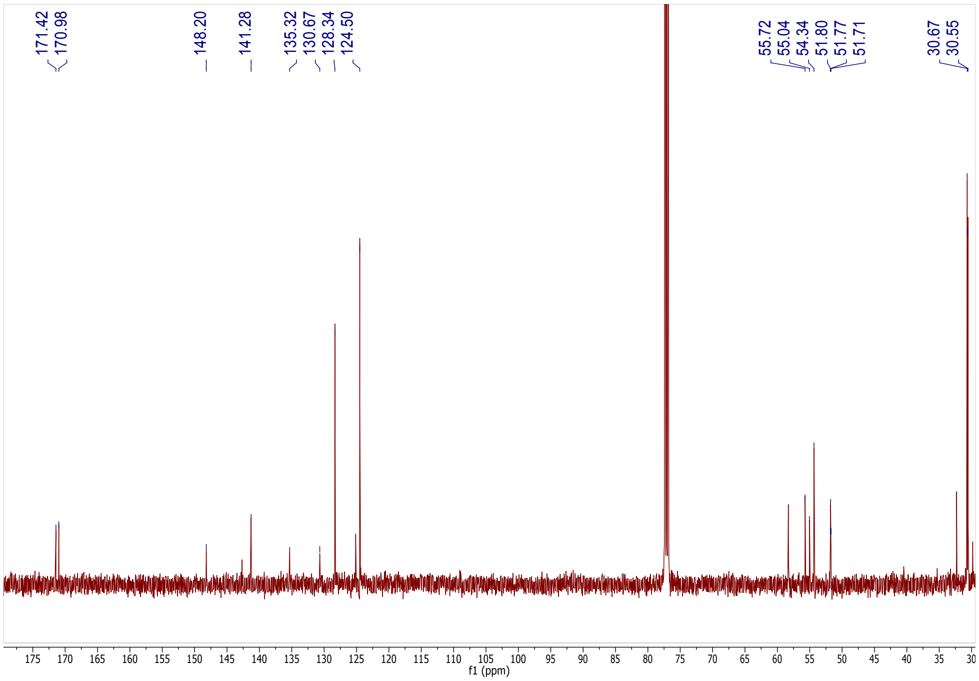


Figure S11. ^{13}C NMR spectra of ^{15}N labelled (1-(4-nitrobenzyl)-1H-1,2,3-triazole-4,5-diyl)bis(methylene)bis(2-bromo-2-methylpropanoate) in $CDCl_3$.

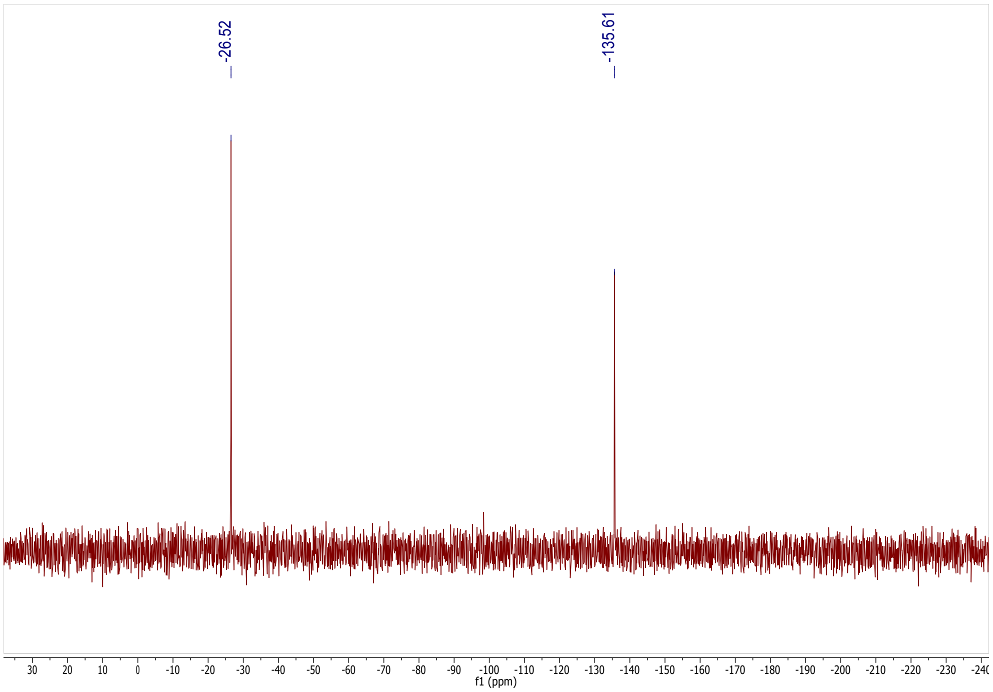


Figure S12. ^{15}N NMR spectra of ^{15}N labelled (1-(4-nitrobenzyl)-1H-1,2,3-triazole-4,5-diyl)bis(methylene)bis(2-bromo-2-methylpropanoate) in $CDCl_3$.

III. CoGEF of model triazole

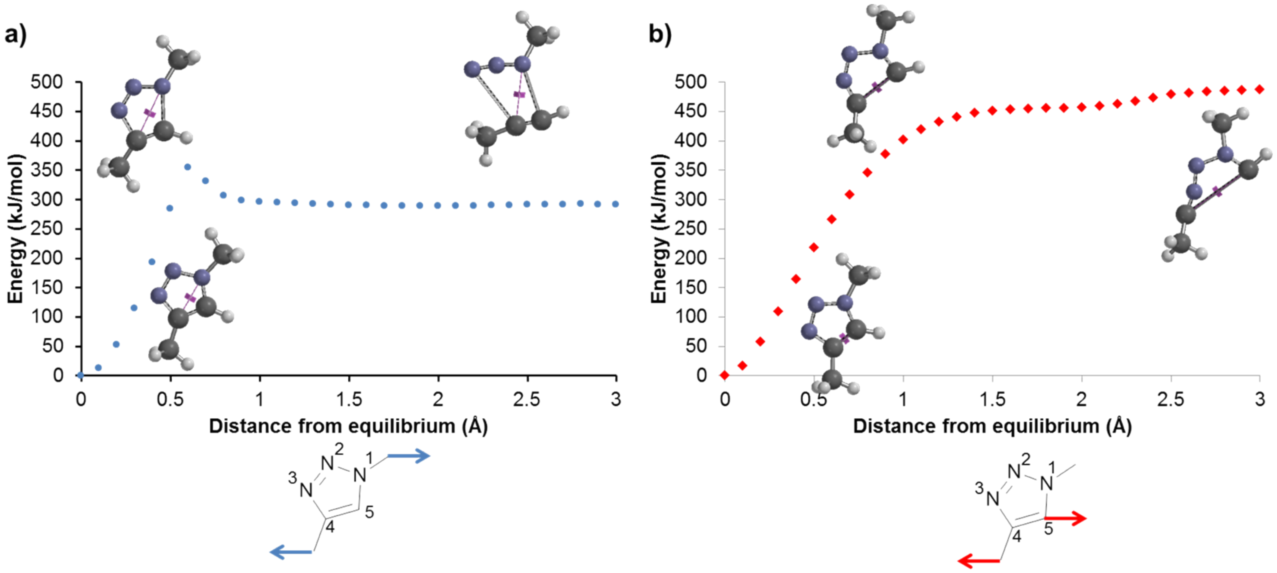


Figure S13. a) model 1,2,3-triazole elongated along the 1,4-substitution vector. b) model 1,2,3-triazole elongated along the 4,5-substitution vector.

IV. Additional GPC results

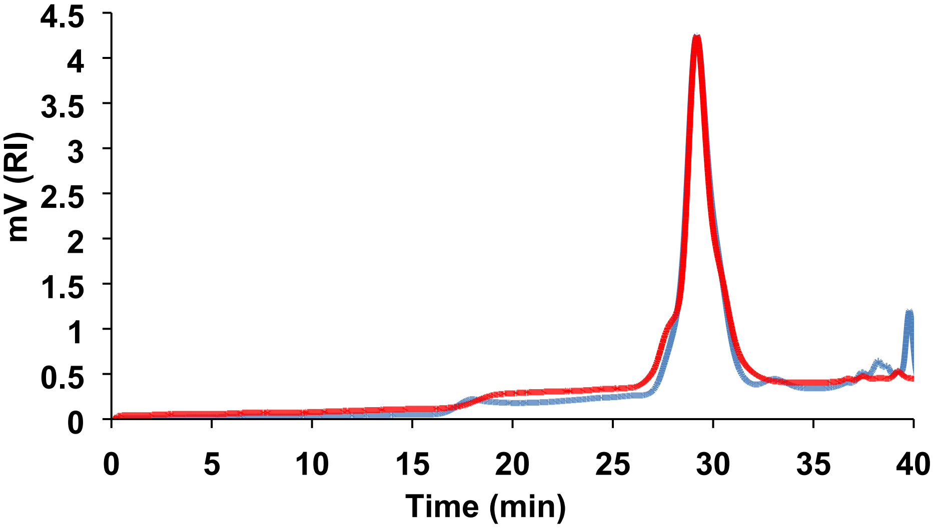


Figure S14. Normalized GPC traces of $\mathbf{5}_{\mathbf{small}}$ before (red) and after (blue) sonication with 4-nitrobenzyl azide.

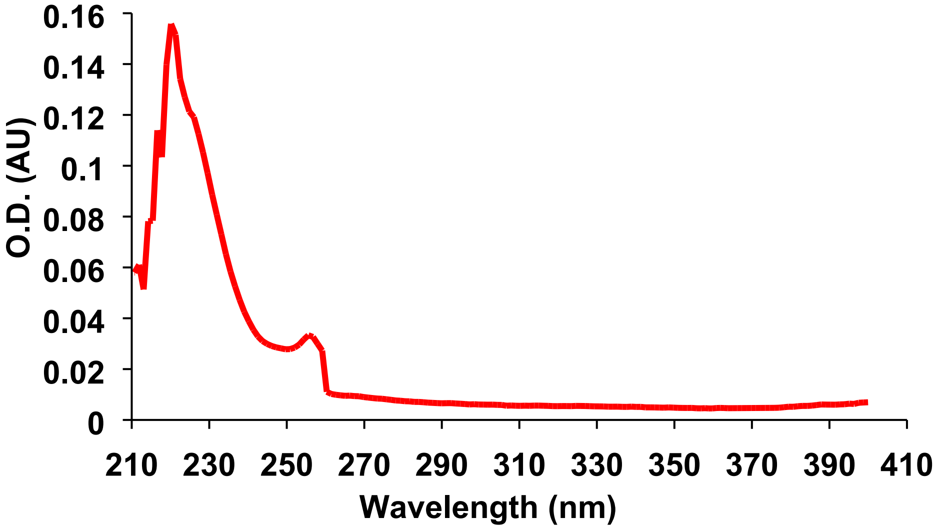


Figure S15. UV spectrum of $\mathbf{5}_{\mathbf{small}}$ after sonication with 4-nitrobenzyl azide from GPC detector (RT = 28.3 min).

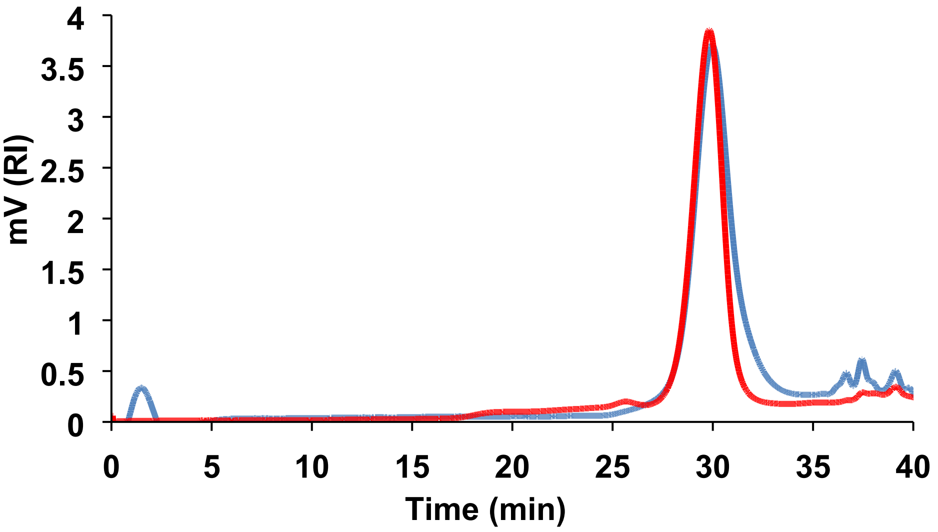


Figure S16. Normalized GPC traces of $\mathbf{6}_{\mathbf{small}}$ before (red) and after (blue) sonication with 4-nitrobenzyl azide.

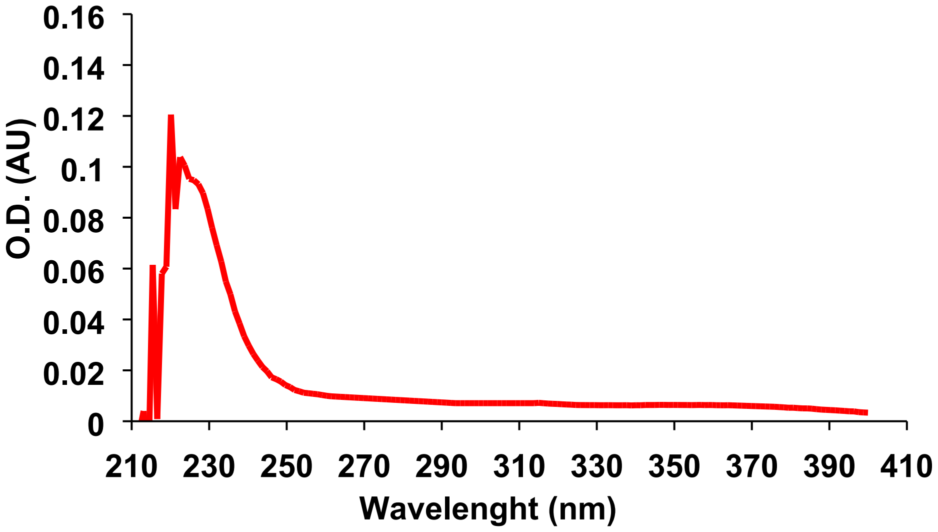


Figure S17. UV spectrum of $\mathbf{6}_{\mathbf{small}}$ after sonication with 4-nitrobenzyl azide from GPC detector (RT = 28.3 min).

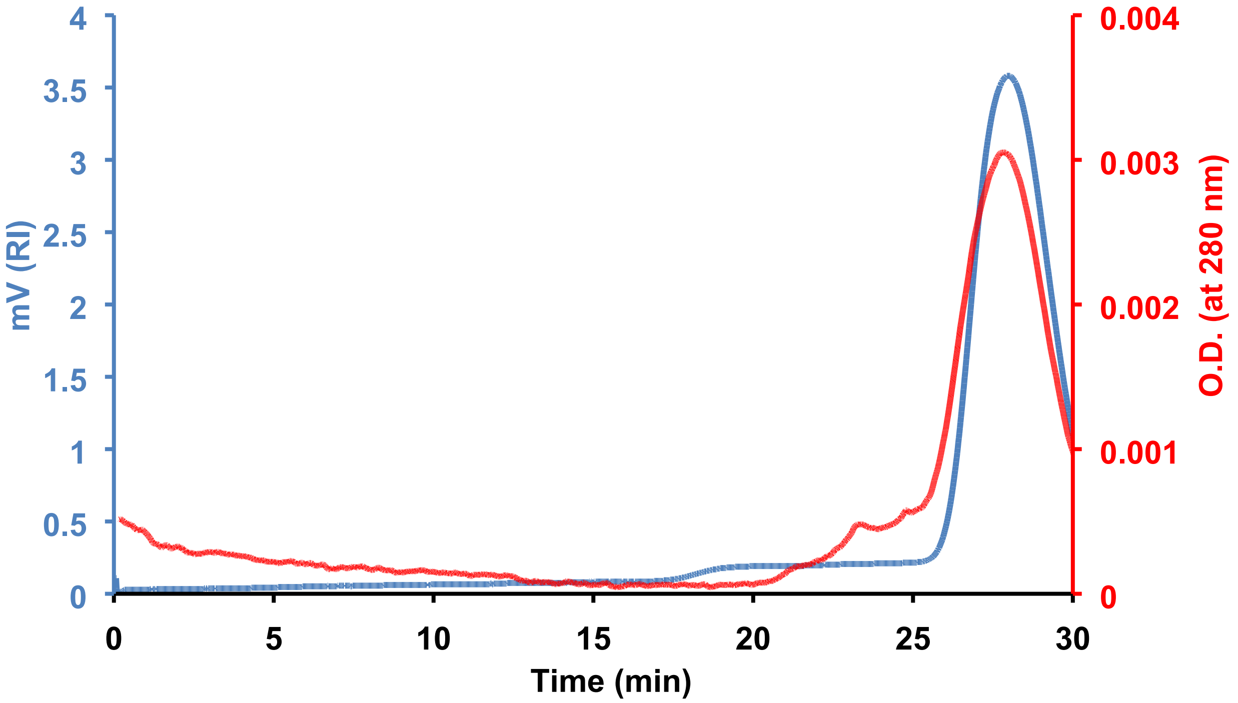


Figure S18. GPC traces of **5** after sonication with 250 mg 4-nitrobenzyl azide and 200 mg but-2-yne-1,4-diol (**2**). This experiment shows **5** still undergoes the proposed mechanochemical reaction with the azide trap, even in the presence of excess of an alkyne which cannot be bend mechanically, and alcohol groups.

V. Mechanophore incorporation

Mechanophore incorporation is calculated directly from the UV-Vis detector of the GPC. Integrating Beer-Lambert on both sides by volume, assuming extinction coefficient ε is a constant in the concentrations measured:

$$\int AdV = \varepsilon d \int CdV$$

Where A is absorption, ε extinction coefficient, d is path length, C is the concentration and V volume. Given that:

$$C = n/V$$

where n is the number of mols of molecules that absorb at 344 nm, then

$$\int CdV = n$$

We get: $\int AdV = \varepsilon dn$

$\int AdV$ is calculated from integrating the chromatogram in the specific wavelength (344 nm), using the limits of the polymer peak; ε of pyrene in THF at 344 nm is 42700 $M^{-1}cm^{-1}$;[4] d for the detector is 1 cm. By applying all values, we find n, the number of chains that are labelled with pyrene:

$$\int AdV = 0.0109\, mL$$

$$n = \frac{0.0109\, mL}{42700\, L/mol \times cm} \times 1\, cm$$

$$n = 2.55\ \times 10^{-10}\, mol$$

The total number of chains that were injected in the GPC can be calculated from the experimental values: concentration 10 mg/mL, out of which 20 μL were injected. Assuming Mw of 113 kDa (and not the final Mw, since there is only one triple bond per chain):

$$n_{total} = 10\frac{mg}{ml} \times 20\ \mu l \ \div 113\frac{kg}{mol}$$

$$n_{total} = 1.77 \ \times 10^{-9}\, mol$$

Now the yield can be calculated:

$$Yield = n/n_{total} \times 100\%$$

$$Yield = 14.4\ \%$$

VI. Reference

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