

Supplementary Material for:

Hybrid Single-Chain Nanoparticles *via* Metal Induced Crosslinking of *N*-Donor Functionalized Polymer Chains

Karen Freytag, Stefanie Säfken, Kai Wolter, Jan C. Namyslo and Eike G. Hübner*

Institute of Organic Chemistry

Clausthal University of Technology

Leibnizstr. 6, DE-38678 Clausthal-Zellerfeld, Germany

E-mail: eike.huebner@tu-clausthal.de

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1. Materials, Equipment and Methods

All air-sensitive operations were performed at a high vacuum line using *Schlenk* techniques. If not noted differently, chemicals were bought from *Sigma*. 2,2'-Azobis(2-methylpropionitrile) (AIBN) was recrystallized from dry ethanol and dried in *vacuo* before use. Toluene and THF were passed through a PS-MD-4 solvent purification system (*inert technology*) for drying (<10 ppm H₂O). 4-Vinylpyridine was degassed, dried with CaH₂ over night and freshly distilled before use. *n*-Butyl acrylate was washed with NaOH (4 wt-%) and water, dried with CaCl₂ and freshly distilled before use. 4-Methoxybenzene was distilled before use. 1,4-Dioxane (*Alfa Aesar*) was dried with sodium/benzophenone and distilled before use. Ethyl 2-bromoisobutyrate (Ebib), tris(2-pyridylmethyl)amine (TPMA), tin(II) 2-ethylhexanoate, 2,5-dibromo-3,4-dinitrothiophene (*TCI*), phenylboronic acid (*Alfa Aesar*), d₈-THF (*Deutero*), PS standard (212 400 g mol⁻¹) Pd(PPh₃)₄, Pd(OAc)₂, Zn(BF₄)₂ (*Alfa Aesar*), NiCl₂, Cu(BF₄)₂, MgCl₂, CoCl₂ and FeCl₂ have been used as received. All polymers containing 4-vinylpyridine have been stabilized with small amounts of 2,6-di-*tert*-butyl-4-methylphenol. Elemental analyses were performed with a Vario EL system (*elementar*). SEC measurements were carried out with a *Waters* 515 HPLC pump and a *Knauer* Smartline RI 2300 detector. For low molecular weight samples, 2 × 5 μm mixed-C and 1 PLgel 1000 Å column from *Polymer Laboratories* or 1 Ultrastyrigel 100 A, 2 × Ultrastyrigel 200 A from *Waters* and 1 Oligopore column from *Polymer Laboratories* were used. For high molecular weight samples, 4 × 20 μm mixed-A columns from *Polymer Laboratories* were used. THF with a flow rate of 1 mL/min at 25 °C was used as eluent. Molecular weights were obtained relative to poly(methyl metacrylate) calibration for molecular weights <12 000 g/mol and relative to polystyrene calibration for higher molecular weights. All molecular weights are referenced relative to poly(*n*-butyl acrylate) according to the universal calibration with *Mark-Houwink* coefficients given in literature ($K_{PS} = 11.4 \cdot 10^{-5} \text{ dL} \cdot \text{g}^{-1}$, $\alpha_{PS} = 0.716$, $K_{PBA} = 12.2 \cdot 10^{-5} \text{ dL} \cdot \text{g}^{-1}$ and $\alpha_{PBA} = 0.700$; $K_{PMMA} = 7.56 \cdot 10^{-5} \text{ dL} \cdot \text{g}^{-1}$, $\alpha_{PMMA} = 0.731$, $K_{PBA} = 6.47 \cdot 10^{-5} \text{ dL} \cdot \text{g}^{-1}$ and $\alpha_{PBA} = 0.765$).^{1,2} Dynamic light scattering measurements were performed with a ALV/CGS-3 (*ALV*) compact goniometer using a 22 mW HeNe Laser (1145P, *JDS Uniphase*) operating with vertically polarized light at $\lambda_0 = 632.8 \text{ nm}$. Scattered light was detected with an ALV/HIGH QE Avalanche Photodiode. Intensity autocorrelation functions were recorded with an ALV-5000/EPP digital correlator. The hydrodynamic radii presented here were obtained from an inverse *Laplace* transformation using the regularized CONTIN algorithm with 150 grid points by the ALV-5000/EPP software version 3.0.2.5 from measurements at 90° scattering angle. Diffusion coefficients have been transformed to R_h assuming a logarithmic mass-weighting in all cases. NMR spectra have been recorded on a *Bruker Avance 400* (*Bruker Corporation*) (400 MHz (¹H), 100 MHz (¹³C)) and *Avance III 600* (600 MHz (¹H), 150 MHz (¹³C)) FT-NMR spectrometer. Chemical shifts are given in ppm relative to the residual solvent signal. Diffusion ordered NMR Spectroscopy (DOSY) data was recorded on the *Bruker Avance III 600* spectrometer equipped with a broad band observed (BBO) probe with z-Gradient. The spectrometer was additionally provided with the NMR thermometer hardware (*Bruker*) that ensured highly stable temperature conditions. Initial calibration of the gradient strength G was conducted by means of a deuterium oxide sample containing H₂O-traces and was found to be 0.548 Tm⁻¹ for the BBO probe. The diffusion ordered spectra were performed in 3 mm NMR tubes (*Wilmad 335*) under calibrated (methanol thermometer) and carefully stabilized temperature conditions, i.e. $T = 298 \pm 0.1 \text{ K}$. The probe head nitrogen gas flow was adjusted to 800 L/h. Optimized pulse repetition delays ($d_1 = 10 \text{ s}$) were obtained from inversion-recovery experiments. Sample spinning was used in order to avoid convection. The applied

pulse sequence was the DOSY Oneshot experiment creating a series of 16 1-D spectra with squared increase of the gradient field strength from 10 to 80%.³ The intergradient delay (diffusion time) Δ (d20) was set to 0.2 s. The corresponding length of the gradient pulse (p30; $\delta/2$) was adjusted to 3.0 ms (2.7 ms for **P3_a-Cu**). Each single spectrum was processed with a line-broadening factor (LB) of 1.0 Hz. The DOSY data were analyzed with the DOSY Toolbox in order to calculate diffusion coefficients and generate the common DOSY plot.⁴ A viscosity of 0.501×10^{-3} Pa·s (25 °C) for d₈-THF has been used for the calculation of the hydrodynamic radii.⁵ Hydrodynamic radii were calibrated relative to a polystyrene standard ($M_n = 212\,400$ g mol⁻¹, $R_h = 14$ nm).⁶

2. Free Radical Polymerization

A 50 mL round-bottom *Schlenk* flask equipped with a magnetic stirring bar was evacuated, heated and backfilled with nitrogen several times. The flask was charged with dry and degassed THF (15.0 mL), *n*-butyl acrylate (4.00 mL, 3.60 g, 0.03 mol) and the appropriate amount of 4-vinylpyridine. The flask was heated to 60 °C and the polymerization was started by addition of AIBN (0.5 mol-% vs. sum of monomers). The mixture was stirred at 60 °C for 24 h. The reaction mixture was cooled down and poured into methanol (200 mL). After 12 h at 4 °C, the resulting two phases were separated and the polymer dissolved in THF (15 mL) and precipitated in methanol (200 mL) again. After phase separation for 12 h at 4 °C, the polymer was isolated and roughly dried in *vacuo*. The polymer was dissolved in benzene (5 wt-%) and freeze-dried until complete removal of the solvents.

3. SCNP Formation of $\mathbf{P3_a}$ + $\text{Cu}(\text{BF}_4)_2$ Monitored by DOSY NMR

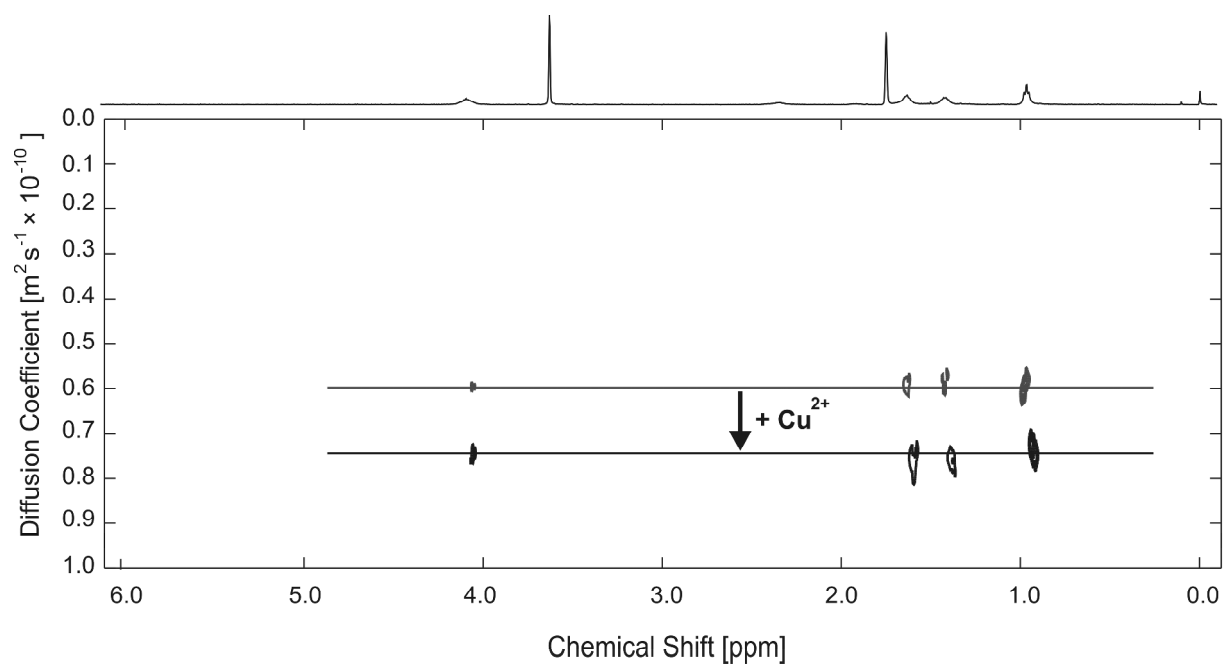


Fig. S1 SCNP formation monitored *via* DOSY NMR upon addition of 0.5 eq $\text{Cu}(\text{BF}_4)_2$ (dissolved in d_8 -THF, $c = 1 \text{ mg/mL}$) to $\mathbf{P3_a}$ (dissolved in d_8 -THF, $c = 1 \text{ mg/mL}$). Grey: pure $\mathbf{P3_a}$, black: after addition of 0.5 eq $\text{Cu}(\text{BF}_4)_2$ (lines are guide to the eye).

4. Elemental Analysis

The copolymer-composition of P(BuA-co-4-VP) has been calculated from the elemental analysis according to:

$$X_{4\text{-VP}} = \frac{w_{\text{N}} \cdot M_{\text{BuA}}}{n_{\text{N},4\text{-VP}} \cdot M_{\text{N}} - w_{\text{N}} \cdot (M_{4\text{-VP}} - M_{\text{BuA}})}$$

With $X_{4\text{-VP}}$ = mol fraction of 4-vinylpyridine, w_{N} = mass percentage of nitrogen according to the elemental analysis of P(BuA-co-4-VP), M_{BuA} = molar mass of *n*-butyl acrylate, $n_{\text{N},4\text{-VP}}$ = number of nitrogen atoms of the monomer 4-vinylpyridine, M_{N} = molar mass of nitrogen, $M_{4\text{-VP}}$ = molar mass of 4-vinylpyridine.

5. Overlap Concentration

Table ST1 Overlap concentration c^* of the precursors **P3_a** – **P8_a** (and control polymers **CP1_f**,

CP2_a) calculated according to $c^* = \frac{3M_n}{4\pi N_A R_g^3} \cdot \gamma$

No.	M_n (g/mol)	M_w/M_n	X (4-VP) (mol-%)	c^* (mg/mL)
CP1_f	82 000	3.13	-	28.9
CP2_a	12 100	1.20	-	59.5
P3_a	51 200	1.25	2.91	47.0
P4_f	69 700	4.37	9.10	27.7
P5_a	21 600	1.23	11.74	58.7
P6_a	13 300	1.50	13.75	65.4
P7_f	11 500	2.79	16.95	94.1
P8_a	5 700	2.21	21.81	-

6. Solvent Content of SCNPs

Table ST2 Solvent content^a (vol-%) of SCNPs obtained by addition of solutions of various metal salts to solutions of the polymers **P3_a** - **P7_f** and control experiments (**CP1_f**, **CP2_a**).

	CP1_f	CP2_a	P3_a	P4_f	P5_a	P6_a	P7_f
+ Cu(BF ₄) ₂	93	90	87	82	54	72	30
+ Pd(OAc) ₂	91	89	87	90	64	80	40
+ Zn(BF ₄) ₂	93	93	86	91	54	82 ^b	56
+ NiCl ₂	92	89	88	85	25	64	30
+ MgCl ₂	89	77	84	82	25	54	30
+ CoCl ₂	92	89	86	88	54	64	62
+ FeCl ₂	94	90	83	89	85 ^c	64	- ^c

^aCalcd. from R_h of SCNP and R_c of the compact globule. ^bAggregation visible in DLS.

^cOxidation occurred.

7. Calculations

Restricted and unrestricted density-functional theory (DFT)-calculations were carried out by using the Jaguar 9.1.013 software⁸ running on Linux 2.6.18-238.el5 SMP (x86_64) on five AMD Phenom II X6 1090T processor workstations (Beowulf-cluster) parallelized with OpenMPI. MM2 optimized structures were used as starting geometries. Complete geometry optimizations were carried out on the LACVP* (*Hay-Wadt* effective core potential (ECP) basis on heavy atoms, N31G6* for all other atoms) basis set and with the hybrid B3LYP density functional. All calculated structures were proven to be true minima by the absence of imaginary frequencies. Spin contamination was below 1% for all calculated copper complexes ($S(S+1) = 0.75$). Plots were obtained using Maestro 10.5.013, the graphical interface of Jaguar. Molecular Dynamics (MD) calculations have been performed with Chem3D 16.0.0.82 (*PerkinElmer Informatics*) on one AMD Phenom II X6 1090T processor workstation. The polymer structures have been preminimized to the nearest local minimum with the MM2 force field as input geometry. For the generation of the copper crosslinked input structures, the fully MD-equilibrated free polymer structure has been used. MM2-MD has been equilibrated for 2.5 ns at 300 K with a step interval of 1 fs. Heating has been performed at 1 kcal atom⁻¹ ps⁻¹. Beginning at 2.5 ns, snapshots were taken every 200 ps for a total run time of 5.3 ns. Snapshots were minimized on the MM2 force field to the nearest local minimum. Radii of gyration (R_g) and solvent accessible surface areas (A_{SA}) have been calculated on the geometry of the minimized snapshots with VMD 1.9.2.⁹ Copper atoms have been removed before calculation of R_g if appropriate. Semi-empirical single-point energy (SPE) calculations have been performed with MOPAC2016 version 17.138W.¹⁰ MM2 optimized geometries of the snapshots have been taken as input structure and copper atoms have been removed before the calculation if appropriate. The PM7 method has been applied with localized molecular orbitals (LMO).

The structures derived from the crosslinked geometry were slightly lower in energy (within the range of 1%), which obviously is physically not meaningful but can readily be explained by the MD/minimization (MM2) and single point calculation (PM7) on a different level of theory.

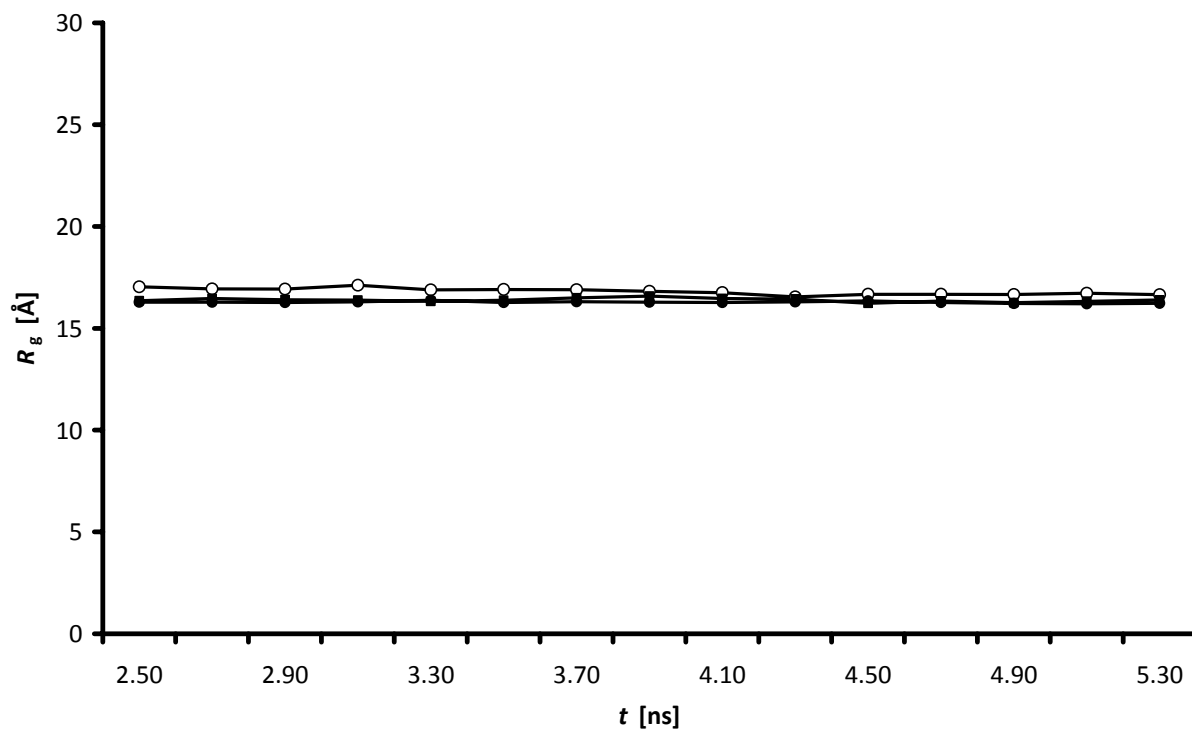


Fig. S2 Radius of gyration (R_g) of the free polymer chain (empty circles) (150 monomer units *n*-butyl acrylate and 30 monomer units 4-vinylpyridine randomly distributed), the copper cross linked chain with 5 (black circles) and 10 (black triangles) cross links. Snapshots have been taken after equilibration for 2.5 ns. R_g has been calculated on the MM2 minimized snapshots and after subsequent removal of the copper atoms if appropriate.

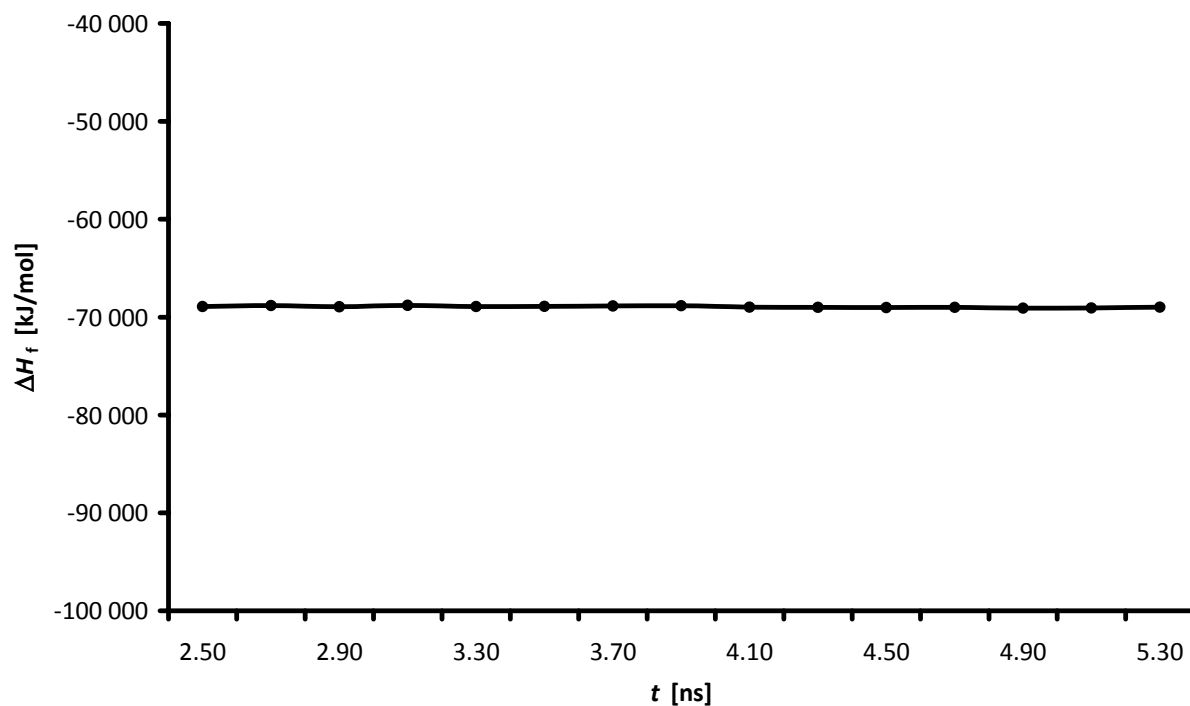


Fig. S3. Heat of Formation (ΔH_f) of the free polymer chain (150 monomer units *n*-butyl acrylate and 30 monomer units 4-vinylpyridine randomly distributed) calculated on the PM7 level of theory on the MM2 minimized snapshots of the MD simulation.

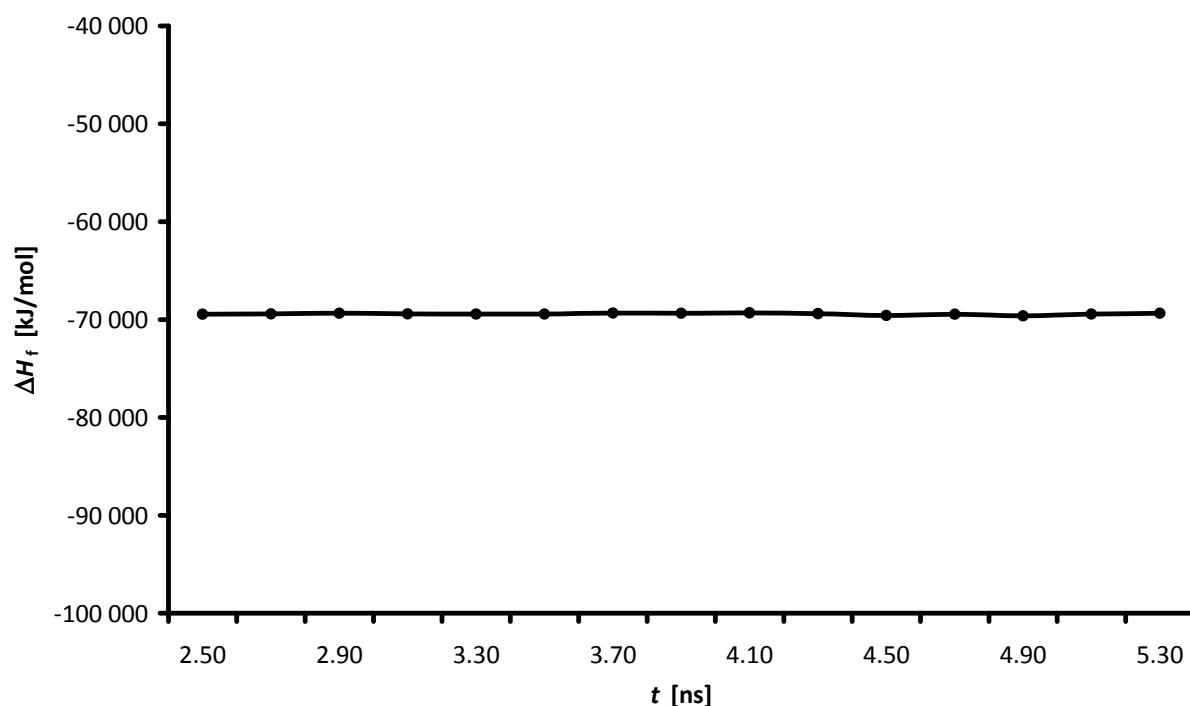


Fig. S4. Heat of Formation (ΔH_f) of the copper cross linked polymer chain (5 cross links) calculated on the PM7 level of theory on the MM2 minimized snapshots of the MD simulation after removal of the copper atoms.

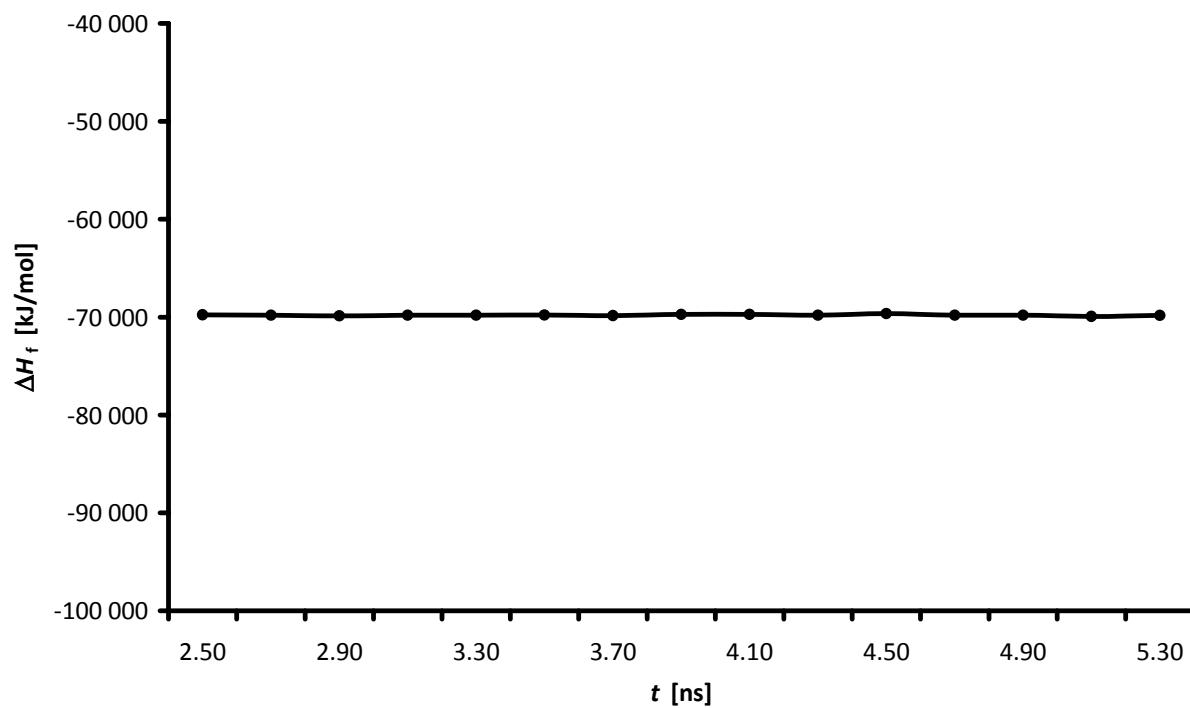
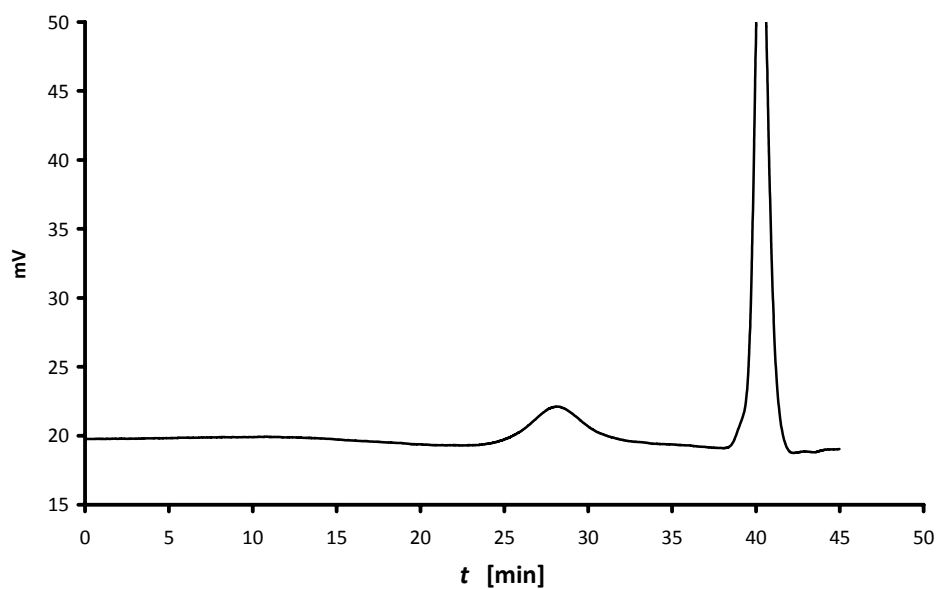


Fig. S5. Heat of Formation (ΔH_f) of the copper cross linked polymer chain (10 cross links) calculated on the PM7 level of theory on the MM2 minimized snapshots of the MD simulation after removal of the copper atoms.

8. Polymer Characterization

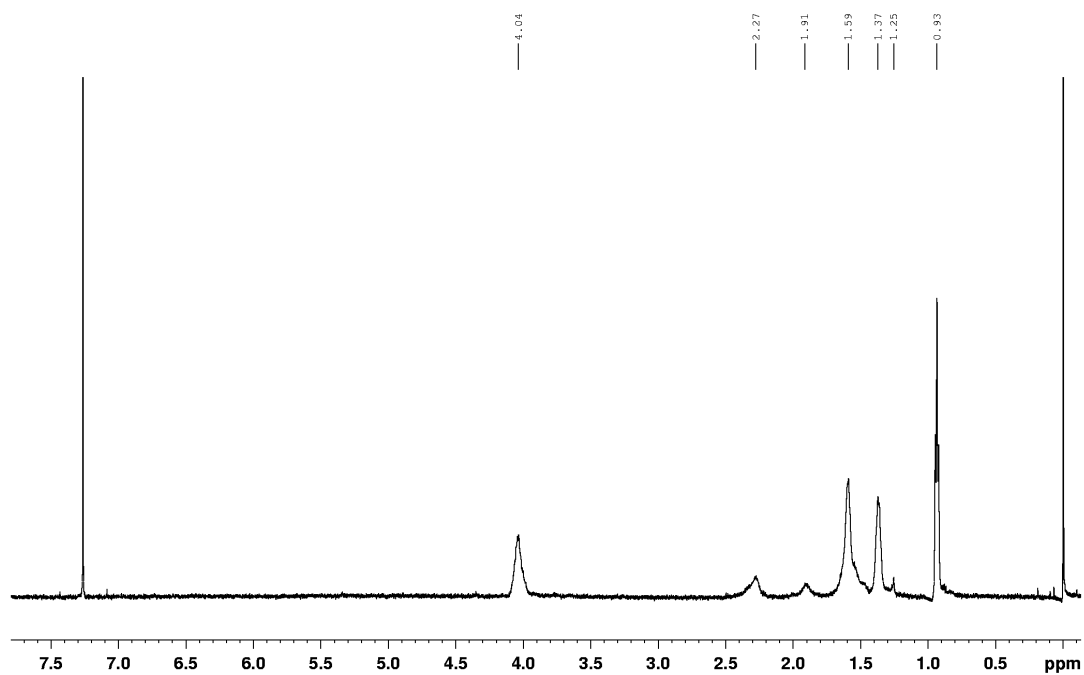
CP1_f:

N-content (%): 0.03



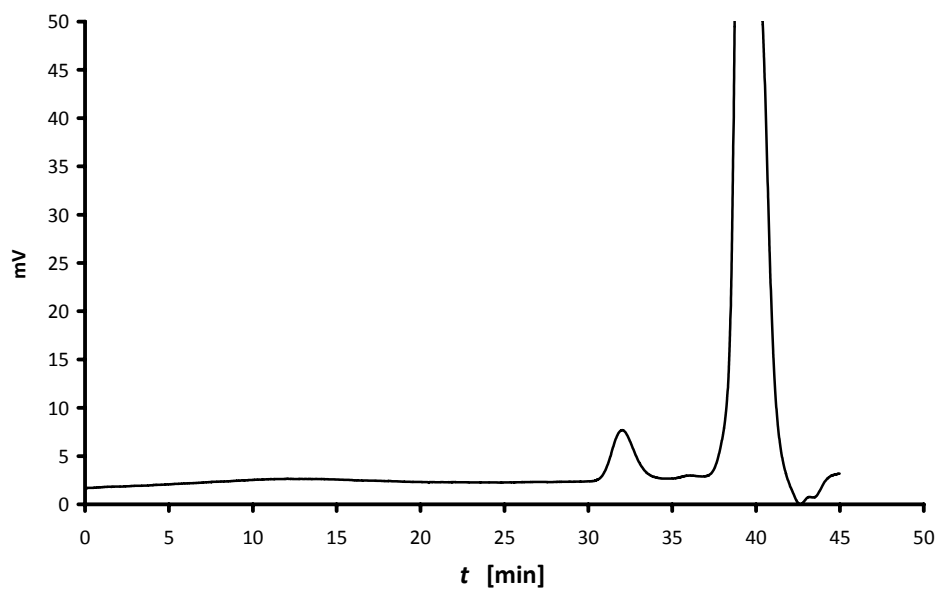
M_n (rel. PS): 76 700 g/mol; M_w : 240 400 g/mol

$^1\text{H-NMR}$ (CDCl_3):



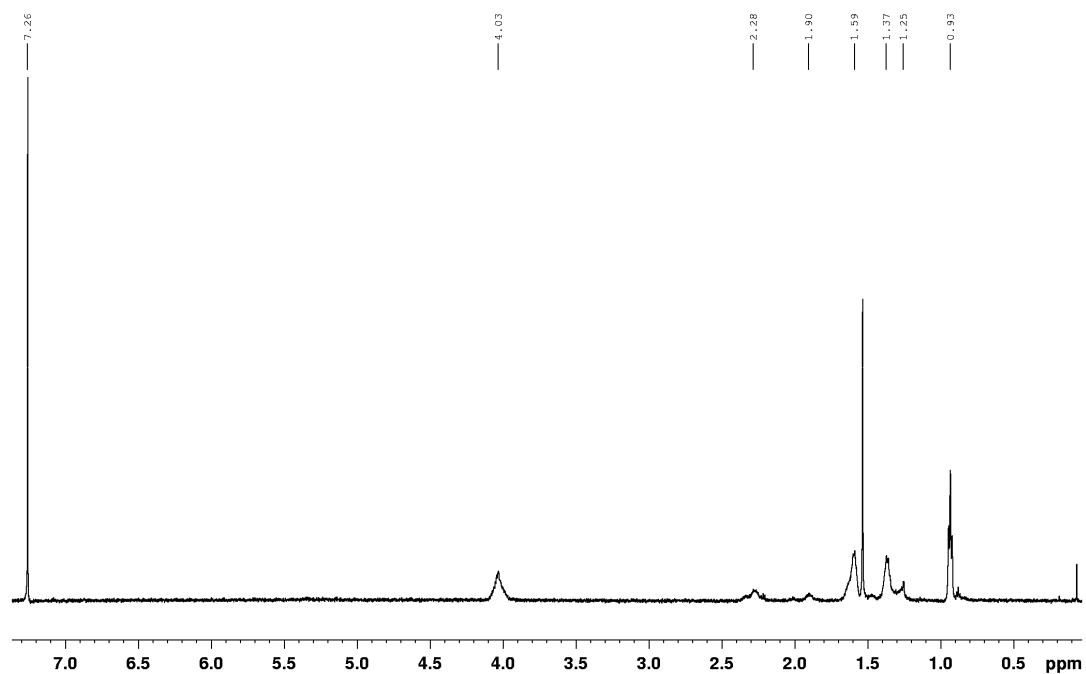
CP2_a:

N-content (%): 0.02



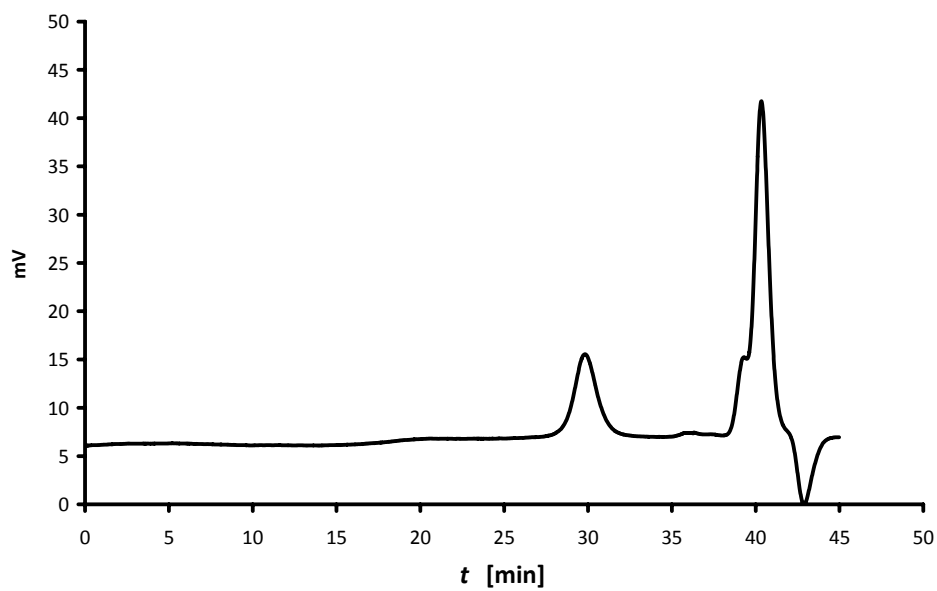
M_n (rel. PS): 11 490 g/mol; M_w : 13 740 g/mol

$^1\text{H-NMR}$ (CDCl_3):



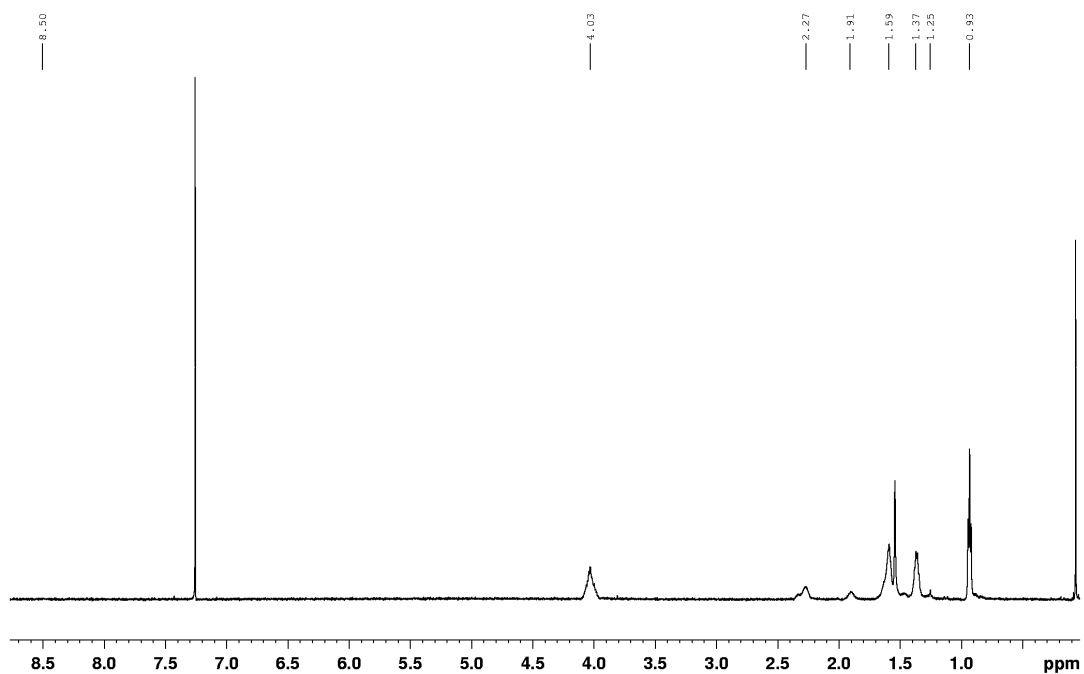
P3_a:

N-content (%): 0.32



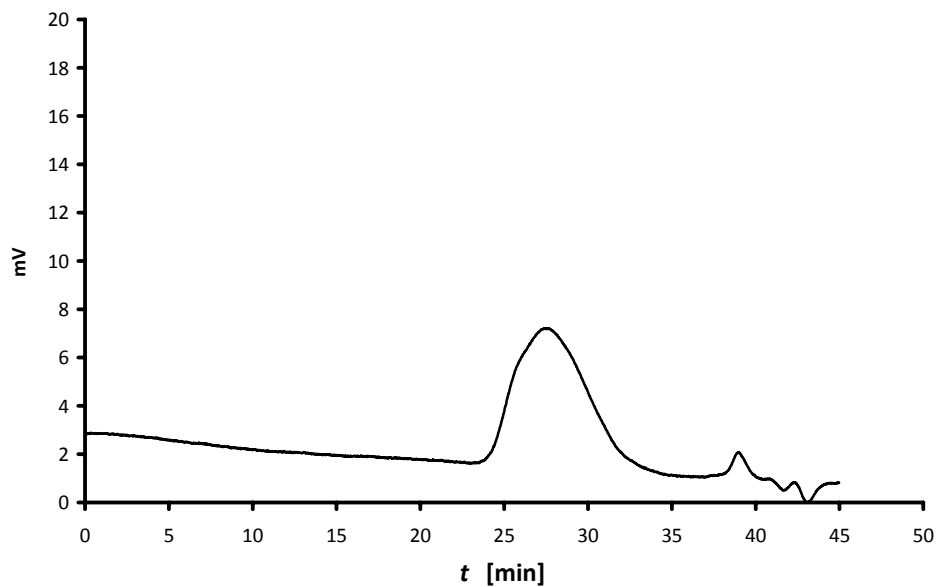
M_n (rel. PS): 48 160 g/mol; M_w : 59 970 g/mol

$^1\text{H-NMR}$ (CDCl_3):



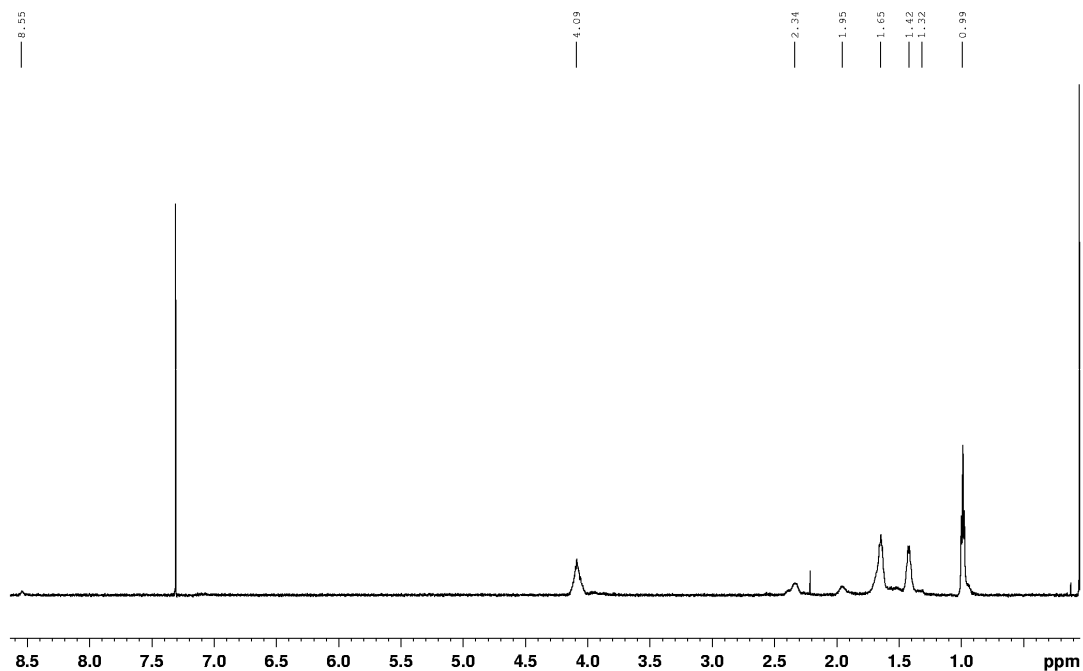
P4f:

N-content (%): 1.01



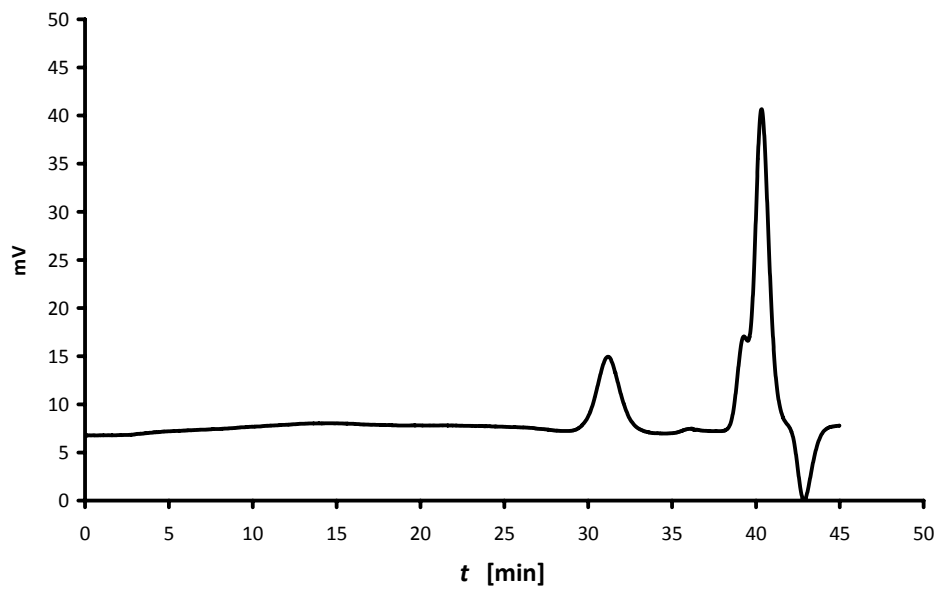
M_n (rel. PS): 56 300 g/mol; M_w : 285 314 g/mol

$^1\text{H-NMR}$ (CDCl_3):



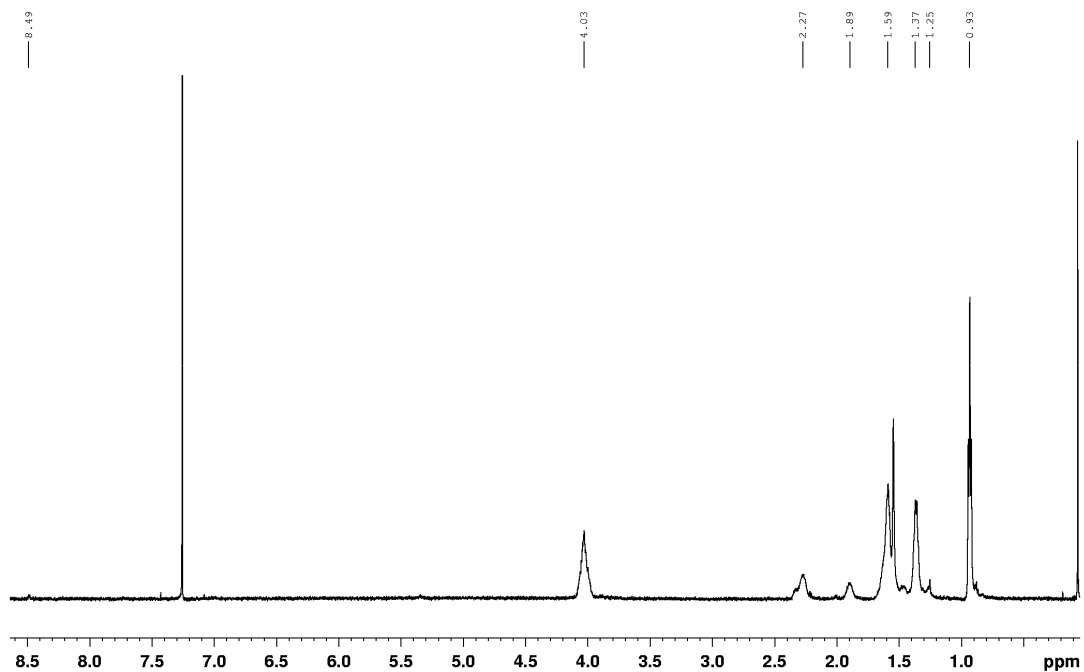
P5_a:

N-content (%): 1.31



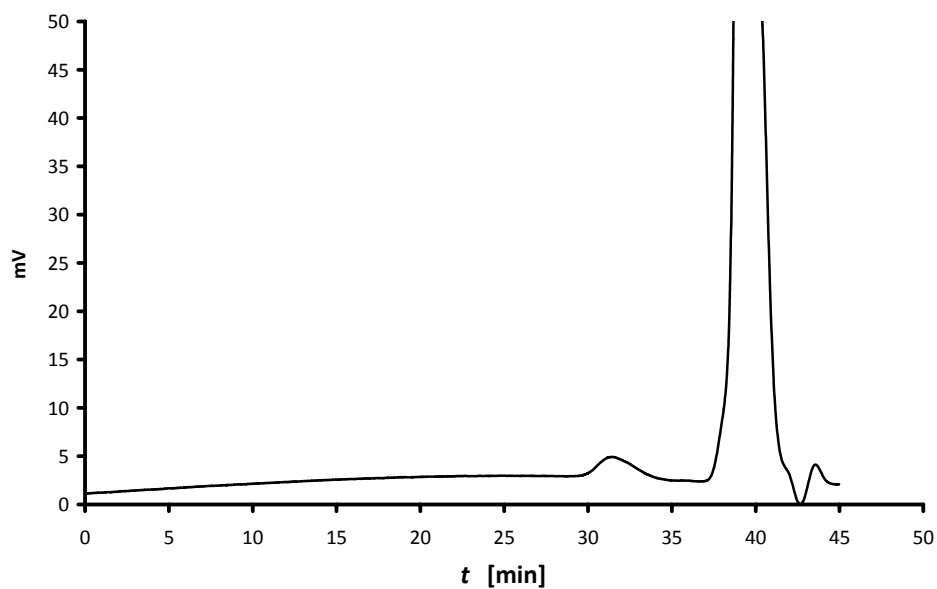
M_n (rel. PS): 20 450 g/mol; M_w : 25 249 g/mol

$^1\text{H-NMR}$ (CDCl_3):



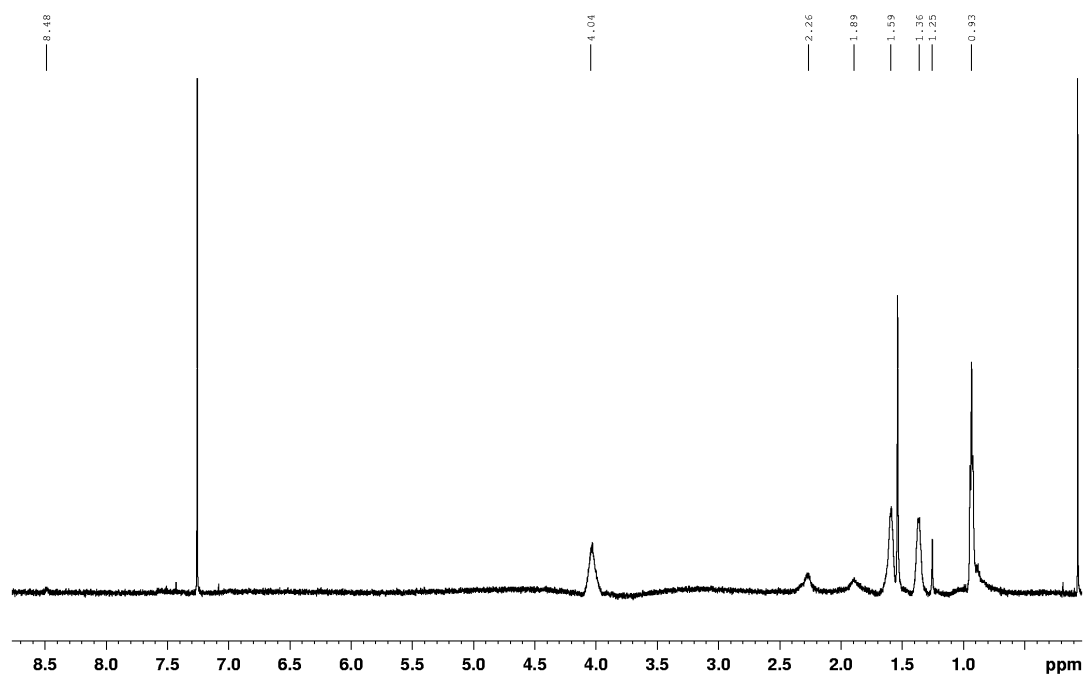
P6_a:

N-content (%): 1.54



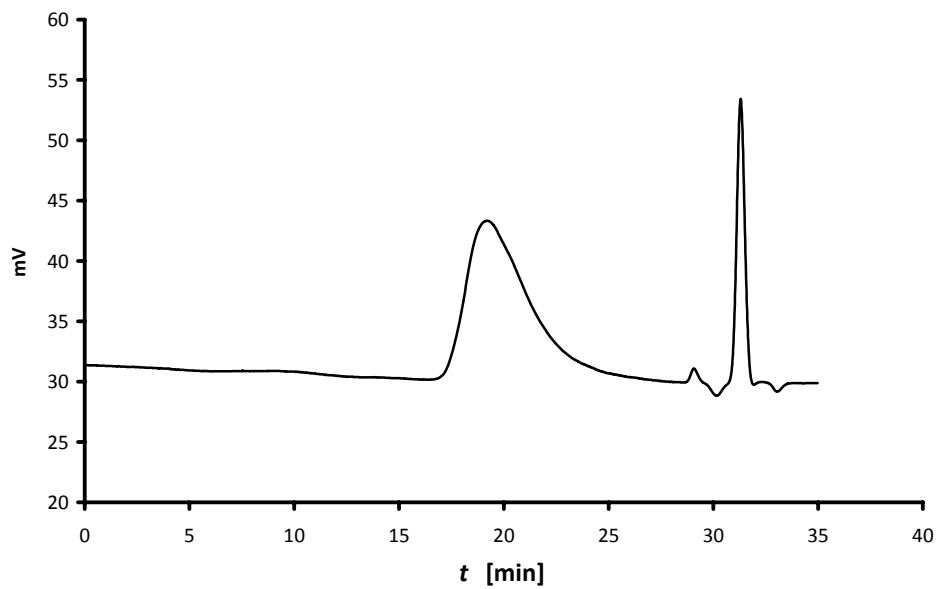
M_n (rel. PS): 12 690 g/mol; M_w : 19 080 g/mol

$^1\text{H-NMR}$ (CDCl_3):



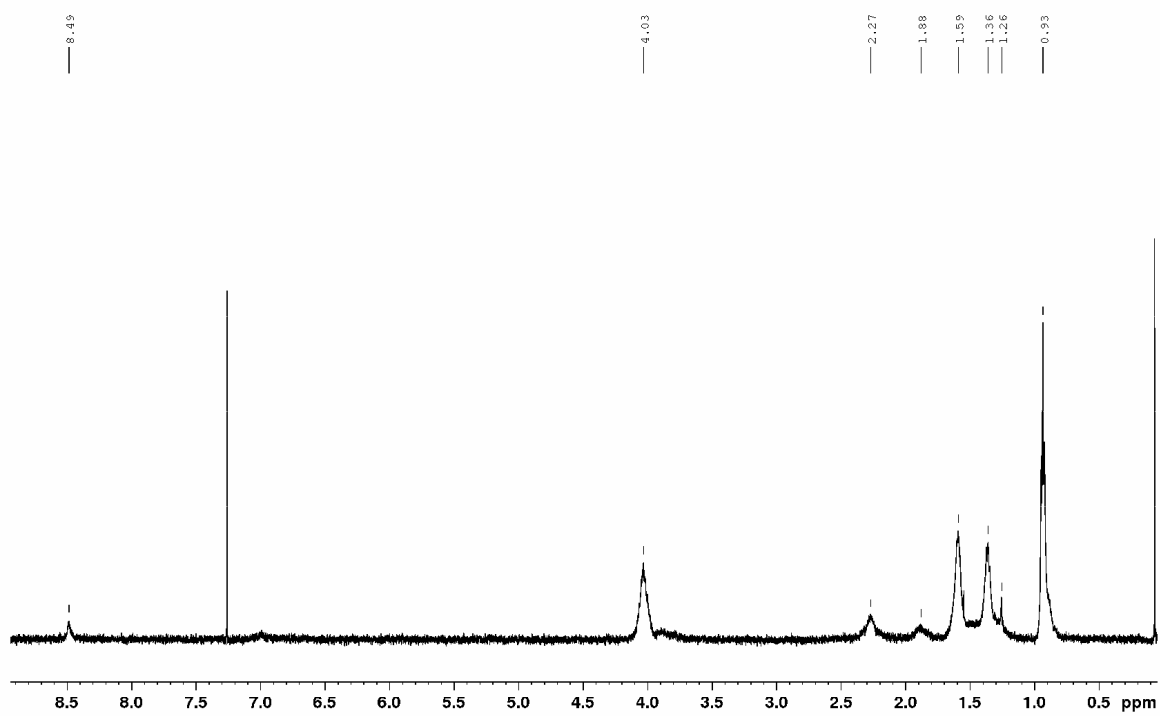
P7f:

N-content (%): 1.91



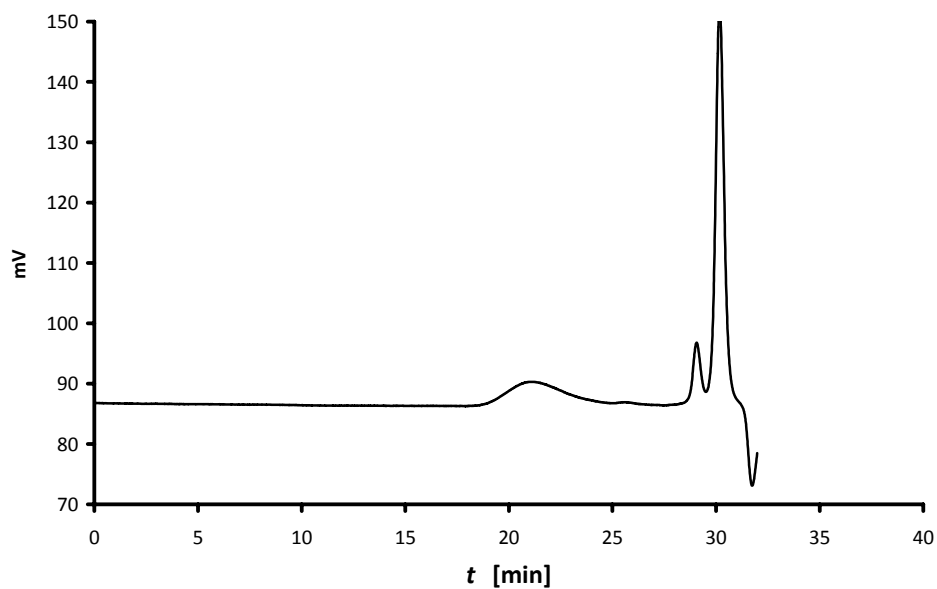
M_n (rel. PS): 12 640 g/mol; M_w : 35 220 g/mol

$^1\text{H-NMR}$ (CDCl_3):



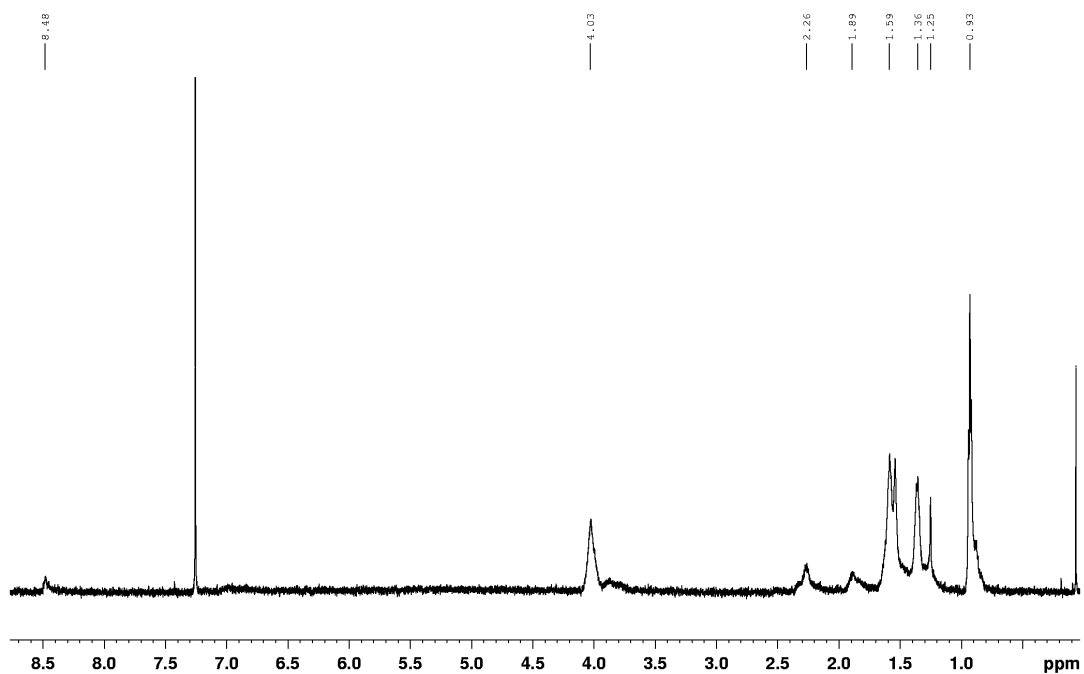
P8_a:

N-content (%): 2.48



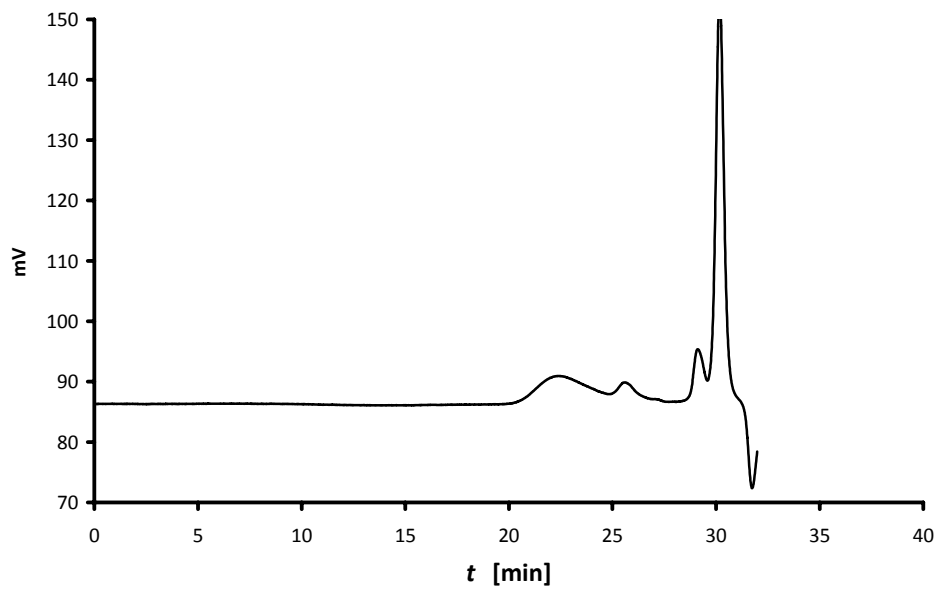
M_n (rel. PS): 5 430 g/mol; M_w : 12 000 g/mol

$^1\text{H-NMR}$ (CDCl_3):



P9_a:

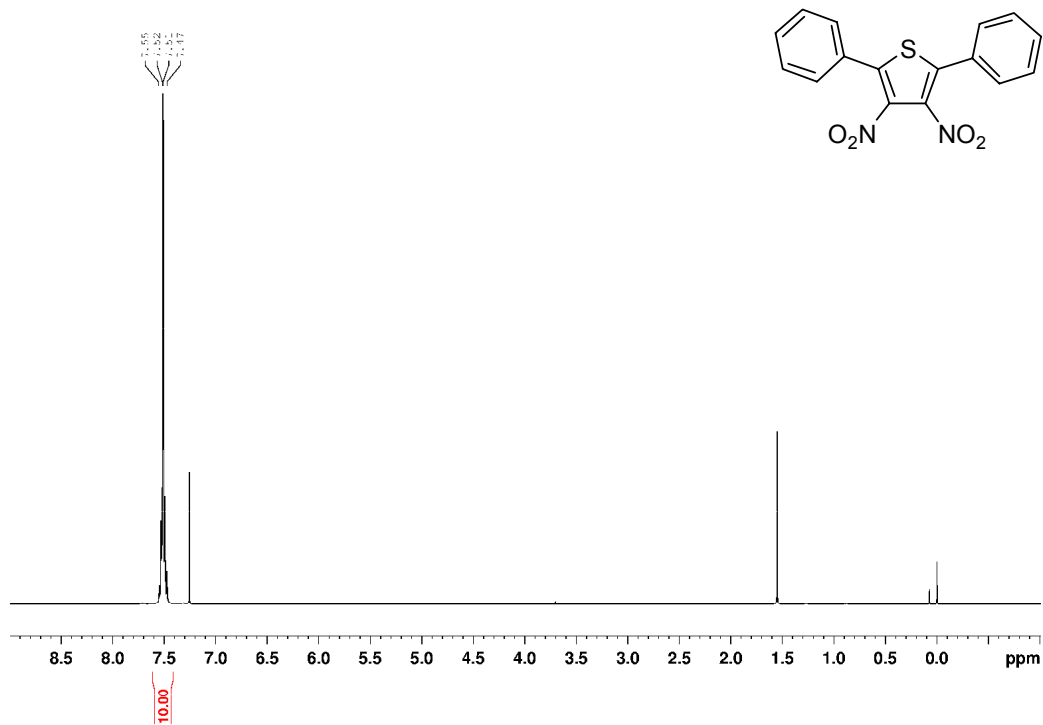
N-content (%): 2.80



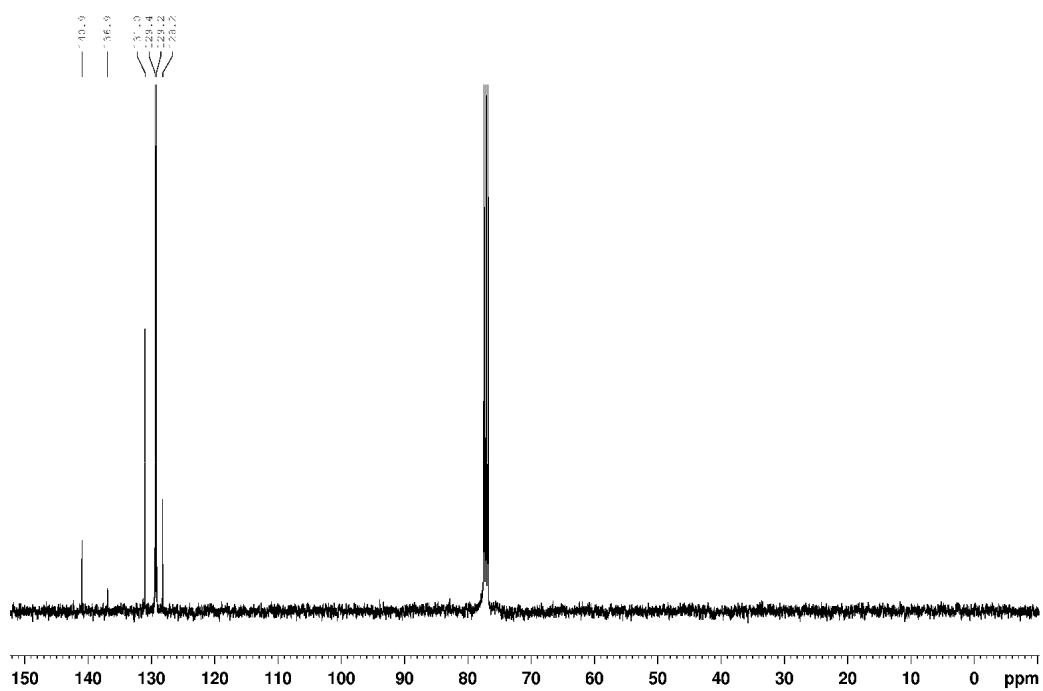
M_n (rel. PS): 1 880 g/mol; M_w : 4 550 g/mol

9. NMR Spectra of 3,4-Dinitro-2,5-diphenylthiophene (3)

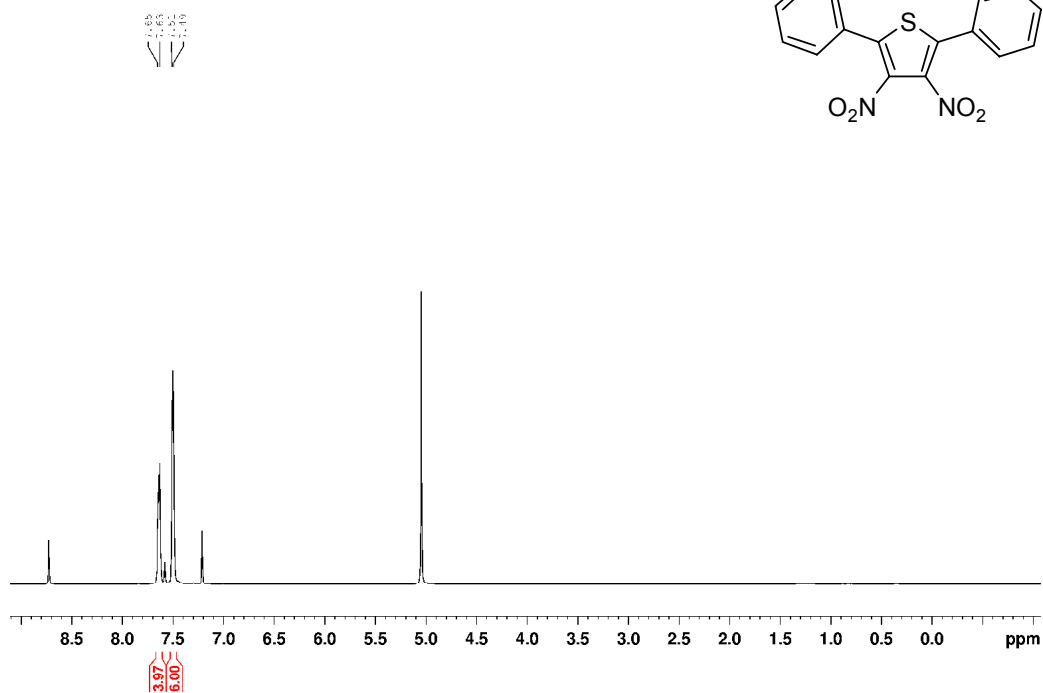
$^1\text{H-NMR}$ (CDCl_3)



$^{13}\text{C-NMR}$ (CDCl_3)

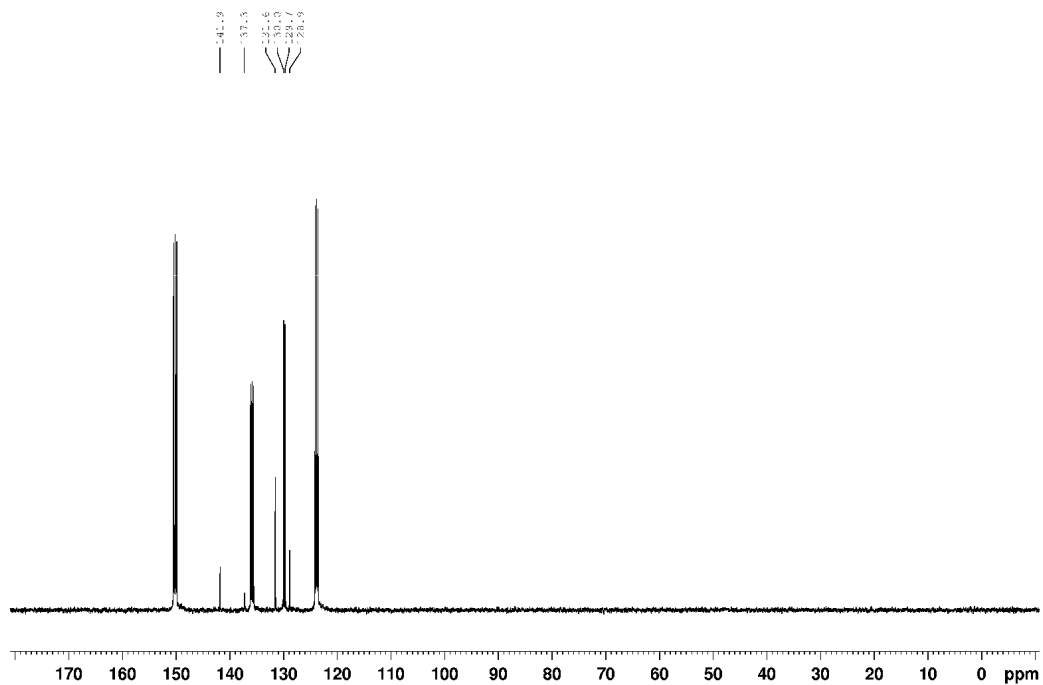


¹H-NMR (d5-pyridine)



¹³C-NMR (d5-pyridine)

¹³C{¹H} (100 MHz, ns 512)



10. References

- 1 S. Beuermann, D. A. Paquet Jr., J. H. McMinn and R. A. Hutchinson, *Macromolecules* 1996, **29**, 4206–4215.
- 2 T. Gruending, T. Junkers, M. Guilhaus and C. Barner-Kowollik, *Macromol. Chem. Phys.* 2010, **211**, 520–528.
- 3 M. D. Pelta, G. A. Morris, M. J. Stchedroff and S. J. Hammond, *Magn. Reson. Chem.* 2002, **40**, S147–S152.
- 4 M. Nilsson, *J. Magn. Reson.* 2009, **200**, 296–302.
- 5 M. Holz, X-a. Mao, D. Seiferling and A. Sacco, *J. Chem. Phys.* 1996, **104**, 669–679.
- 6 L. J. Fetters, N. Hadjichristidis, J. S. Lindner and J. W. Mays, *J. Phys. Chem. Ref. Data* 1994, **23**, 619–640.
- 7 Q. Ying and B. Chu, *Macromolecules* 1987, **20**, 362–366.
- 8 Jaguar, version 9.1, Schrodinger, Inc., New York, NY, 2016.
- 9 W. Humphrey, A. Dalke and K. Schulten, *J. Mol. Graphics* 1996, **14**, 33–38.
- 10 MOPAC2016, Version: 17.138W, James J. P. Stewart, Stewart Computational Chemistry.