Electronic supplementary materials *Mendeleev Commun.*, 2020, **30**, 703–705

Synthesis and biological evaluation of novel bispyridinium salts containing naphthalene-2,7-diylbis(oxy) spacer

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1. Biological Experiments

1.1 Sample Preparation

Samples were provided by the collaborator and stored frozen at -20 °C. Samples were prepared in DMSO and water to a final testing concentration of 32 µg ml^{-1} or 20 µM (unless otherwise indicated in the data sheet) and serially diluted 1:2 fold for 8 times. Each sample concentration was prepared in 384-well plates, non-binding surface plate (NBS; Corning 3640) for each bacterial/fungal strain, tissue-culture treated (TC-treated; Corning 3712/3764) black for mammalian cell types and polypropylene 384-well (PP; Corning 3657) for haemolysis assays, all in duplicate (n=2), and keeping the final DMSO concentration to a maximum of 0.5%. All the sample preparation was done using liquid handling robots.

Compounds that showed notable solubility issues during stock solution preparation are detailed in the Data sheet for the individual Project.

1.2 Antibacterial Assay

1.2.1 Procedure

All bacteria were cultured in Cation-adjusted Mueller Hinton broth (CAMHB) at 37 °C overnight. A sample of each culture was then diluted 40-fold in fresh broth and incubated at 37 °C for 1.5-3 h. The resultant mid-log phase cultures were diluted (CFU/mL measured by OD_{600}), then added to each well of the compound containing plates, giving a cell density of 5 x 10^5 CFU/mL and a total volume of 50 µl. All the plates were covered and incubated at 37 °C for 18 h without shaking.

1.2.2 Analysis

Inhibition of bacterial growth was determined measuring absorbance at 600 nm (OD_{600}), using a Tecan M1000 Pro monochromator plate reader. The percentage of growth inhibition was calculated for each well, using the negative control (media only) and positive control (bacteria without inhibitors) on the same plate as references.

The percentage of growth inhibition was calculated for each well, using the negative control (media only) and positive control (bacteria without inhibitors) on the same plate. The *MIC* was determined as the lowest concentration at which the growth was fully inhibited, defined by an inhibition ≥ 80%. In addition, the maximal percentage of growth inhibition is reported as DMax, indicating any compounds with partial activity.

Hits were classified by *MIC* ≤ 16 µg/mL or *MIC* ≤ 10 µM in either replicate (n=2 on different plates).

1.3 Antifungal Assay

1.3.1 Procedure

Fungi strains were cultured for 3 days on Yeast Extract-Peptone Dextrose (YPD) agar at 30 °C. A yeast suspension of 1 x 10^6 to 5 x 10^6 CFU/ml (as determined by OD_{530}) was prepared from five colonies. The suspension was subsequently diluted and added to each well of the compound-containing plates giving a final cell density of fungi suspension of 2.5 x 10^3 CFU/ml and a total volume of 50 µl. All plates were covered and incubated at 35 °C for 36 h without shaking.

1.3.2 Analysis

Growth inhibition of *C. albicans* was determined measuring absorbance at 630 nm (OD_{630}), while the growth inhibition of *C. neoformans* was determined measuring the difference in absorbance between 600 and 570 nm ($OD_{600-570}$), after the addition of resazurin (0.001% final concentration) and incubation at 35 °C for 2 h. The absorbance was measured using a Biotek Multiflo Synergy HTX plate reader.

In both cases, the percentage of growth inhibition was calculated for each well, using the negative control (media only) and positive control (fungi without inhibitors) on the same plate. The *MIC* was determined as the lowest concentration at which the growth was fully inhibited, defined by an inhibition ≥ 80% for *C. albicans* and an inhibition ≥ 70% for *C. neoformans*. Due to a higher variance in growth and inhibition, a lower threshold was applied to the data for *C. neoformans*. In addition, the maximal percentage of growth inhibition is reported as D_{Max}, indicating any compounds with marginal activity.

Hits were classified by *MIC* ≤ 16 μg/mL or *MIC* ≤ 10 μM in either replicate (n=2 on different plates).

1.4 Cytotoxicity Assay

1.4.1 Procedure

HEK293 cells were counted manually in a Neubauer haemocytometer and then plated in the 384-well plates containing the compounds to give a density of 5000 cells/well in a final volume of 50 μL. DMEM supplemented with 10% FBS was used as growth media and the cells were incubated together with the compounds for 20 h at 37 °C in 5% CO_2.

1.4.2 Analysis

Cytotoxicity (or cell viability) was measured by fluorescence, ex: 560/10 nm, em: 590/10 nm ($F_{560/590}$), after addition of 5 μl of 25 μg ml^{-1} resazurin (2.3 μg ml^{-1} final concentration) and after incubation for further 3 h at 37 °C in 5% CO_2. The fluorescence intensity was measured using a Tecan M1000 Pro monochromator plate reader, using automatic gain calculation.

CC_{50} (concentration at 50% cytotoxicity) were calculated by curve fitting the inhibition values vs. log(concentration) using a sigmoidal dose-response function, with variable fitting values for bottom, top and slope. In addition, the maximal percentage of cytotoxicity is reported as D_{Max}, indicating any compounds with partial cytotoxicity.

The curve fitting was implemented using Pipeline Pilot's dose-response component, resulting in similar values to curve fitting tools such as GraphPad's Prism and IDBS's XlFit. Any value with > indicate sample with no activity (low D_{Max} value) or samples with CC_{50} values above the maximum tested concentration (higher D_{Max} value).

Cytotoxic samples were classified by CC_{50} ≤ 32 μg ml^{-1} or CC_{50} ≤ 10 μM in either replicate (n=2 on different plates). In addition, samples were flagged as partial cytotoxic if D_{Max} ≥ 50%, even with CC_{50} > the maximum tested concentration.

1.5 Haemolysis Assay

1.5.1 Procedure

Human whole blood was washed three times with 3 volumes of 0.9% NaCl and then resuspended in same to a concentration of 0.5 x 10^8 cells per ml, as determined by manual cell count in a Neubauer haemocytometer. The washed cells were then added to the 384-well compound-containing plates for a final volume of 50 μL. After a 10 min shake on a plate shaker the plates were then incubated for 1 h at 37 °C. After incubation, the plates were centrifuged at 1000 *g* for 10 min to pellet cells and debris, 25 μl of the supernatant was then transferred to a polystyrene 384-well assay plate.

1.5.2 Analysis

Haemolysis was determined by measuring the supernatant absorbance at 405 mm (OD_{405}). The absorbance was measured using a Tecan M1000 Pro monochromator plate reader.

HC_{10} and HC_{50} (concentration at 10% and 50% haemolysis, respectively) were calculated by curve fitting the inhibition values vs. log(concentration) using a sigmoidal dose-response function with variable fitting values for top, bottom and slope. In addition, the maximal percentage of haemolysis is reported as D_{Max}, indicating any compounds with partial haemolysis.

The curve fitting was implemented using Pipeline Pilot's dose-response component, resulting in similar values to curve fitting tools such as GraphPad's Prism and IDBS's XlFit. Any value with > indicate sample with no activity (low D_{Max} value) or samples with HC_{10} values above the maximum tested concentration (higher D_{Max} value).

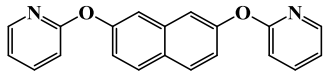
Haemolysis samples were classified by $HC_{10} \leq 32$ μg ml^{-1} or $HC_{10} \leq 10$ μM in either replicate (n=2 on different plates). In addition, samples were flagged as partial haemolytic if $D_{Max} \geq 50\%$, even with HC_{10} > the maximum tested concentration.

2. Chemical Experimental Details

Reagents were purchased and used without further purification. Reactions were monitored by TLC on silica gel 60 F254 aluminum sheets under UV light. All products were analyzed by NMR spectroscopy on Bruker AM300 and DRX500 spectrometers at ambient temperature in DMSO-d6 and $CDCl_3$. Biologically tested compound (Product) purities were confirmed by HPLC on a Stayer 0892 series HPLC system with Luna® 5 μm C18 100 Å, LC column 250 x 4.6 mm. Mobile phase: 85:15 MeCN/H_2O (0.25 M $NaClO_4$, 0.1% H_3PO_4). All melting points were determined on a Gallenkamp melting point apparatus in open capillaries and are uncorrected. Mass spectra were recorded on a Finnigan MAT INCOS 50 mass-spectrometer. IR spectra were recorded with a Bruker ALPHA-T FT-IR spectrometer in KBr pellets. The ESI contains detailed experimental protocols, summaries of spectral data, and spectra.

3. Synthesis and Characterization of Substrates and Products

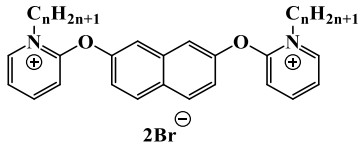
Synthesis of 2,2'-[naphtalene-2,7-diylbis(oxy)]dipyridine 2 (2N2,7BO):



The mixture of 2,7-dihydroxynaphthalene (1.60 g, 10 mmol), 2-bromopyridine (3.16 g, 20 mmol), potassium phosphate (8.48 g, 40 mmol), copper(I) iodide (1.90 g, 10 mmol) and picolinic acid (0.25 g, 2 mmol) in dry DMSO (50 ml) was heated to 90 °C for 24 h in argon atmosphere. The solvent was removed under reduced pressure, ethyl acetate (50 ml) was added to the crude residue, and the mixture was heated under reflux for 1 hour. The solid was filtered off and the filter cake was washed with hot ethyl acetate (20 ml). The organic filtrate was concentrated under reduced pressure, and the residue was purified by recrystallization from heptane to afford white solid product **2** (2.26 g, 7.2 mmol, 72% yield) [S1]

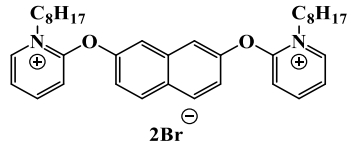
$C_{22}H_{16}N_2O_2$; M. w. 314.34; White solid; M. p. 103-106°C; ^{1}H NMR (500 MHz, $CDCl_3$): δ 6.98 (d, J = 8.3 Hz, 2H, $2CH_{py}$), 7.05 (dd, J = 7.1, 5.1 Hz, 2H, $2CH_{py}$), 7.29 (dd, J = 8.8, 2.1 Hz, 2H, $2CH_{Ar}$), 7.53 (d, J = 2.1 Hz, 2H, $2CH_{Ar}$), 7.74 (ddd, J = 8.3, 7.1, 1.6 Hz, 2H, $2CH_{py}$), 7.90 (d, J = 8.8 Hz, 2H, $2CH_{Ar}$), 8.25 (dd , J = 5.1, 1.6 Hz, 2H, $2CH_{py}$) ppm; ^{13}C NMR (150 MHz, $CDCl_3$): δ 111.6, 116.7, 119.1, 120.7, 127.7, 129.4, 134.8, 140.2, 147.5, 152.2, 163.0 ppm.

Synthesis of 2,2'-[naphtalene-2,7-diylbis(oxy)]bis(1-alkylpyridinium) dibromides 3 (2N2,7BO-n,Br)



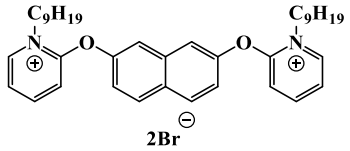
To a solution of compound **2** (0.31 g, 1 mmol) in acetonitrile (3 ml) was added alkyl bromide (4 mmol). The mixture was heated under reflux for 7 days, then cooled and filtered. The filtered solid was washed with cold acetone (10 ml) and dried to give a white solid product **3**. The yields of **3a-e** were 70-85% depending on the alkyl bromide.

2,2'-[Naphtalene-2,7-diylbis(oxy)]bis(1-octylpyridinium) dibromide (3a, 2N2,7BO-8,Br):



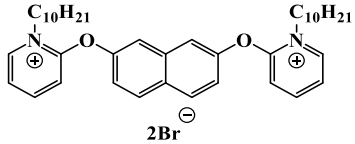
$C_{36}H_{48}Br_2N_2O_2$; M. w. 700.6; White solid (0.60 g, 0.85 mmol, 85% yield); M. p. 75-78°C; 1H NMR (300 MHz, DMSO-d_6): δ 0.83 (t, J = 6.4 Hz, 6H, 2CH3), 1.14-1.51 (m, 20H, 10CH2), 1.91-2.07 (m, 4H, $2CH_2$), 4.68 (t, J = 6.8 Hz, 4H, $2CH_2N^+$), 7.32 (d, J = 8.7 Hz, 2H, $2CH_{py}$), 7.72-7.84 (m, 8H), 8.14 (d, J = 1.7 Hz, 2H, $2CH_{Ar}$), 8.37 (d, J = 9.0 Hz, 4H, CH_{Ar}), 8.47 (t, J = 7.6 Hz, 2H, $2CH_{py}$), 8.99 (d, J = 5.6 Hz, 2H, $2CH_{py}$) ppm; ^{13}C NMR (75 MHz, DMSO-d_6): δ 13.9, 22.0, 25.7, 28.4, 28.5, 28.7, 31.1, 54.8, 113.7, 118.4, 120.6, 120.8, 130.6, 131.7, 134.5, 143.8, 148.5, 150.2, 158.7 ppm; ν_{max}, (KBr): 3435, 2921, 2854, 1635, 1582, 1506, 1462, 1161, 960, 777 cm^{-1}

2,2'-[Naphtalene-2,7-diylbis(oxy)]bis(1-nonylpyridinium) dibromide (3b, 2N2,7BO-9,Br):



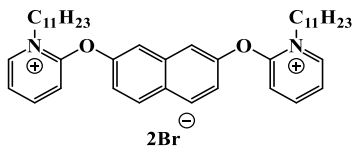
$C_{38}H_{52}Br_2N_2O_2$; M. w. 728.7; White solid (0.546 g, 0.75 mmol, 75% yield); M. p. °C; 1H NMR (300 MHz, DMSO-d_6): δ 0.83 (t, J = 6.4 Hz, 6H, 2CH3), 1.12-1.49 (m, 24H, 12CH2), 1.96-2.08 (m, 4H, $2CH_2$), 4.67 (t, J = 6.8 Hz, 4H, $2CH_2N^+$), 7.32 (d, J = 8.7 Hz, 2H, $2CH_{py}$), 7.72-7.84 (m, 8H), 8.14 (d, J = 1.7 Hz, 2H, $2CH_{Ar}$), 8.36 (d, J = 9.0 Hz, 4H, CH_{Ar}), 8.47 (t, J = 7.6 Hz, 2H, $2CH_{py}$), 8.99 (d, J = 5.6 Hz, 2H, $2CH_{py}$) ppm; ^{13}C NMR (75 MHz, DMSO-d_6): δ 13.8, 22.1, 25.6, 28.4, 28.5, 28.8, 28.9, 31.1, 55.0, 113.6, 118.4, 120.5, 120.6, 130.5, 131.7, 134.3, 143.7, 148.4, 150.2, 158.6 ppm; ν_{max}, (KBr): 3434, 2925, 2854, 1635, 1581, 1506, 1461, 1147, 963, 777 cm^{-1}

2,2'-[Naphtalene-2,7-diylbis(oxy)]bis(1-decylpyridinium) dibromide (3c, 2N2,7BO-10,Br):



$C_{40}H_{56}Br_2N_2O_2$; M. w. 756.7; White solid (0.54 g, 0.72 mmol, 72% yield); M. p. 139-142°C; 1H NMR (300 MHz, DMSO-d_6): δ 0.81 (t, J = 6.4 Hz, 6H, 2CH3), 1.09-1.52 (m, 28H, 14CH2), 1.91-2.09 (m, 4H, $2CH_2$), 4.67 (t, J = 6.8 Hz, 4H, $2CH_2N^+$), 7.31 (d, J = 8.7 Hz, 2H, $2CH_{py}$), 7.72-7.84 (m, 8H), 8.14 (d, J = 1.7 Hz, 2H, $2CH_{Ar}$), 8.37 (d, J = 9.0 Hz, 4H, CH_{Ar}), 8.46 (t, J = 7.6 Hz, 2H, $2CH_{py}$), 8.97 (d, J = 5.6 Hz, 2H, $2CH_{py}$) ppm; ^{13}C NMR (75 MHz, DMSO-d_6): δ 13.8, 22.0, 25.6, 28.3, 28.6, 28.7, 28.8, 31.2, 54.8, 113.6, 118.4, 120.5, 120.8, 130.5, 131.7, 134.5, 143.7, 148.4, 150.2, 158.6 ppm; ν_{max}, (KBr): 3434, 2925, 2854, 1635, 1581, 1506, 1461, 1147, 963, 777 cm^{-1}

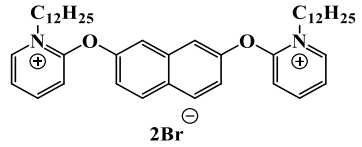
2,2'-[Naphtalene-2,7-diylbis(oxy)]bis(1-undecylpyridinium) dibromide (3d, 2N2,7BO-11,Br):



$C_{42}H_{60}Br_2N_2O_2$; M. w. 784.8; White solid (0.55 g, 0.7 mmol, 70% yield); M. p. 92-95°C; 1H NMR (300 MHz, DMSO-d_6): δ 0.82 (t, J = 6.4 Hz, 6H, 2CH3), 1.08-1.52 (m, 32H, 16CH2), 1.91-2.07 (m, 4H, $2CH_2$), 4.68 (t, J = 6.8 Hz, 4H, $2CH_2N^+$), 7.31 (d, J = 8.7 Hz, 2H, $2CH_{py}$), 7.72-7.84 (m, 8H), 8.13 (d, J = 1.7 Hz, 2H, $2CH_{Ar}$), 8.36 (d, J = 9.0 Hz, 4H, CH_{Ar}), 8.47 (t, J = 7.6 Hz, 2H, $2CH_{py}$), 8.98 (d, J = 5.6 Hz, 2H, $2CH_{py}$) ppm; ^{13}C NMR (75 MHz, DMSO-d_6): δ 14.1, 22.2, 25.8,

26.1, 28.5, 28.8, 28.9, 29.1, 31.4, 55.1, 113.8, 118.6, 120.7, 121.1, 130.8, 132.0, 134.7, 143.9, 148.7, 150.4, 158.9 ppm; ν_{max}, (KBr): 3419, 2925, 2853, 1636, 1581, 1504, 1462, 1159, 962, 777 cm^{-1}

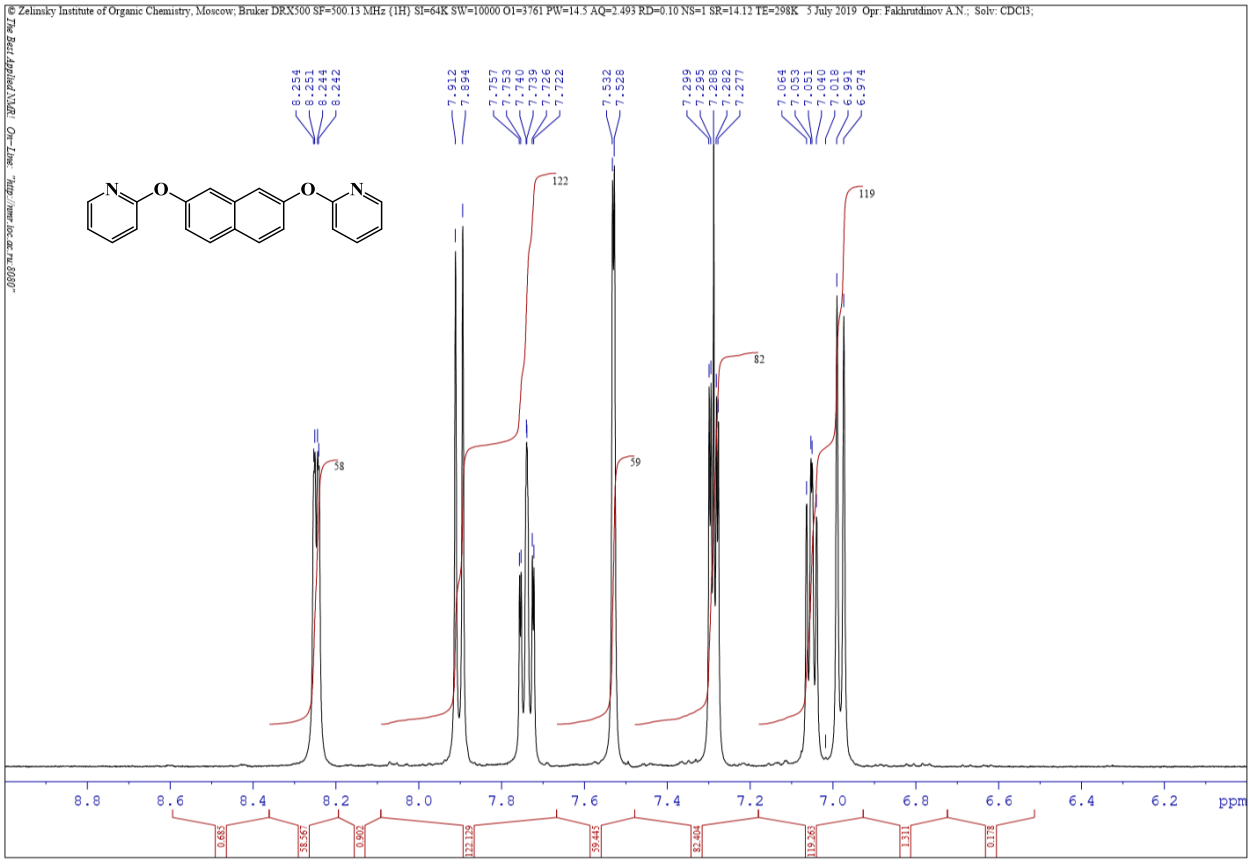
2,2'-[Naphtalene-2,7-diylbis(oxy)]bis(1-dodecylpyridinium) dibromide (3e, 2N2,7BO-12,Br):

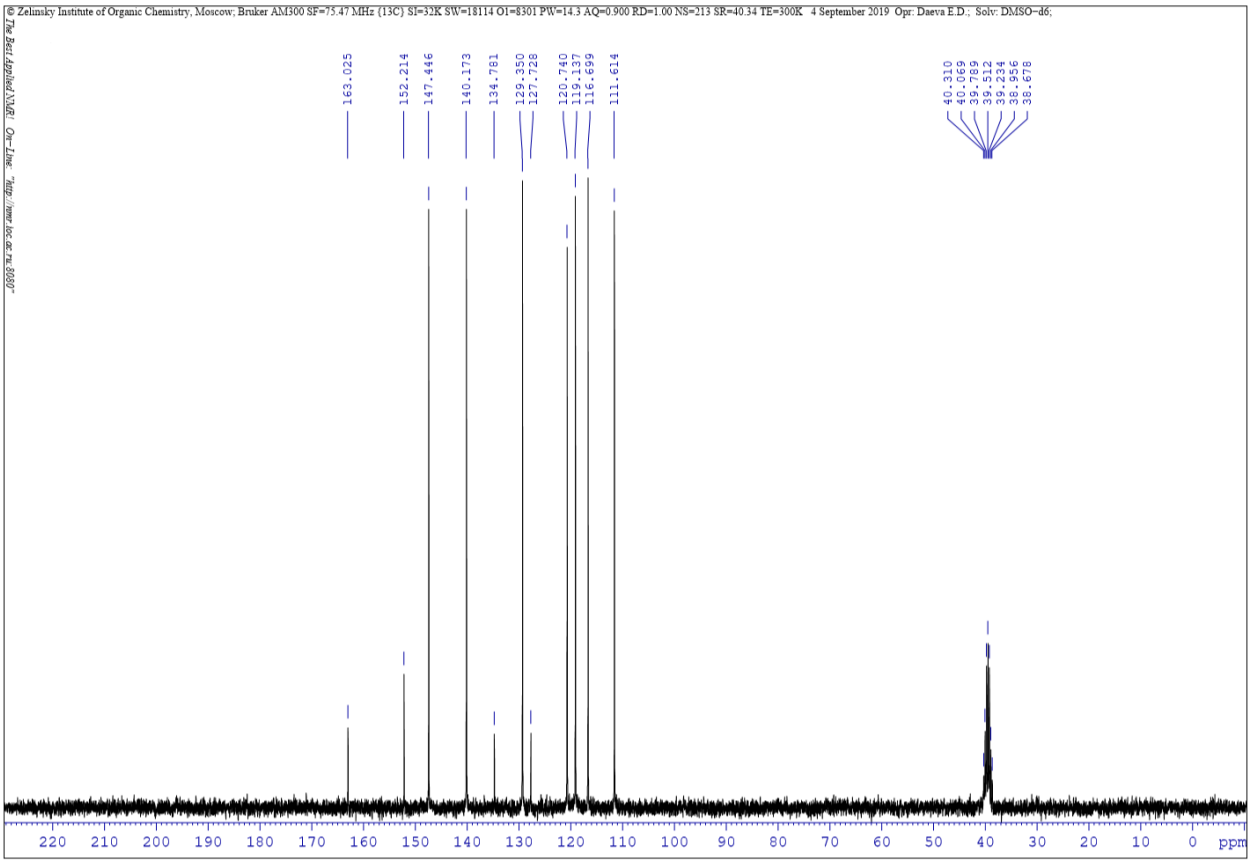


$C_{44}H_{64}Br_2N_2O_2$; M. w. 812.8; White solid (0.57 g, 0.7 mmol, 70% yield); M. p. 105-108°C; 1H NMR (300 MHz, DMSO-d_6): δ 0.83 (t, J = 6.4 Hz, 6H, 2CH3), 1.14-1.51 (m, 36H, 18CH2), 1.91-2.07 (m, 4H, $2CH_2$), 4.67 (t, J = 6.8 Hz, 4H, $2CH_2N^+$), 7.30 (d, J = 8.7 Hz, 2H, $2CH_{py}$), 7.72-7.84 (m, 8H), 8.12 (d, J = 1.7 Hz, 2H, $2CH_{Ar}$), 8.36 (d, J = 9.0 Hz, 4H, CH_{Ar}), 8.46 (t, J = 7.6 Hz, 2H, $2CH_{py}$), 8.96 (d, J = 5.6 Hz, 2H, $2CH_{py}$) ppm; ^{13}C NMR (75 MHz, DMSO-d_6): δ 13.8, 21.9, 25.5, 28.3, 28.5, 28.6, 28.7, 28.8, 28.9, 31.1, 54.7, 113.6, 118.3, 120.5, 120.7, 130.5, 131.6, 134.4, 143.7, 148.4, 150.1, 158.6 ppm; ν_{max}, (KBr): 3439, 2919, 2852, 1636, 1583, 1504, 1465, 1162, 961, 777 cm^{-1}

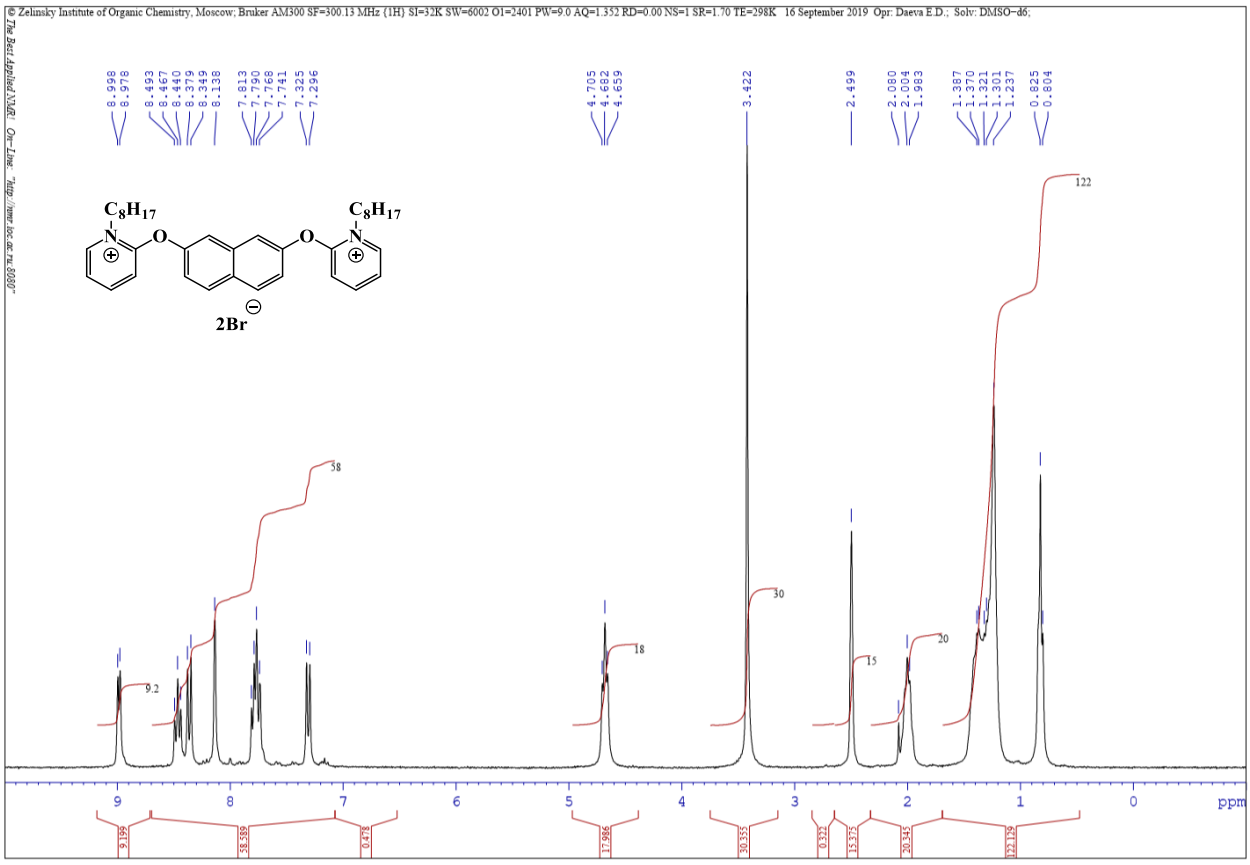
4. ^{1}H NMR, ^{13}C NMR and HPLC Spectra

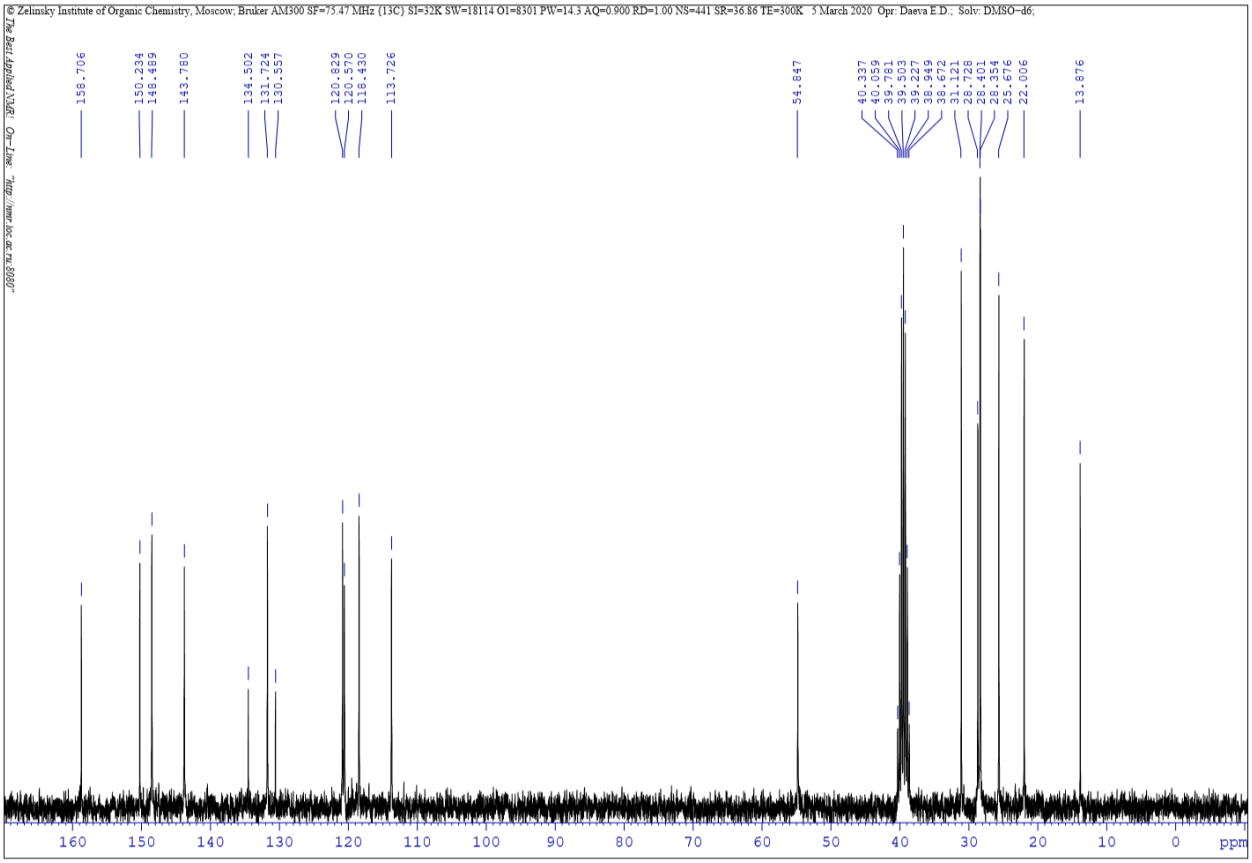
2N2,7BO 2

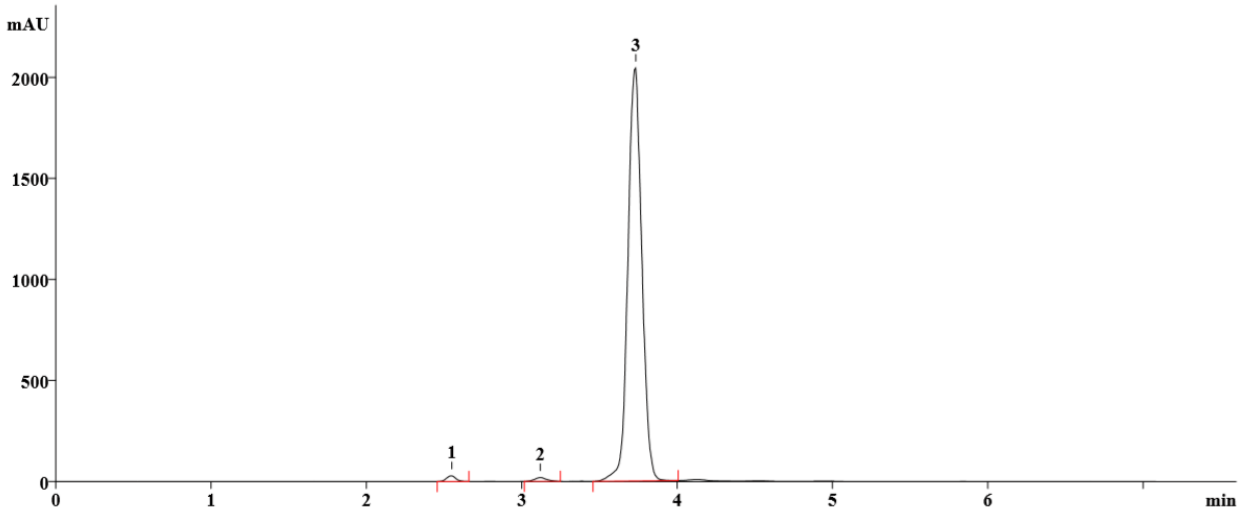




2N2,7BO-8,Br, 3a



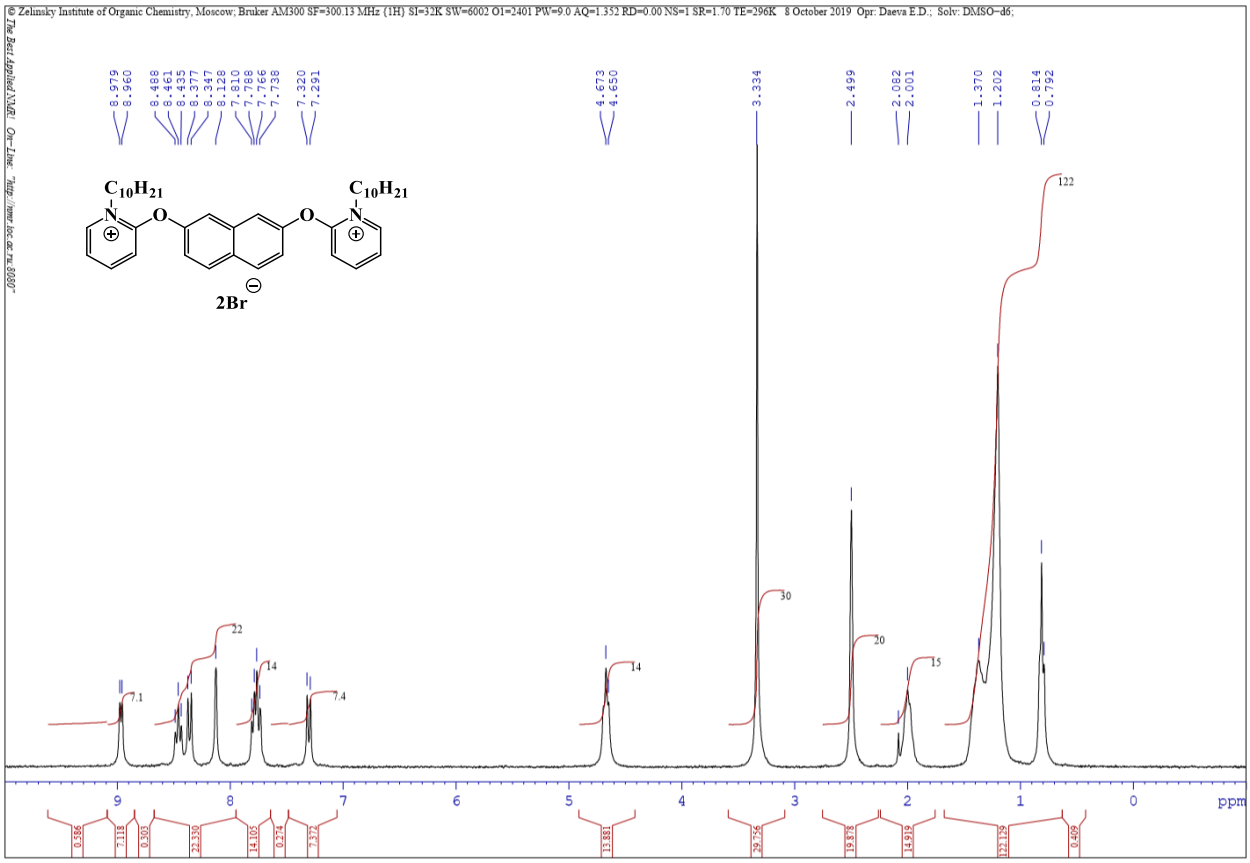


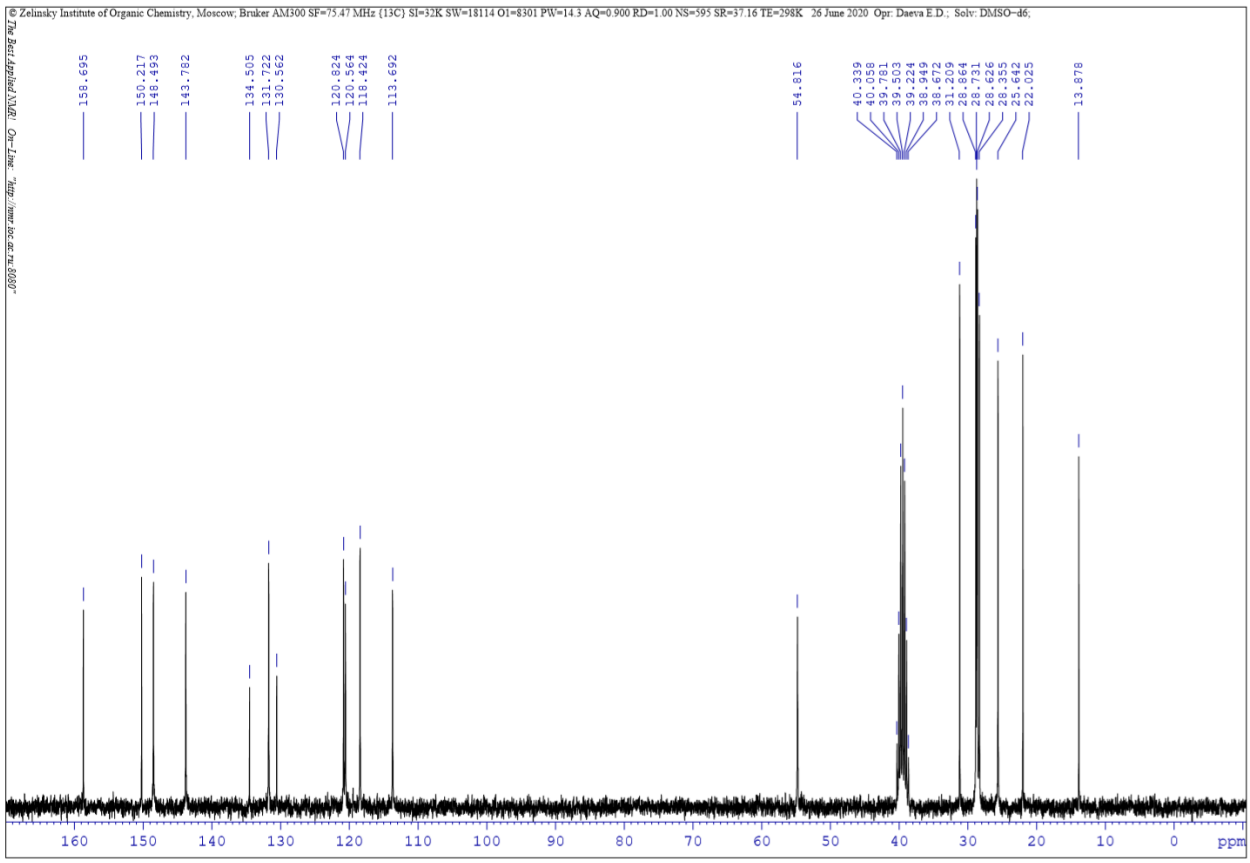


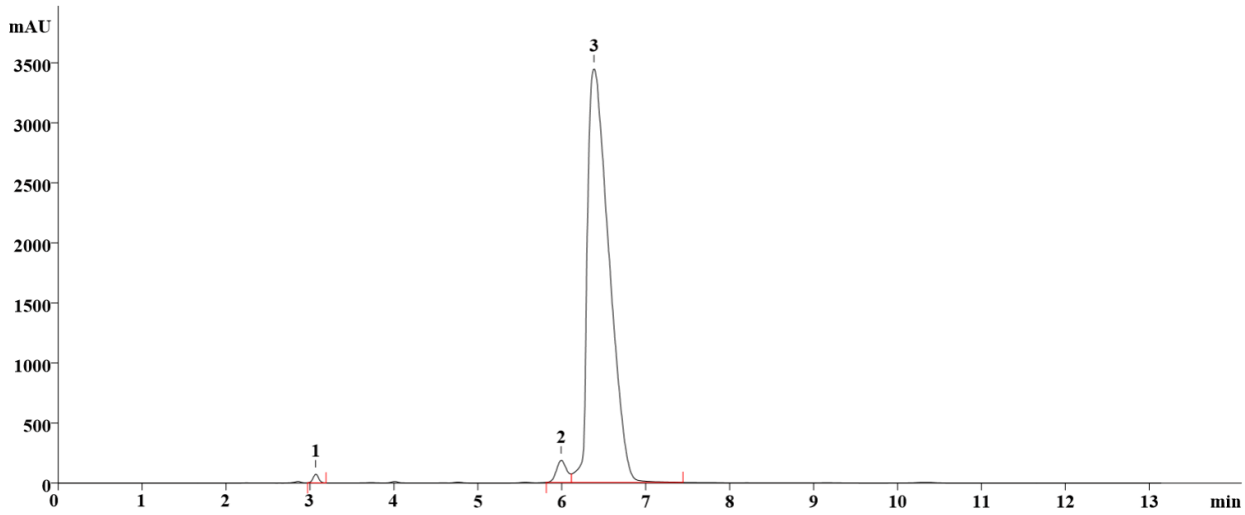
Peak table

Peak	Retention min	Area	Height	Width h/2	Area%	Type
1	2,55	114,127	27,770	0,0645	0,881	BB :
2	3,12	99,119	18,458	0,0818	0,765	BB :
3	3,73	12735,514	2042,445	0,0957	98,353	BB :

2N2,7BO-10,Br, 3c







Peak table

Peak	Retention min	Area	Height	Width h/2	Area%	Type
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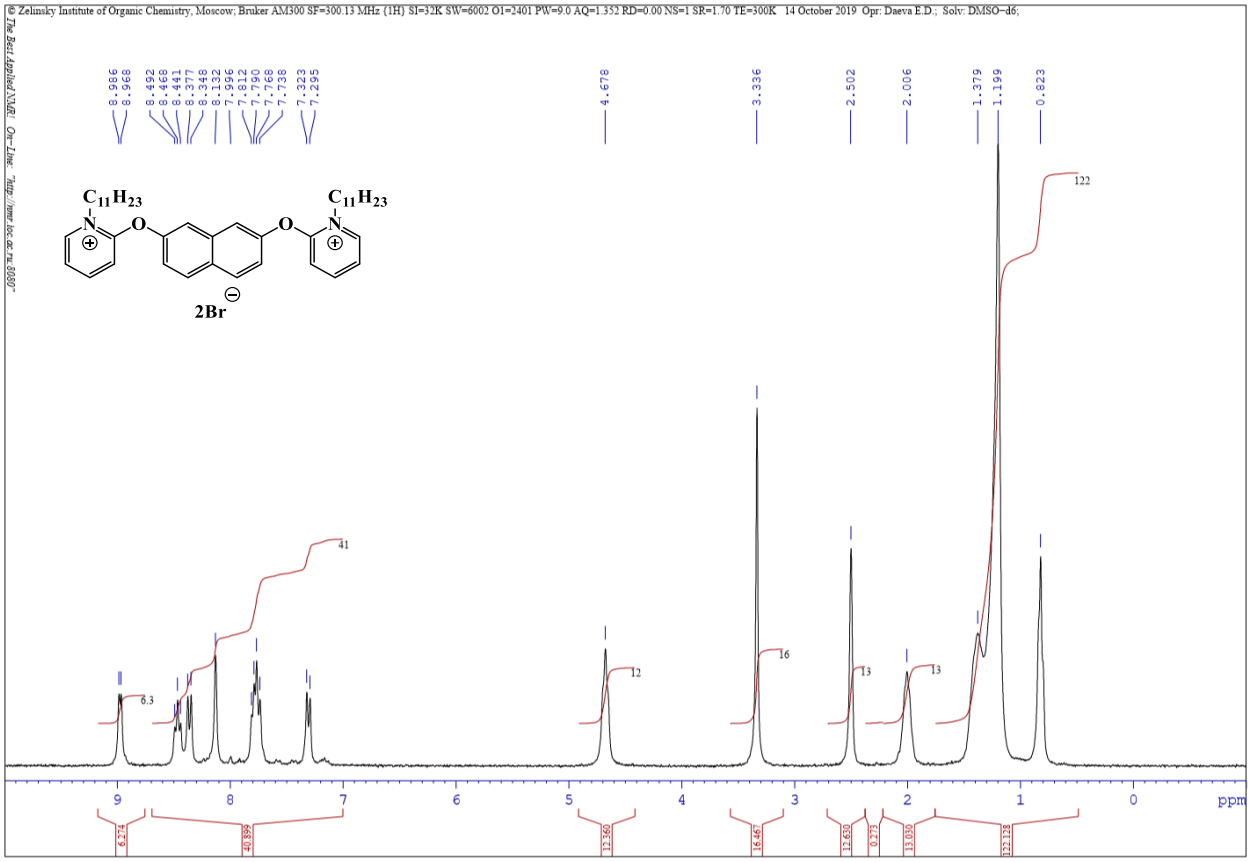
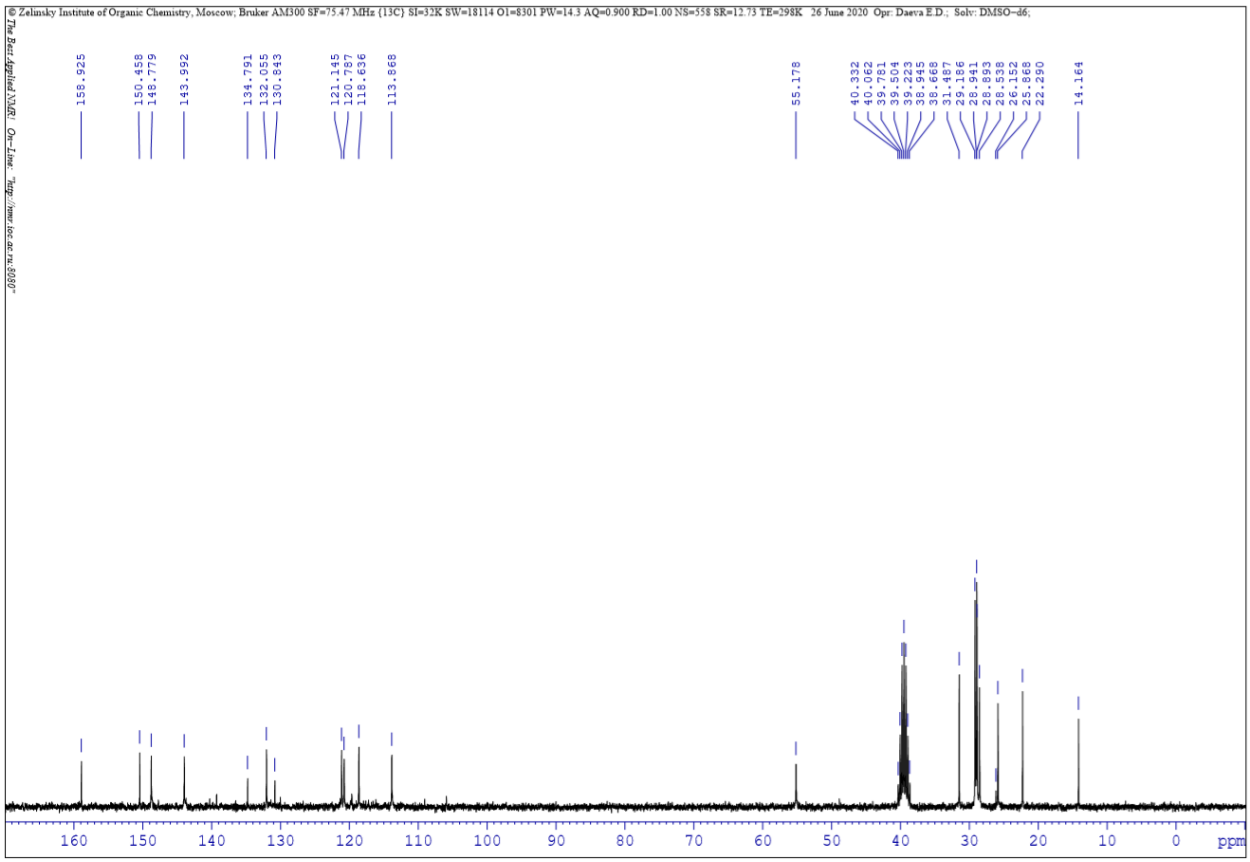
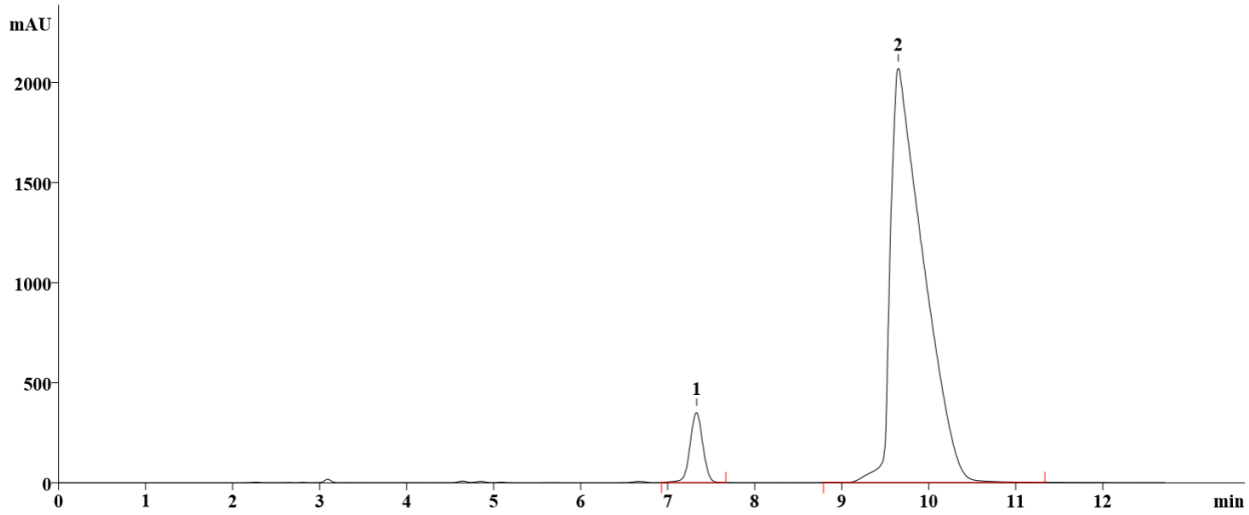
2	6,00	1585,808	183,238	0,137	2,510	BD :
3	6,38	61254,367	3441,620	0,284	96,971	DB :

2N2,7BO-11,Br, 3d



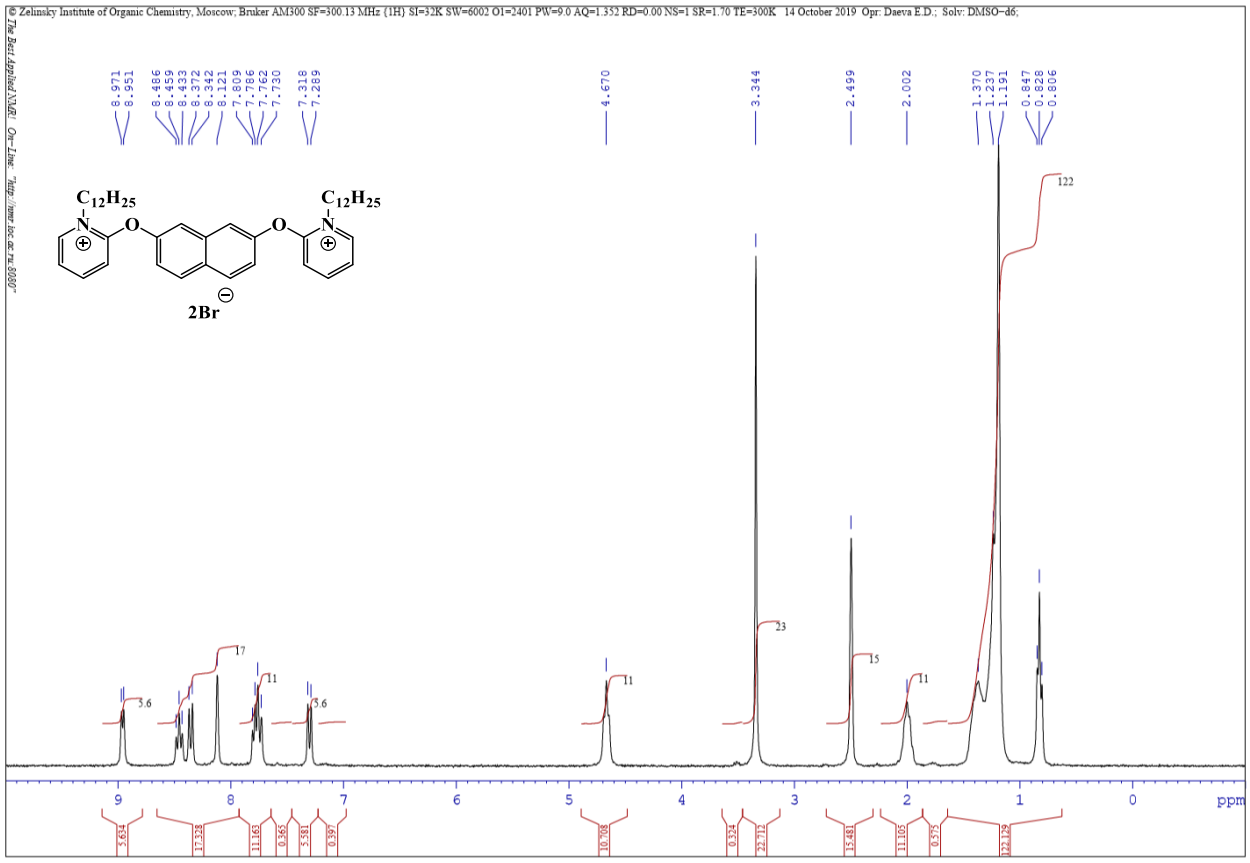


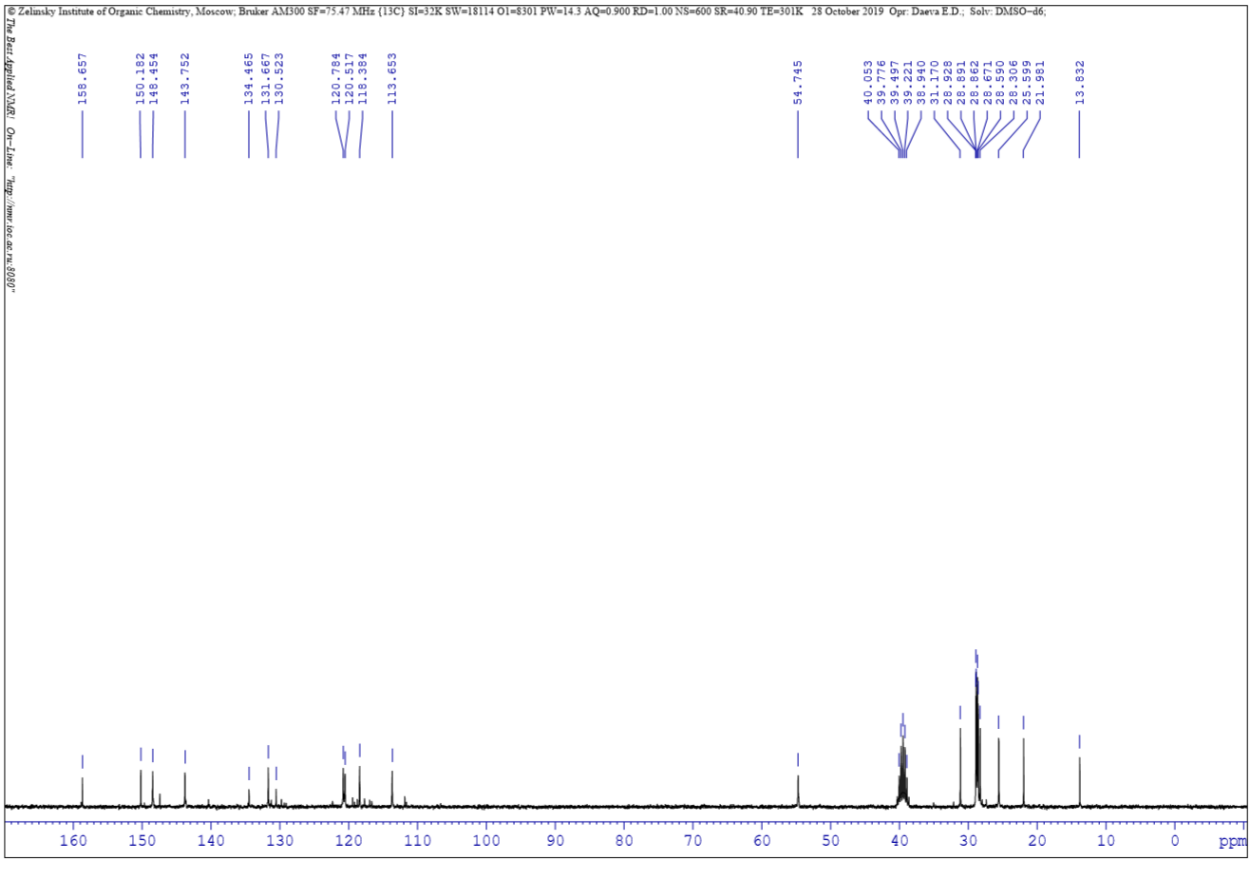


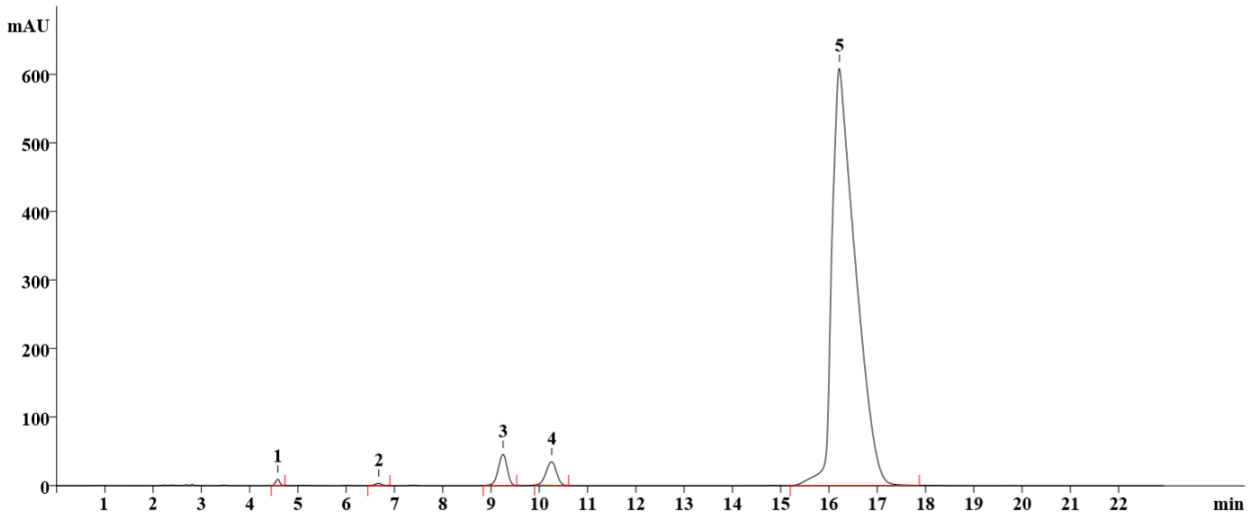
Peak table

Peak	Retention min	Area	Height	Width h/2	Area%	Type
1	7,33	3572,662	349,023	0,158	6,146	BB :
2	9,65	54561,818	2068,407	0,414	93,584	BB :

2N2,7BO-12,Br, 3e







Peak table

Peak	Retention min	Area	Height	Width h/2	Area%	Type
1	4,58	53,832	8,947	0,0931	0,248	BB :
2	6,67	30,912	3,139	0,153	0,142	BB :
3	9,25	577,660	45,017	0,198	2,662	BB :
4	10,25	515,115	34,262	0,234	2,374	BB :
5	16,21	20521,246	608,330	0,529	94,573	BB :