

Supporting Information

Linear Photophysics and Femtosecond Nonlinear Spectroscopy of a Star-Shaped Squaraine Derivative with Efficient Two-Photon Absorption

Taihong Liu,¹ Mykhailo V. Bondar,² Kevin D. Belfield,^{1,3} Dane Anderson,^{4,5} Artëm E. Masunov,^{4,5,6}
David J. Hagan,^{6,7} Eric W. Van Stryland^{6,7}

¹*College of Science and Liberal Arts, New Jersey Institute of Technology, University Heights, Newark,
NJ 07102, USA*

²*Institute of Physics NASU, Prospect Nauki, 46, Kiev-28, 03028, Ukraine*

³*School of Chemistry and Chemical Engineering, Shaanxi Normal University, Xi'an, 710062, P.R.
China*

⁴*NanoScience Technology Center, University of Central Florida, 12424 Research Parkway, PAV400,
Orlando, Florida, 32826, USA*

⁵*Department of Chemistry, University of Central Florida, 4111 Libra Drive
PSB225, Orlando, FL 32816-2366, USA*

⁶*Department of Physics, University of Central Florida, 4111 Libra Drive
PSB430, Orlando, Florida 32816, USA*

⁷*CREOL, The College of Optics and Photonics, University of Central Florida, P.O. Box 162366, Orlando,
FL 32816, USA*

Table of Contents

1. Materials and methods	S3
2. Experimental section	S4
2.1. Synthesis of compound 1-2	S4
2.2. Synthesis of compound 1-3	S4
2.3. Synthesis of compound 1-4	S5
2.4. Synthesis of compound 1-5	S5
2.5 Synthesis of unsymmetrical squaraine dye 1-6	S6
2.6 Synthesis of star-shaped squaraine dye 1	S7
3. ¹ H and ¹³ C NMR spectra of the compounds	S8
4. References	S13

1. Materials and methods

All reagent chemicals and solvents were used as purchased without further purification unless otherwise noted. Solvents used for optical measurements were spectral grade quality. Thin-layer chromatography (TLC) was performed on precoated silica gel 60 F254 plates. Column chromatography was performed over silica gel 230-400 mesh. The ^1H and ^{13}C NMR measurements were performed at room temperature by a Bruker Avance III NMR spectrometer with tetramethylsilane (TMS) as an internal reference. High-resolution mass data were obtained in positive mode on an Apex-ultra 70

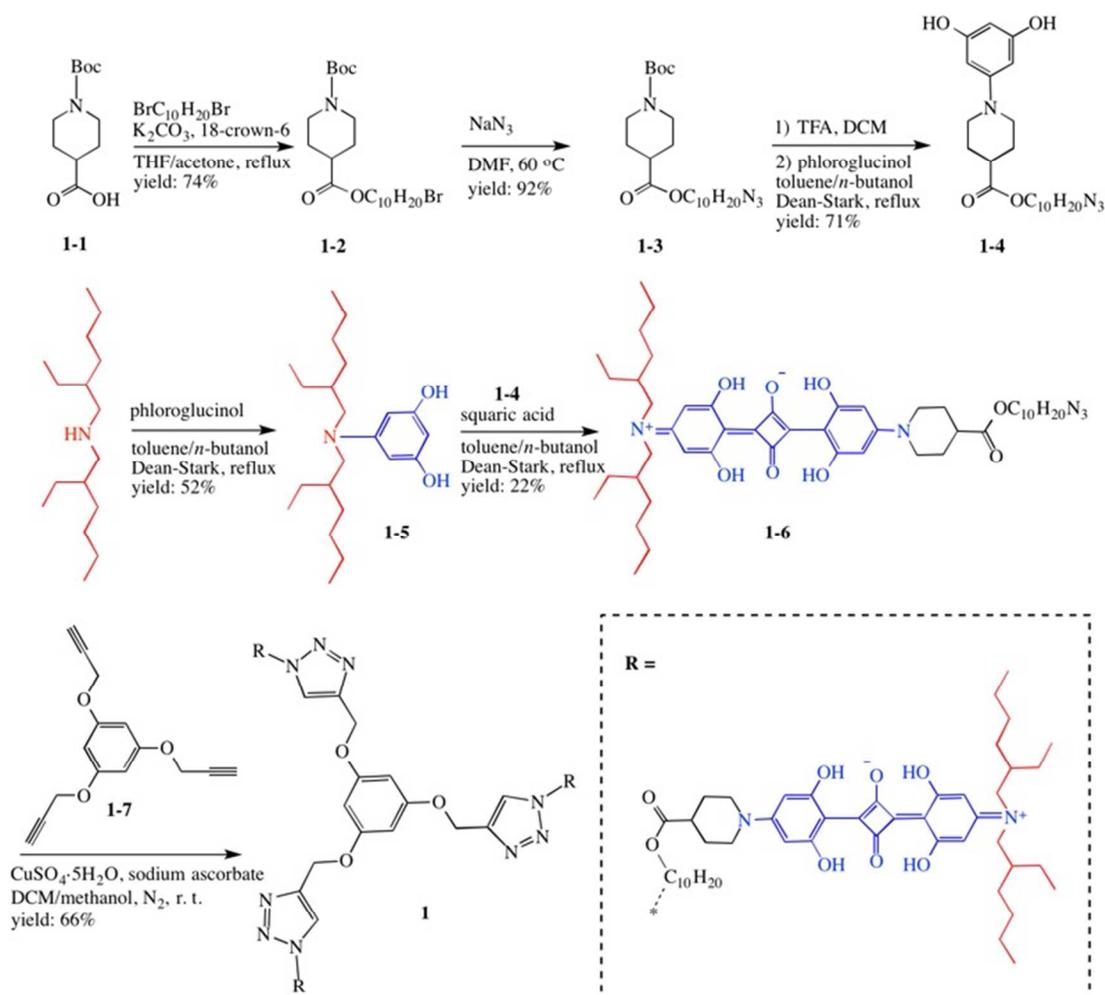


Figure S1. Synthesis route of compound 1.

Hybrid fourier transform mass spectrometer (Bruker Daltonics) using ESI techniques at the Department of Chemistry, Rutgers University-Newark, Newark, NJ. The compounds Boc-protected piperidine-4-carboxylic acid (**1-1**)^{1, 2} and 1,3,5-tris(2-propynyloxy)benzene (**1-7**)^{3, 4} were performed based on the reported literatures.

2. Experimental section

The synthesis route of compound **1** is reported in Figure S1.

2.1. Synthesis of compound 1-2

Starting material **1-1** (5.0 g, 21.8 mmol), 1,10-dibromodecane (7.85 g, 26.2 mmol), K₂CO₃ (3.91 g, 28.3 mmol) and 18-crown-6 (1.5 g, 5.6 mmol) were mixed in acetone/THF mixture (240 mL, 1/1, v/v) and refluxed overnight. The precipitate was filtered off and the solvent was concentrated. The mixture was washed with water, extracted with dichloromethane (DCM) and dried over anhydrous Na₂SO₄. The organic solvent was removed under reduced pressure, and the residue was subjected to column chromatography (3/1, v/v, *n*-hexane/ethyl acetate on silica, R_f≈0.49), affording compound **1-2** (7.20 g, 73.8%) as a colorless oil. ¹H NMR (400 MHz, CDCl₃, ppm) δ: 4.10-4.00 (4 H), 3.44-3.39 (2 H, CH₂Br), 2.87-2.81 (2 H), 2.48-2.41 (1 H, CH_{pip}), 1.91-1.82 (4 H), 1.68-1.57 (4 H), 1.47-1.36 (12 H), 1.31-1.29 (9 H, Boc). ¹³C NMR (100 MHz, CDCl₃, ppm) δ: 174.93 (C=O, ester), 155.00 (C=O, Boc), 79.85 (C_q, Boc), 64.94, 41.50, 34.30, 33.11, 29.67, 29.63, 29.47, 29.01, 28.90, 28.74, 28.43 (CH₃, Boc), 28.31, 26.18.

2.2. Synthesis of compound 1-3

Compound **1-2** (3.7 g, 8.2 mmol) and NaN₃ (0.8 g, 12.4 mmol) in DMF (30 mL) were heated at 60 °C for 10 h. After cooling down to room temperature, the reaction mixture was poured into water and extracted with ethyl acetate several times. The combined organic layers were washed with water, dried over anhydrous Na₂SO₄. After removal of the solvent *in vacuo*, the compound **1-3** (3.1 g, 91.7%) was

obtained as a colorless oil, which was pure enough and used in the subsequent reaction without further purification. ^1H NMR (400 MHz, CDCl_3 , ppm) δ : 4.09-4.00 (4 H), 3.28-3.22 (2 H, CH_2N_3), 2.87-2.80 (2 H), 2.47-2.40 (1 H, CH_{pip}), 1.89-1.85 (2 H), 1.64-1.56 (6 H), 1.46-1.44 (9 H), 1.38-1.26 (12 H). ^{13}C NMR (100 MHz, CDCl_3 , ppm) δ : 174.91 (C=O, ester), 154.99 (C=O, Boc), 79.81 (C_q , Boc), 64.91, 51.75 (CH_2N_3), 41.48, 29.66, 29.46, 29.39, 29.12, 28.89, 28.72, 28.71, 28.30 (CH_3 , Boc), 26.98, 26.16.

2.3. Synthesis of compound 1-4

Compound **1-3** (2.5 g, 6.1 mmol) was dissolved in DCM and the solution was cooled to 0 °C. Then trifluoroacetic acid was added and the reaction progress was monitored by TLC method using *n*-hexane/ethyl acetate (3/1, v/v) as the eluent. After complete conversion of the starting material, the solution was poured into water, neutralized with NaOH solution, and extracted with DCM. The combined organic layers were dried over anhydrous MgSO_4 , filtered and evaporated under reduced pressure to yield the crude product as a colorless oil that was used without further purification. Then phloroglucinol (0.92 g, 7.30 mmol) and *n*-butanol/toluene mixture (70 mL, 2/1, v/v) were added and the reaction mixture was heated at reflux with a Dean–Stark apparatus for 8 h. Excess solvent was removed under reduced pressure, which left a reddish oil that was purified by column chromatography (1/1, v/v, *n*-hexane/ethyl acetate on silica, $R_f \approx 0.33$), affording compound **1-4** (1.8 g, 70.9%) as a pale solid. ^1H NMR (400 MHz, $\text{DMSO}-d_6$, ppm) δ : 8.88 (s, 2 H, phenol-*H*), 5.77 (s, 2 H, Ar*H*), 5.69 (s, 1 H, Ar*H*), 4.02 (2 H), 3.49-3.44 (2 H), 3.33-3.28 (2 H), 2.71-2.64 (2 H), 2.48-2.42 (1 H, CH_{pip}), 1.88-1.82 (2 H), 1.65-1.48 (m, 6 H), 1.33-1.25 (m, 12 H). ^{13}C NMR (100 MHz, $\text{DMSO}-d_6$, ppm) δ : 175.03 (C=O, ester), 159.55, 153.59, 95.31, 94.78, 64.58, 51.40 (CH_2N_3), 48.71, 41.08, 29.59, 29.34, 29.27, 29.02, 28.89, 28.22, 26.91, 26.11. MS (m/z): $[\text{M}+\text{H}]^+$ Calculated for $\text{C}_{22}\text{H}_{35}\text{N}_4\text{O}_4$, 419.2653; Found, 419.2664.

2.4. Synthesis of compound 1-5

In a 250 mL round flask, a mixture of phloroglucinol (5.0 g, 39.6 mmol) and bis(2-ethylhexyl)amine (9.5 g, 39.6 mmol) in *n*-butanol/toluene mixture (180 mL, 2/1, v/v) was heated at reflux with a Dean-Stark apparatus for 8 h. The pale-red solution was then cooled, and the solvents were evaporated under reduced pressure to give a reddish oil. The resulting crude product was purified by column chromatography (2/1, v/v, *n*-hexane/ethyl acetate on silica, $R_f \approx 0.52$) to give compound **1-5** (7.2 g, 52.0%) as a brown viscous liquid. The product was used immediately for the next step. ^1H NMR (DMSO- d_6 , 400 MHz, ppm): δ 8.72 (s, 2 H, phenol-*H*), 5.55 (s, 2 H, Ar*H*), 5.51 (s, 1 H, Ar*H*), 3.06 (4 H), 1.70 (2 H), 1.18-1.29 (16 H), 0.80-0.88 (m, 12 H). ^{13}C NMR (DMSO- d_6 , 100 MHz, ppm): δ 159.16, 150.39, 92.26, 91.63, 56.27, 36.88, 30.51, 28.57, 23.82, 23.17, 14.34, 11.00. MS (m/z): $[\text{M}+\text{H}]^+$ Calculated for $\text{C}_{22}\text{H}_{40}\text{NO}_2$, 350.3054; Found, 350.3069.

2.5. Synthesis of unsymmetrical squaraine dye 1-6

In a 250 mL round bottom flask, compound **1-4** (2.09 g, 5.0 mmol), **1-5** (1.75 g, 5.0 mmol) and squaric acid (0.57 g, 5.0 mmol) were added to *n*-butanol/toluene mixture (160 mL, 1/1, v/v). The resulting mixture was heated at reflux with a Dean–Stark apparatus for 12 h to generate a dark green solution. After cooling, excess solvent was removed under reduced pressure and the resulting solid was purified by column chromatography (50/1, v/v, DCM/methanol on silica, $R_f \approx 0.71$), which afforded compound **1-6** (0.93 g, 22.0%) as a typically blue solid. ^1H NMR (400 MHz, CDCl_3 , ppm) δ : 11.03 (s, 2 H, phenol-*H*), 10.89 (s, 2 H, phenol-*H*), 5.91 (s, 2 H, Ar*H*), 5.82 (s, 2 H, Ar*H*), 4.12-4.05 (2 H), 3.95-3.84 (2 H), 3.38-3.27 (4 H), 3.27-3.22 (2 H), 3.20-3.09 (2 H), 2.67-2.56 (1 H, CH_{pip}), 2.05-1.95 (2 H), 1.88-1.73 (4 H), 1.66-1.55 (4 H), 1.41-1.21 (28 H), 0.93-0.87 (12 H). ^{13}C NMR (100 MHz, CDCl_3 , ppm) δ : 181.33, 173.90, 163.01, 162.83, 162.51, 160.76, 158.94, 158.14, 103.39, 102.26, 94.64, 94.27, 64.91, 56.68, 51.48(CH_2N_3), 46.55, 40.76, 38.23, 30.43, 29.38, 29.18, 29.11, 28.84, 28.47, 27.79, 26.70, 25.88, 23.79, 23.07, 14.03, 10.62. MS (m/z): $[\text{M}+\text{H}]^+$ Calculated for $\text{C}_{48}\text{H}_{72}\text{N}_8\text{O}_8$, 846.5375; Found, 846.5361.

2.6. Synthesis of star-shaped squaraine dye 1

Compound **1-6** (0.85 g, 1.0 mmol), compound **1-7** (0.08 g, 0.33 mmol) and $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (0.05 g, 0.2 mmol) were dissolved in a mixture of DCM/methanol (30 ml, 5/1, v/v), then the solution was degassed using bubbling nitrogen for 30 min. Sodium ascorbate (0.08 g, 0.4 mmol) in methanol solution was added and the mixture was stirred under nitrogen atmosphere overnight. After evaporation of the solvent, the residue was taken up in DCM and washed with water. The organic layer was dried over anhydrous Na_2SO_4 and removed under reduced pressure. Then the crude product was purified by column chromatography (20/1, v/v, DCM/methanol on silica, $R_f \approx 0.40$), which afforded compound **1** (0.61 g, 65.7%) as a blue solid. ^1H NMR (400 MHz, CDCl_3 , ppm) δ : 11.03 (s, 6 H, phenol-*H*), 10.88 (s, 6 H, phenol-*H*), 7.63 (s, 3 H, triazole-*H*), 6.28 (s, 3 H, benzyl-Ar*H*), 5.90 (s, 6 H, Ar*H*), 5.82 (s, 6 H, Ar*H*), 5.14 (s, 6 H, $-\text{OCH}_2$ -triazole), 4.36 (6 H), 4.08 (6 H), 3.95-3.84 (6 H), 3.49 (6 H), 3.31 (12 H), 3.15 (6 H), 2.66-2.57 (3 H, CH_{pip}), 2.06-1.70 (18 H), 1.60 (12 H), 1.40-1.17 (78 H), 0.90 (36 H). ^{13}C NMR (100 MHz, CDCl_3 , ppm) δ : 181.61, 174.25, 163.29, 163.09, 162.67, 161.00, 160.45, 159.18, 158.43, 144.08 (triazole), 122.97 (triazole), 103.64, 102.58, 95.28, 94.93, 94.57, 65.20, 62.43 ($-\text{OCH}_2$ -triazole), 56.99, 50.78, 46.85, 41.05, 38.54, 30.73, 30.60, 29.66, 29.59, 29.46, 29.27, 28.88, 28.78, 28.11, 26.80, 26.18, 24.09, 23.40, 14.37, 10.95. MS (m/z): $[\text{M}+\text{H}]^+$ Calculated for $\text{C}_{159}\text{H}_{226}\text{N}_{15}\text{O}_{27}$, 2777.6767; Found, 2778.0.

3. ^1H and ^{13}C NMR spectra of the compounds

Fig. S2. ^1H NMR spectra of compound 1-2

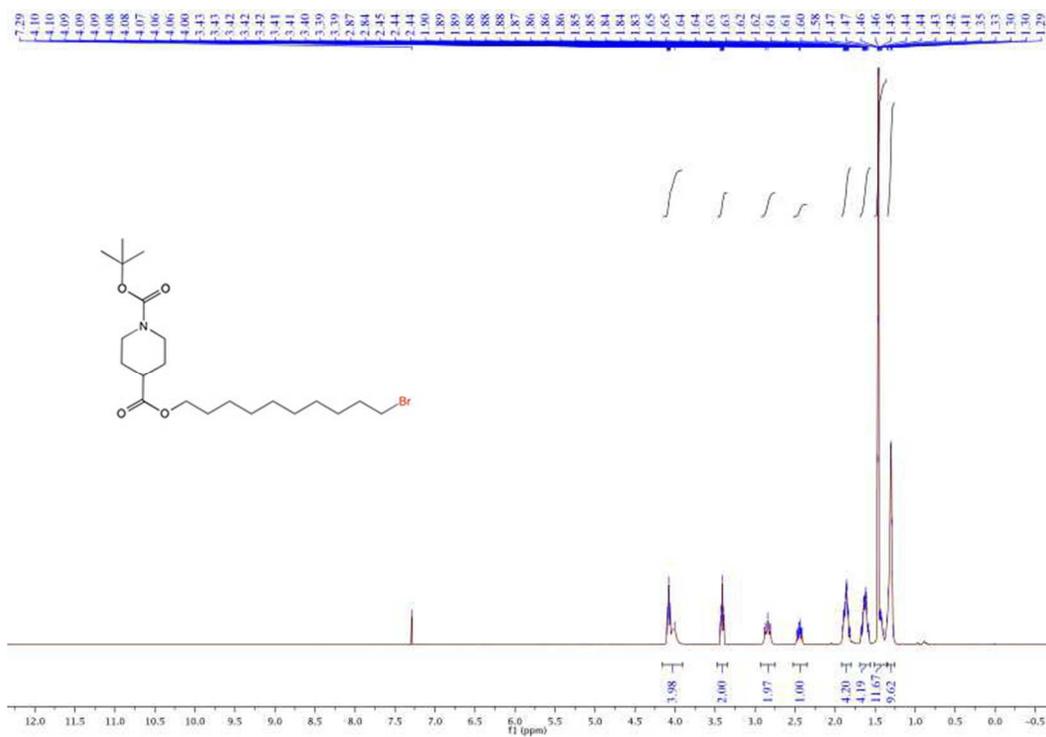


Fig. S3. ^{13}C NMR spectra of compound 1-2

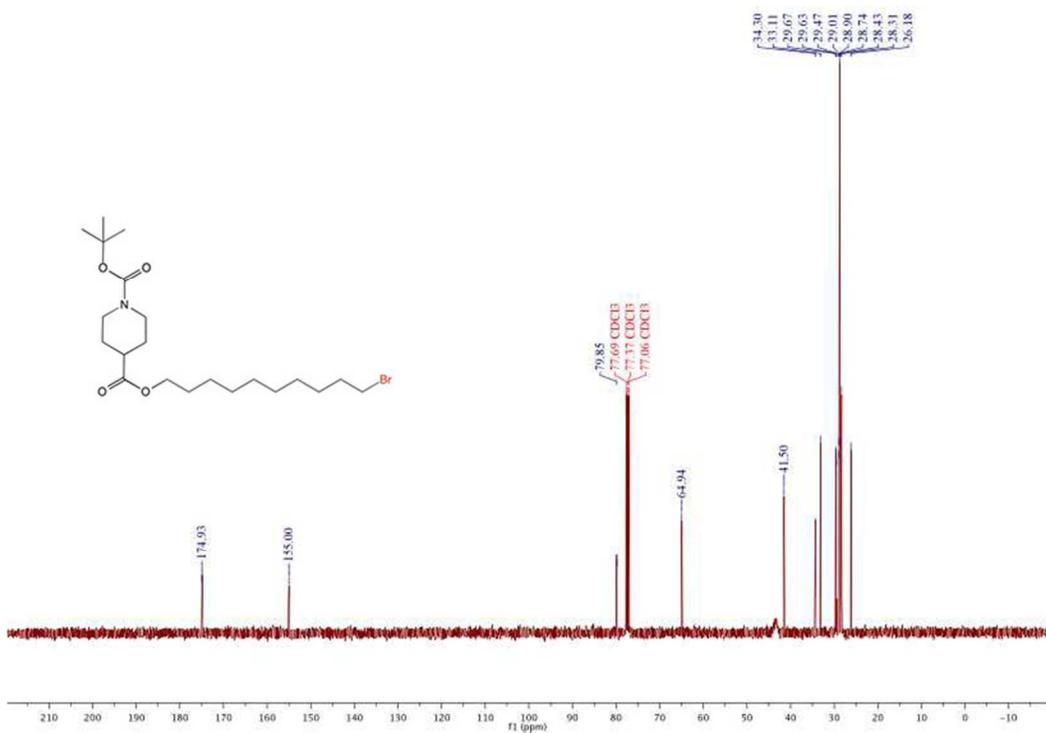


Fig. S4. ^1H NMR spectra of compound 1-3

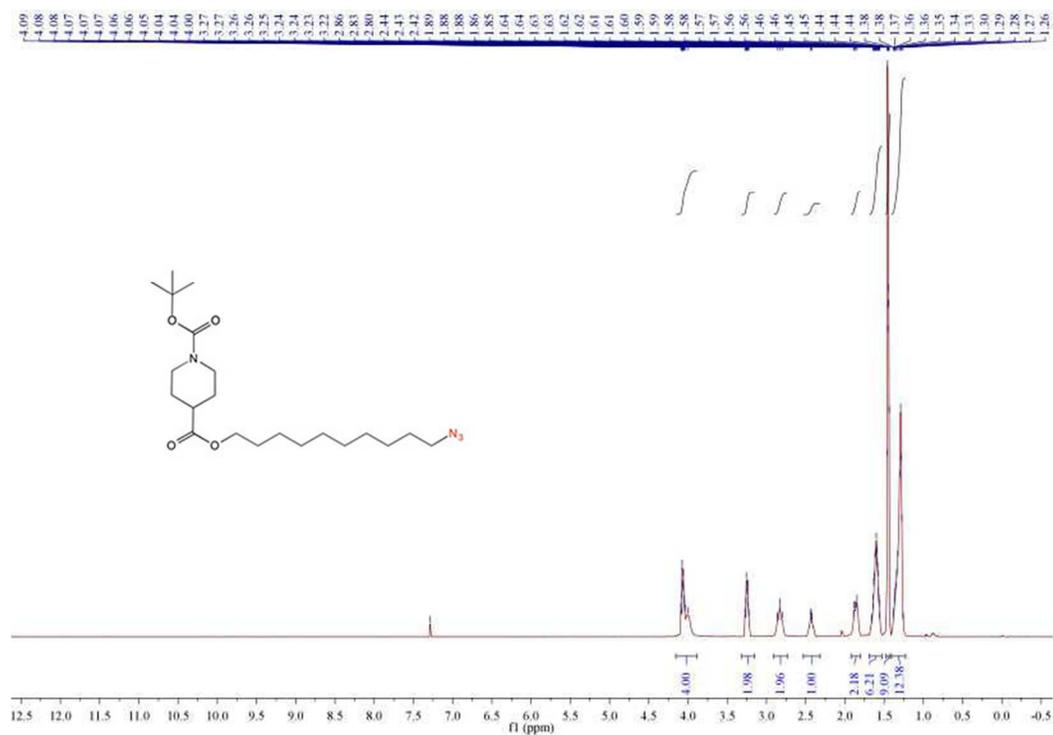


Fig. S5. ^{13}C NMR spectra of compound 1-3

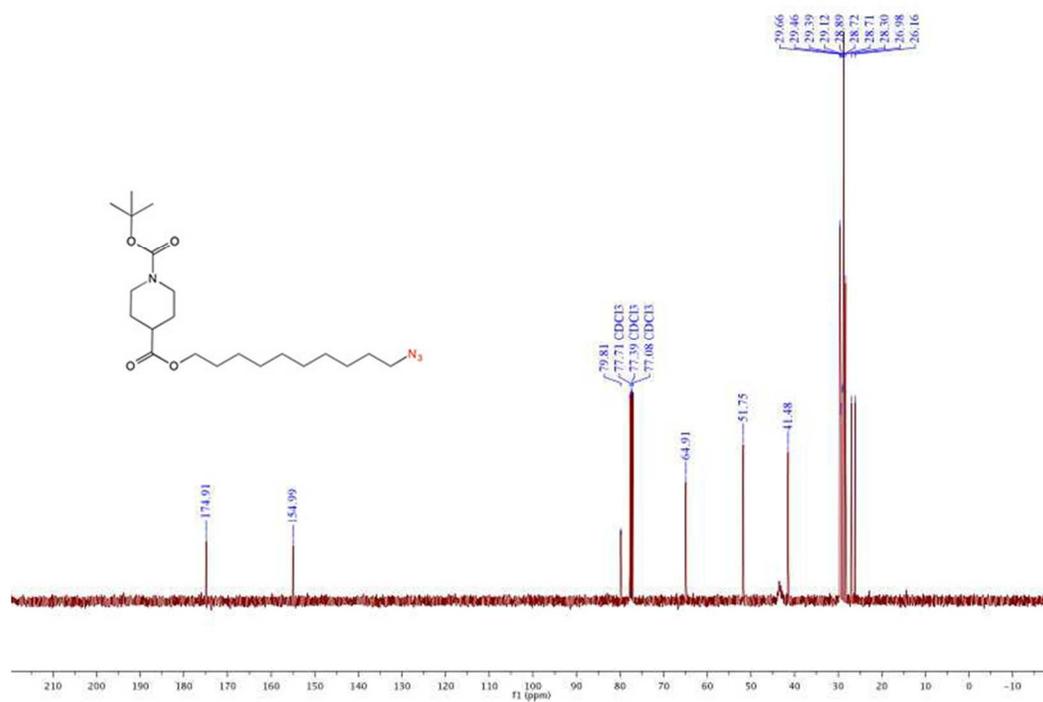


Fig. S6. ^1H NMR spectra of compound 1-4

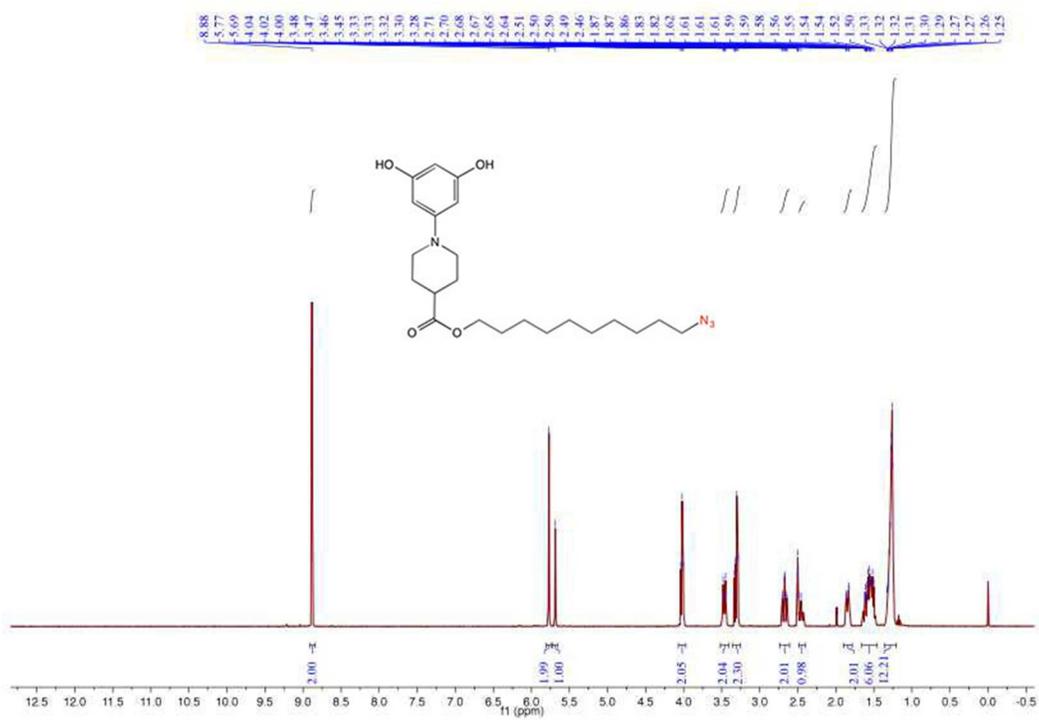


Fig. S7. ^{13}C NMR spectra of compound 1-4

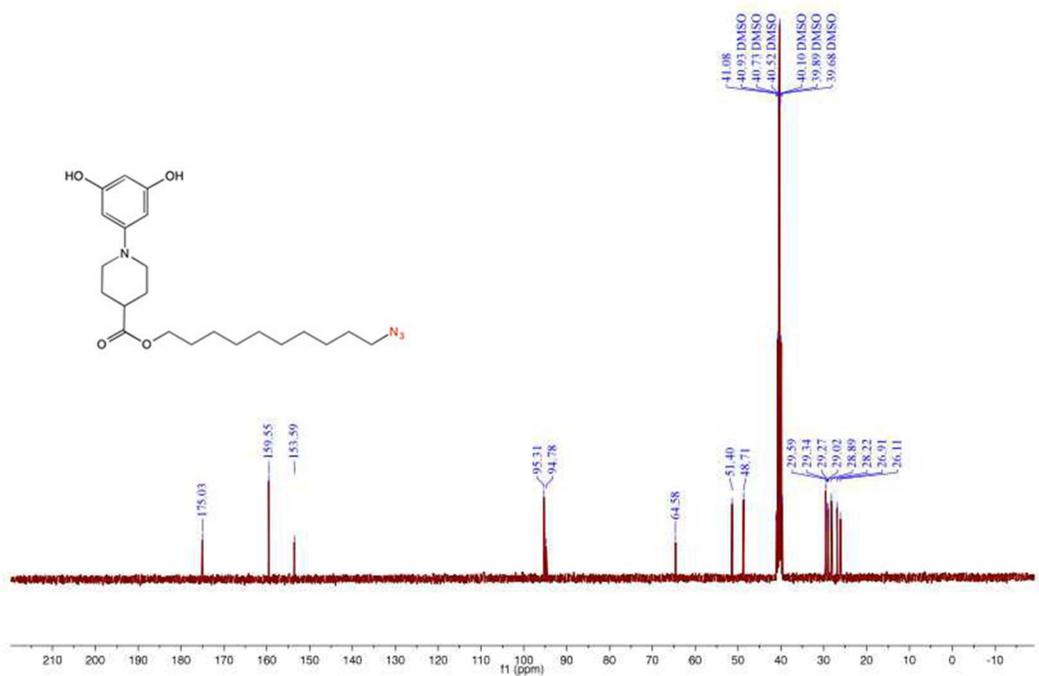


Fig. S8. ^1H NMR spectra of unsymmetrical squaraine dye 1-6

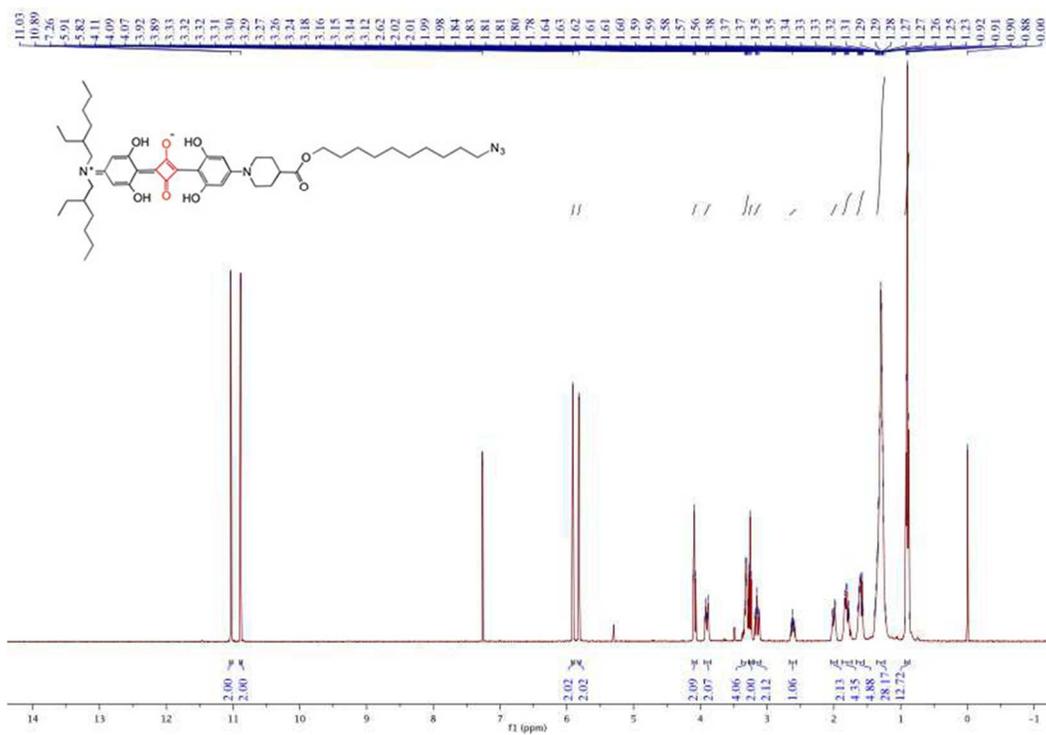


Fig. S9. ^{13}C NMR spectra of unsymmetrical squaraine dye 1-6

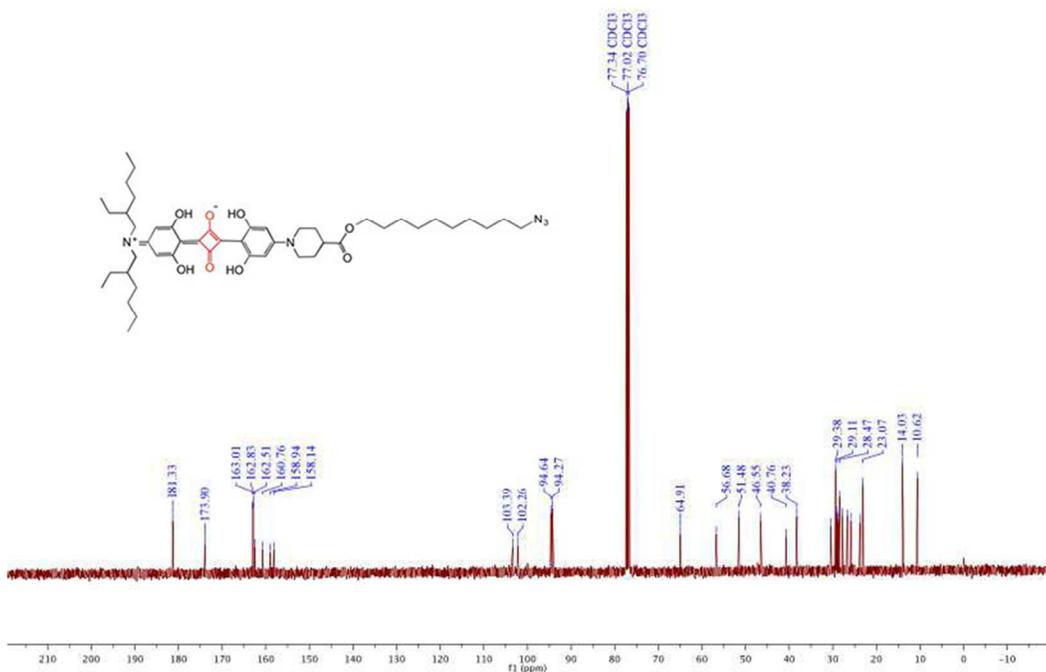


Fig. S10. ^1H NMR spectra of star-shaped squaraine dye **1**

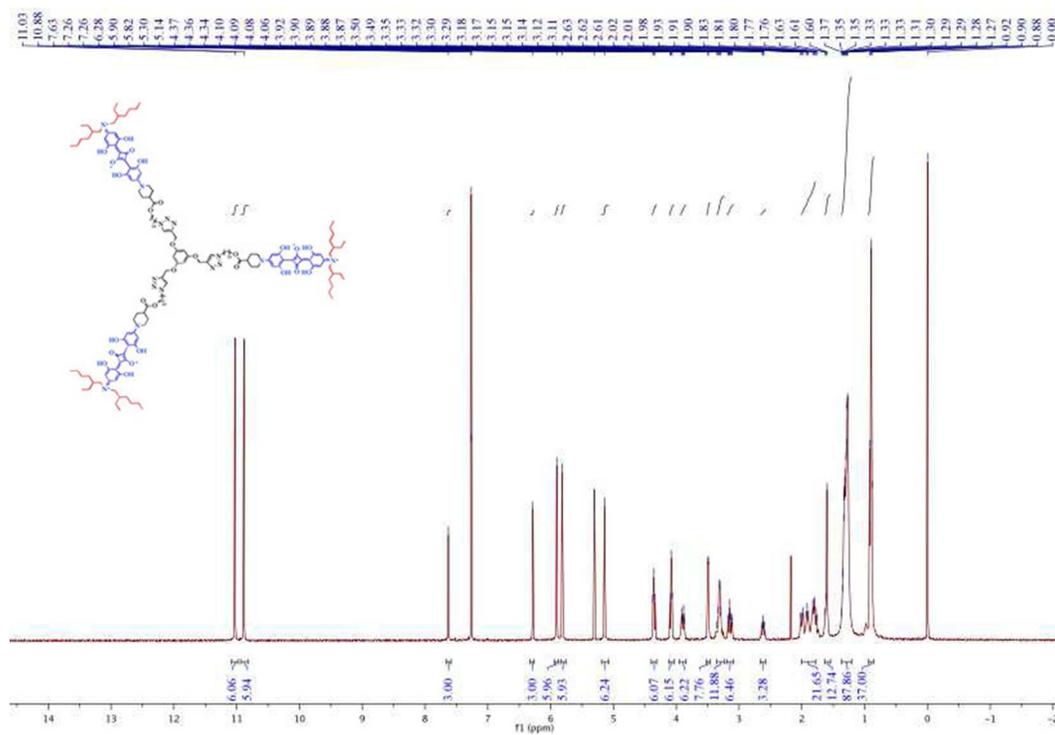
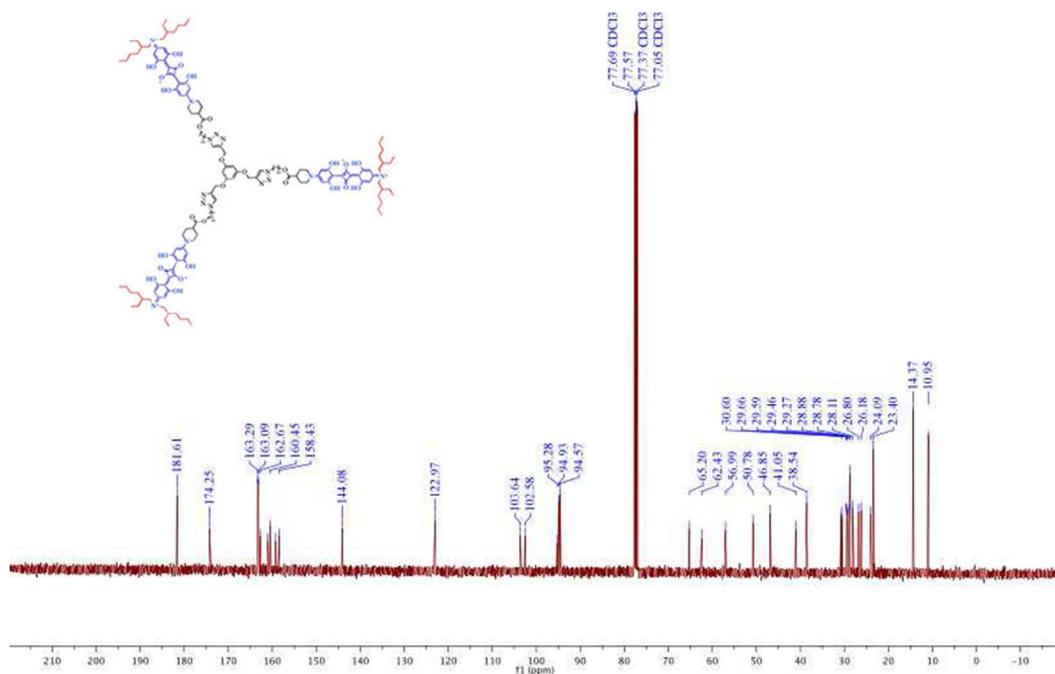


Fig. S11. ^{13}C NMR spectra of star-shaped squaraine dye **1**



4. References

1. Klein, S. I.; Molino, B. F.; Czekaj, M.; Gardner, C. J.; Chu, V.; Brown, K.; Sabatino, R. D.; Bostwick, J. S.; Kasiewski, C.; Bentley, R.; Windisch, V.; et al. Design of a New Class of Orally Active Fibrinogen Receptor Antagonists *J. Med. Chem.* **1998**, *41*, 2492-2502.
2. Zlatoidsky, P.; Maliar, T., Synthesis and Structure-Activity Relationship Study of the New Set of Trypsin-Like Proteinase Inhibitors *Eur. J. Med. Chem.* **1999**, *34*, 1023-1034.
3. Mallard-Favier, I.; Blach, P.; Cazier, F.; Delattre, F., Efficient Synthesis of a Fluorescent Tripod Detection System for Pesticides by Microwave-Assisted Click Chemistry. *Carbohydr. Res.* **2009**, *344*, 161-166.
4. Elshan, N. G. R. D.; Jayasundera, T.; Anglin, B. L.; Weber, C. S.; Lynch, R. M.; Mash, E. A., Trigonal Scaffolds for Multivalent Targeting of Melanocortin Receptors. *Org. Biomol. Chem.* **2015**, *13*, 1778-1791.