

Supporting Information

Synthesis of Heterocyclic-Fused Benzopyrans via the Pd(II)-Catalyzed C–H Alkenylation/C–O Cyclization of Flavones and Coumarins

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Korea

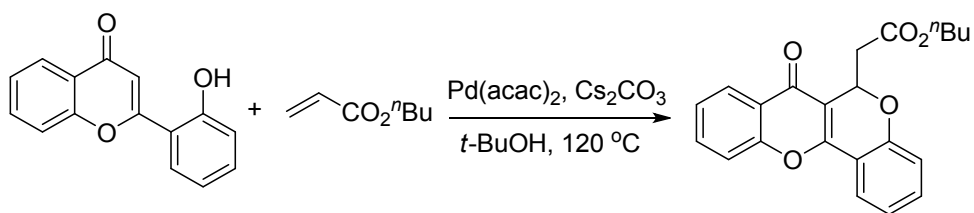
I. Optimization Study

Appendix I

Spectral Copies of ¹H- and ¹³C-NMR Data Obtained in this Study

I. Optimization Study

Table S1. Oxidant screening.^a

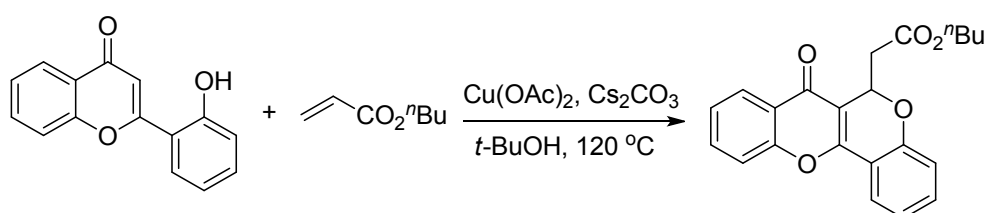


Entry	Oxidant (equiv)	Time	Yield (%)
1	AgOAc (2)	3h	-
2	$\text{Cu}(\text{OAc})_2 \cdot \text{H}_2\text{O}$ (3)	3h	53%
3	CuOAc (3)	5h	56%
4	$\text{Cu}(\text{TFA})_2 \cdot n\text{H}_2\text{O}$ (3)	11h	> 10%
5	$\text{Cu}(\text{OTf})_2$ (3)	3h	-
6	$\text{Cu}(\text{OPiv})_2$ (3)	3h	-
7	$\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ (3)	11h	> 10%
8	CuO (3)	11h	> 10%
9	$\text{Cu}(\text{acac})_2$ (3)	11h	> 10%
10	$\text{K}_2\text{S}_2\text{O}_8$ (3)	19h	trace
11	$\text{Ce}(\text{SO}_4)_2$ (3)	19h	trace
12	$\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ (2)	6h	38%
13	$\text{PhI}(\text{OAc})_2$ (2)	3h	-
14	CAN (2)	19h	trace
15	Oxone (2)	19h	12%
16	FeCl_3 (3)	3h	-
17	DDQ (2)	3h	-
18	TEMPO (2)	3h	-
19	PhCO_3tBu (2)	3h	12%
20	MnO_2 (2)	7h	11%
21	MnCl_2 (3)	7h	13%
22	CuF_2 (3)	11h	10%

23	CuCl ₂ (3)	3h	trace
24	CuBr ₂ (3)	24h	31%
25	CuCl (3)	24h	17%
26	CuBr (3)	11h	21%
27	CuI (3)	24h	20%

[a] Reactions were conducted with flavone, butyl acrylate (2 equiv), Pd catalyst (0.2 equiv), oxidant, and base (2 equiv) in *t*-BuOH at 120 °C.

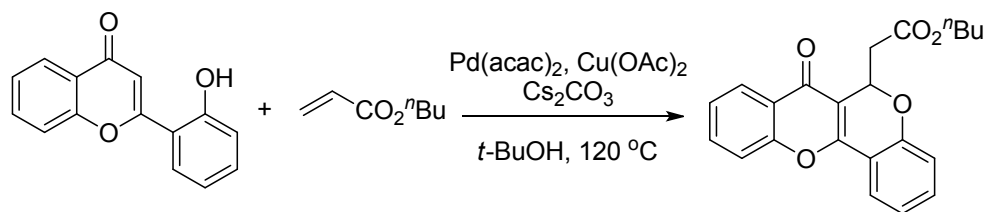
Table S2. Pd screening.^a



Entry	Oxidant (equiv)	Time	Yield (%) ^b
1	Pd(TFA) ₂ (0.2)	3h	42%
2	Pd(OPiv) ₂ (0.2)	3h	53%
3	Pd(acac) ₂ (0.2)	3h	60%
4	Pd(SO ₄) ₂ (0.2)	3h	39%
5	Pd(NO ₃) ₂ ·nH ₂ O (0.2)	3h	32%
6	PdCl ₂ (TMEDA) ₂ (0.2)	3h	-
7	Pd(HFac) ₂ (0.2)	3h	48%
8	Pd(MeCN) ₄ (BF ₄) ₂ (0.2)	3h	48%
9	PdCl ₂ (0.2)	2.5h	15%
10	Pd ₂ (dba) ₃ (0.1)	2.5h	30%
11	PdCl ₂ (PPh ₃) ₂ (0.1)	2.5h	35%
12	Pd(dppf)Cl ₂ (0.1)	6h	59%
13	Pd(PPh ₃) ₄ (0.1)	2.5h	45%

[a] Reactions were conducted with flavone, butyl acrylate (2 equiv), Pd catalyst, oxidant (3 equiv), and base (2 equiv) in *t*-BuOH at 120 °C.

Table S3. Additive screening.^a



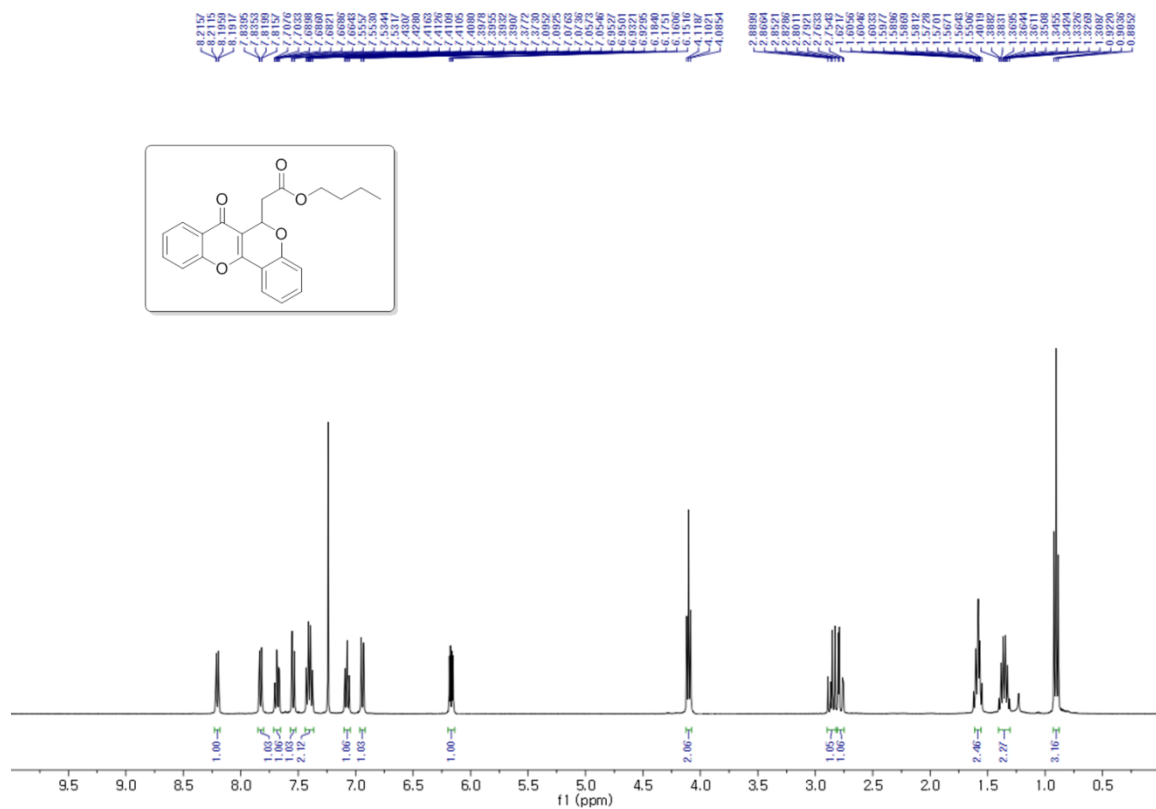
Entry	Additive (0.2 equiv)	Yield (%) ^b
1	Al ₂ O ₃	74%
2	V ₂ O ₅	57%
3	ZnBr ₂	56%
4	Co(OAc) ₂	56%
5	MnO ₂	60%
6	Mn(OAc) ₂ ·3H ₂ O	64%
7	LiOTf	65%
8	KOTf	58%
9	Sm(OTf) ₃	59%
10	In(OTf) ₃	58%
11	Sn(OTf) ₂	63%
12	4A MS	43%
13	silica gel	50%

[a] Reactions were conducted with flavone, butyl acrylate (2 equiv), Pd catalyst (0.2 equiv), oxidant (3 equiv), additive (0.2 equiv), and base (2 equiv) in *t*-BuOH at 120 °C.

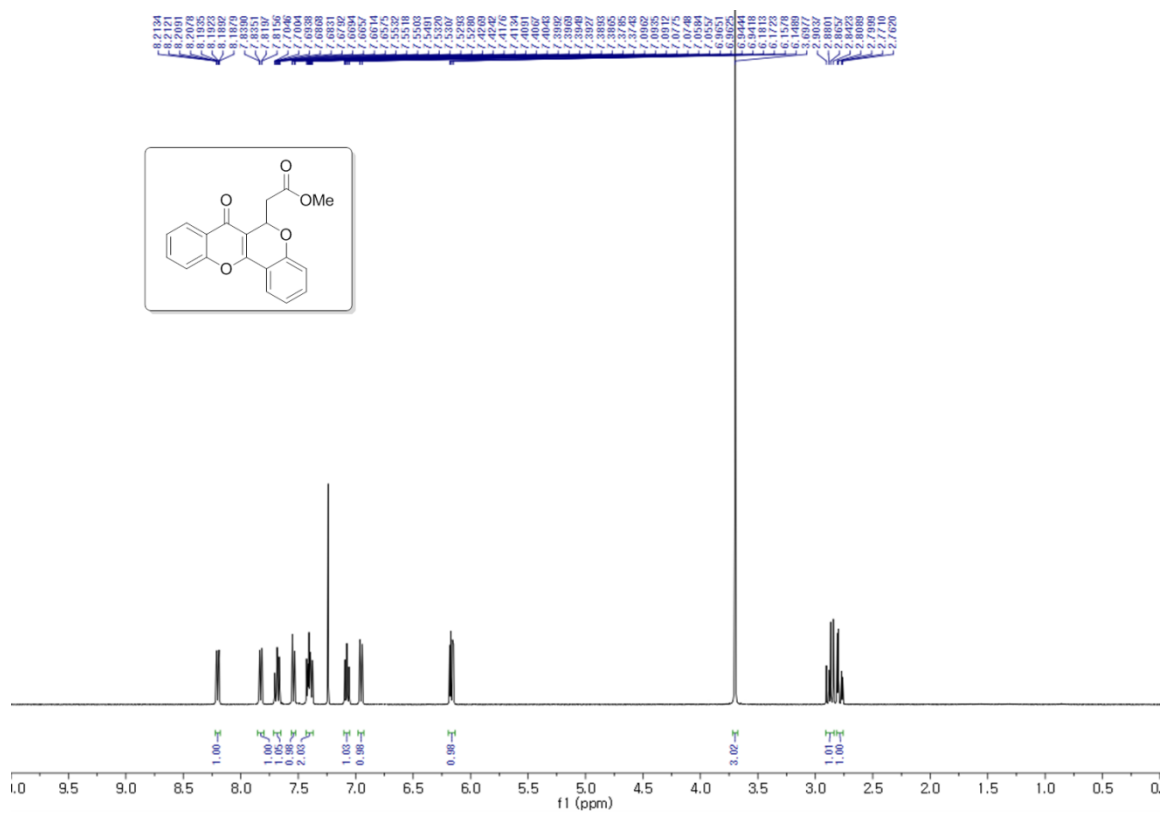
Appendix I

Spectral Copies of ^1H and ^{13}C NMR Data Obtained in this Study

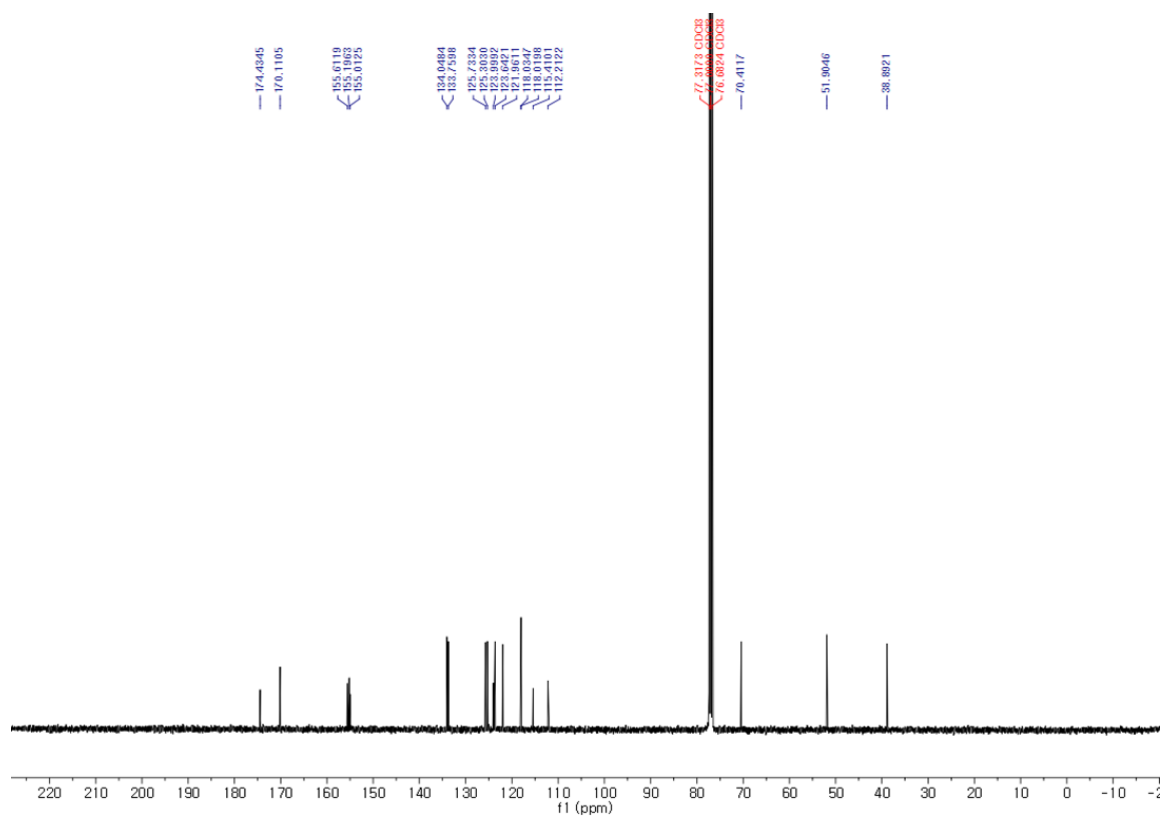
Butyl 2-(7-Oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3a)



Methyl 2-(7-Oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3b)

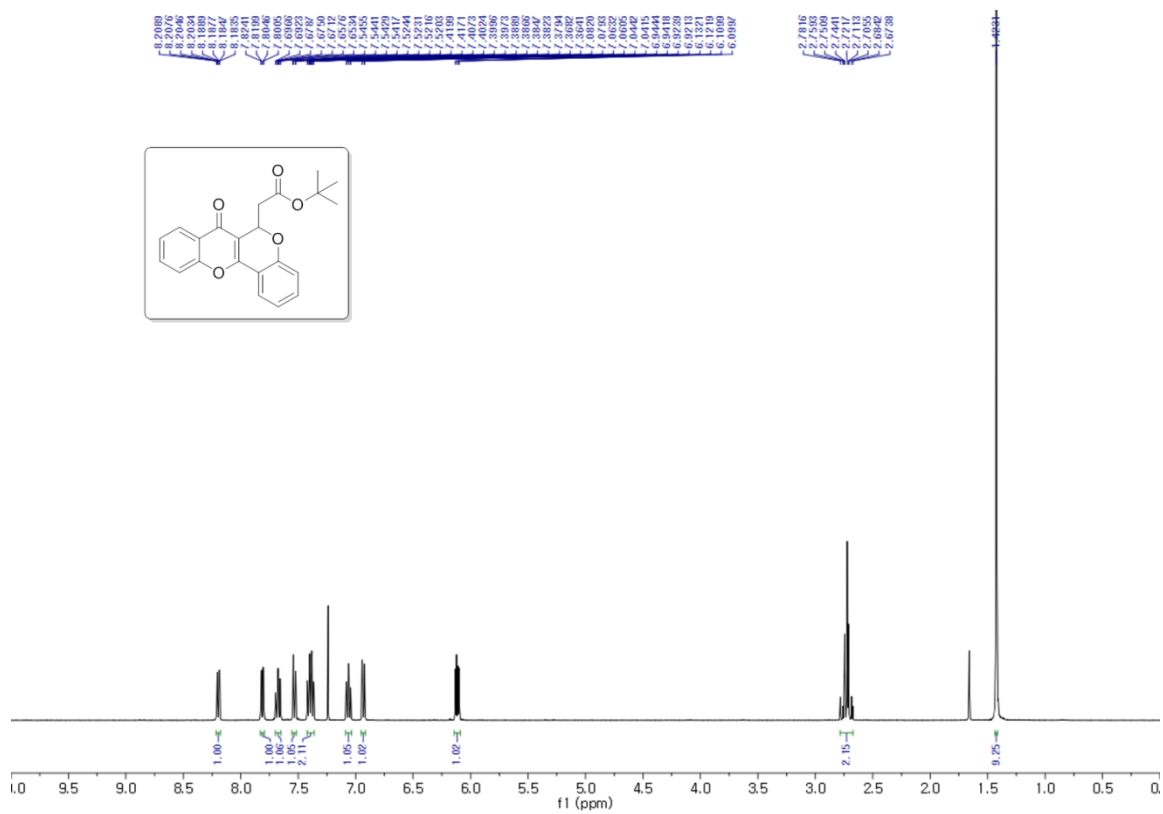


400 MHz, ^1H NMR in CDCl_3

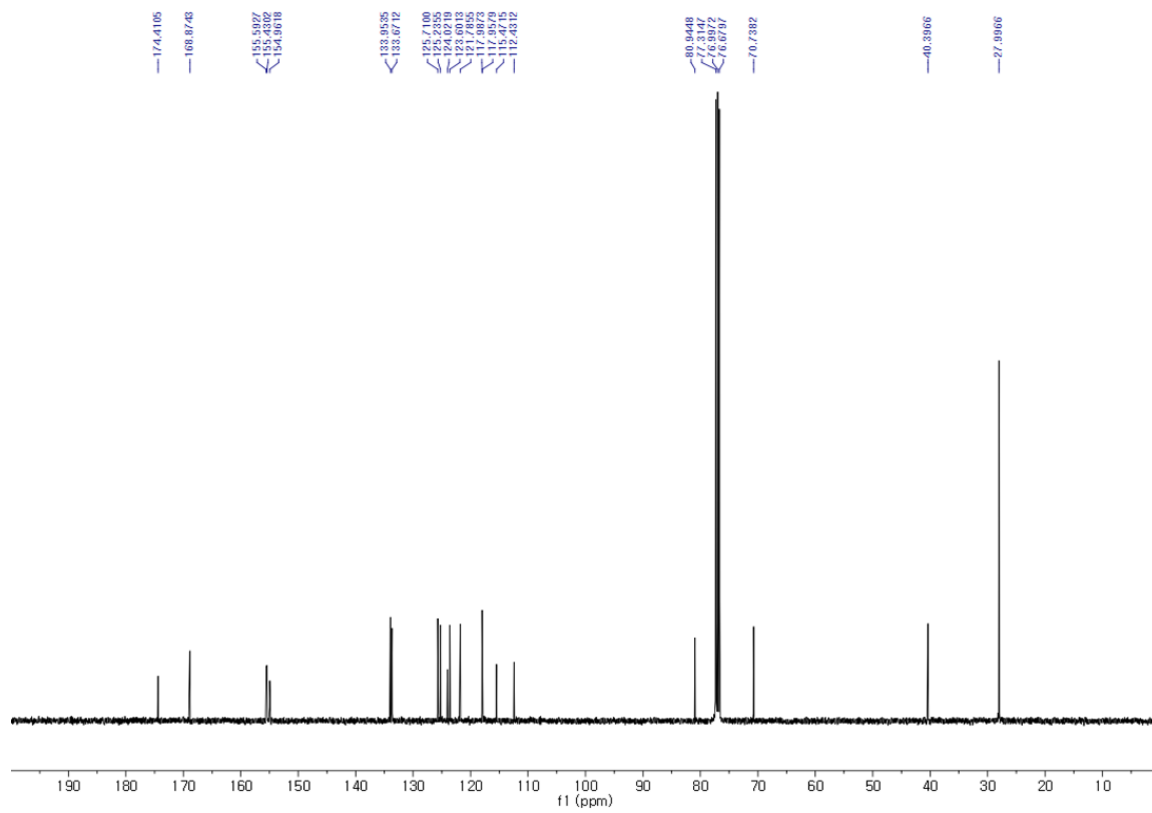


100 MHz, ^{13}C NMR in CDCl_3

tert-Butyl 2-(7-Oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3c)

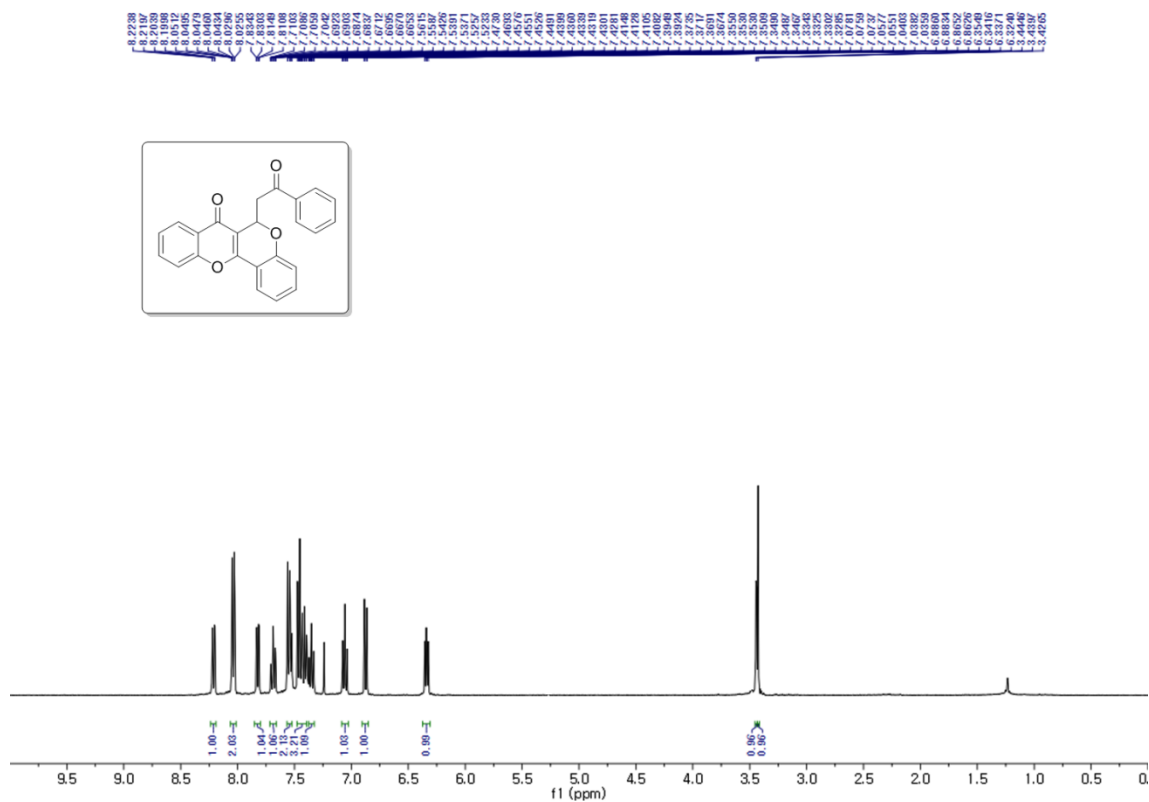


400 MHz, ^1H NMR in CDCl_3

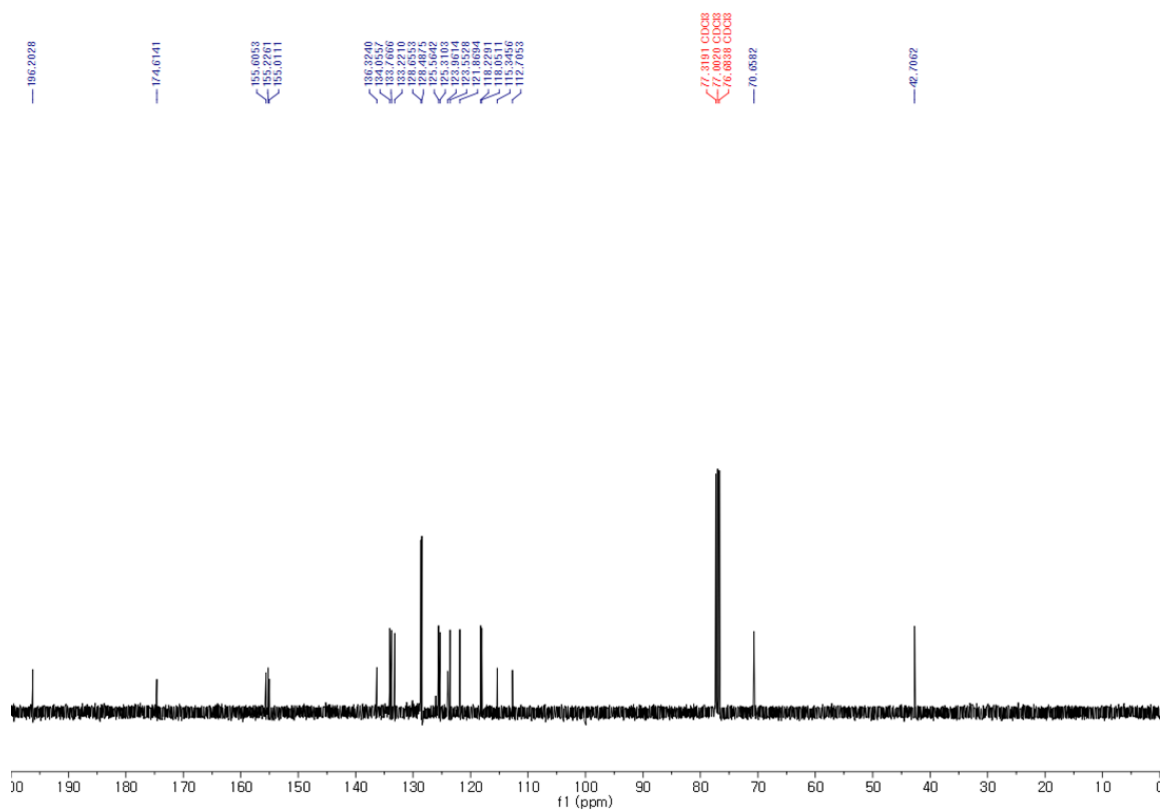


100 MHz, ^{13}C NMR in CDCl_3

6-(2-Oxo-2-phenylethyl)chromeno[4,3-b]chromen-7(6H)-one (3d)

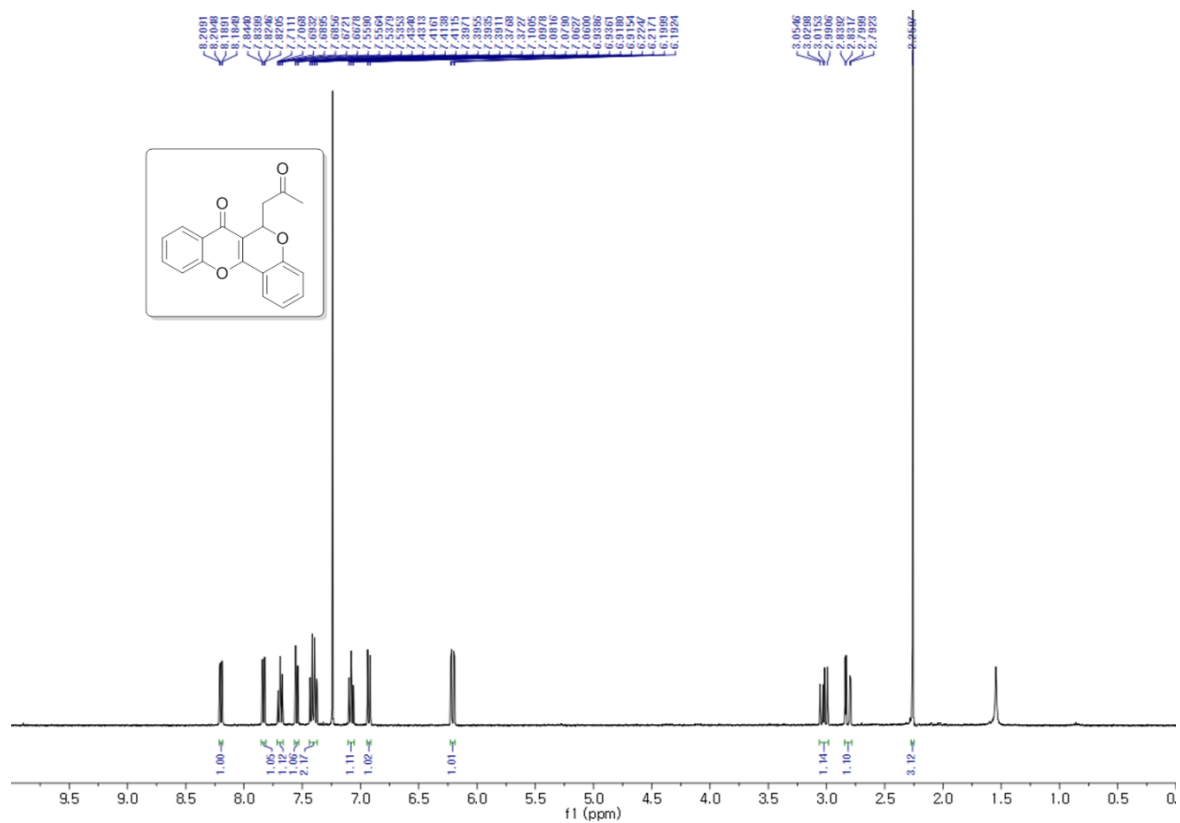


400 MHz, ¹H NMR in CDCl₃

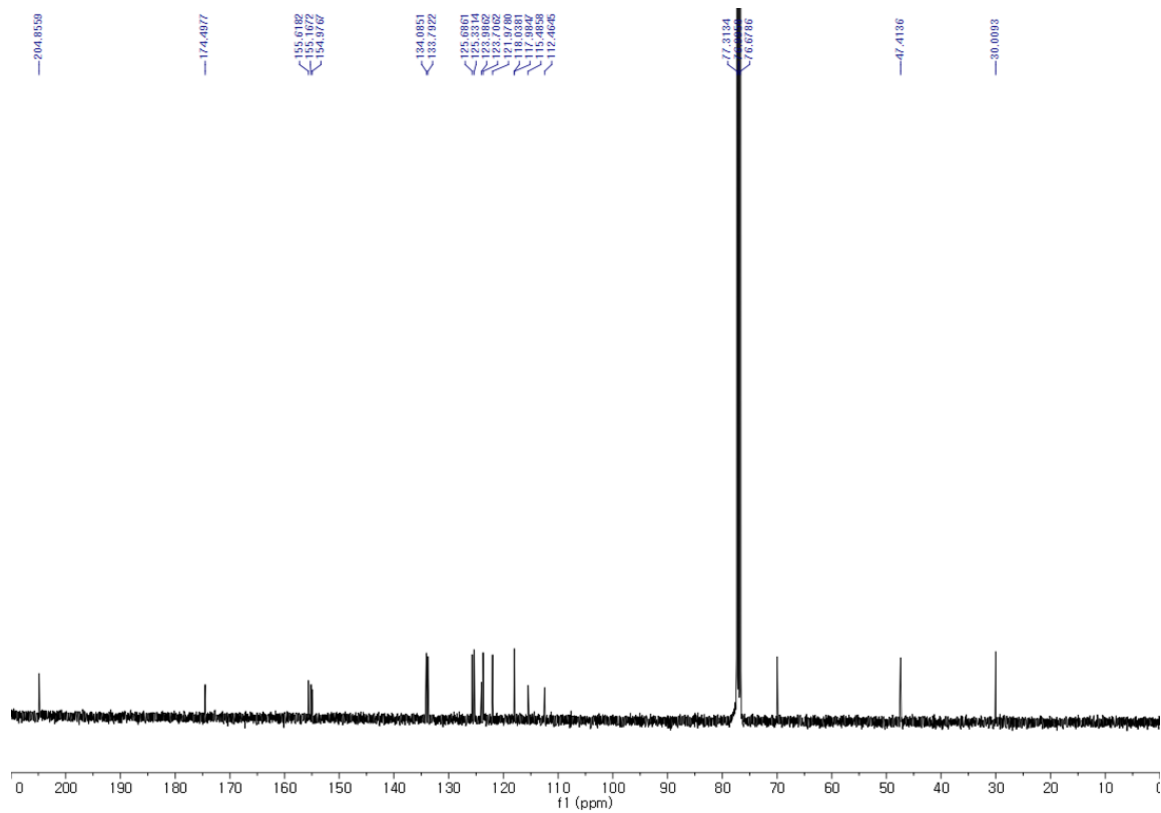


100 MHz, ¹³C NMR in CDCl₃

6-(2-Oxopropyl)chromeno[4,3-b]chromen-7(6H)-one (3e)

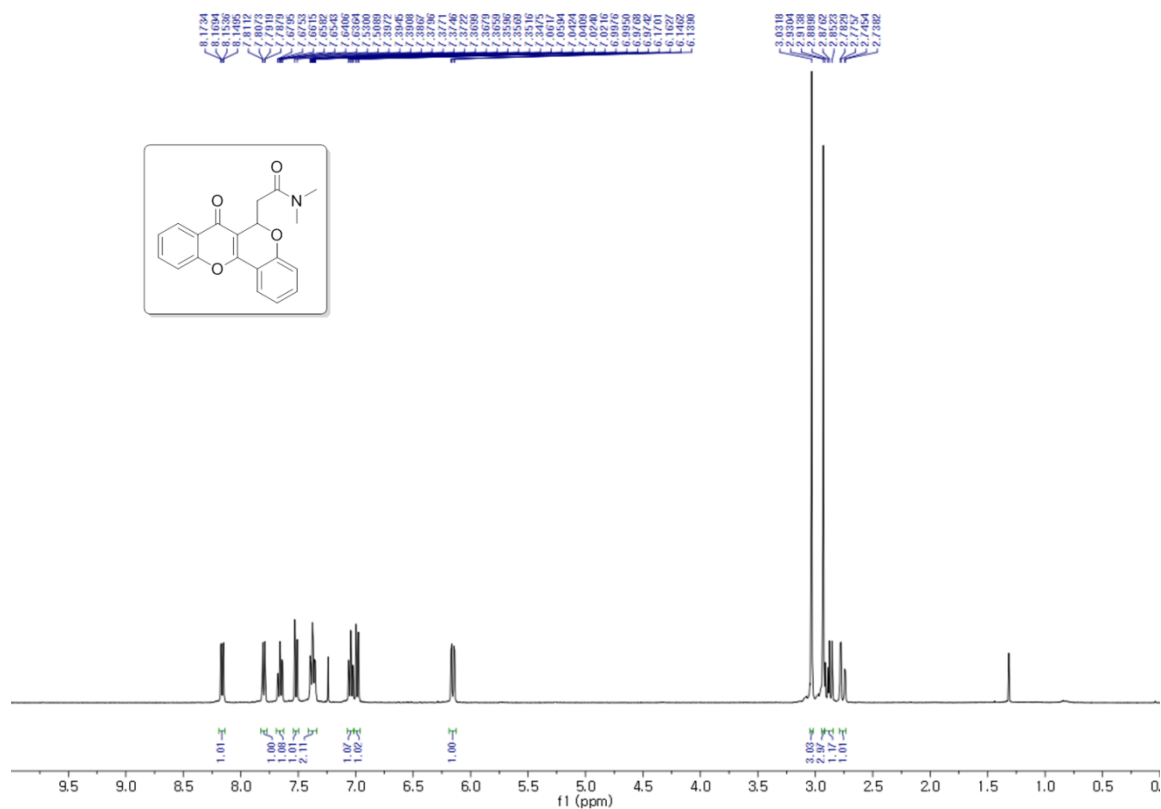


400 MHz, ¹H NMR in CDCl₃

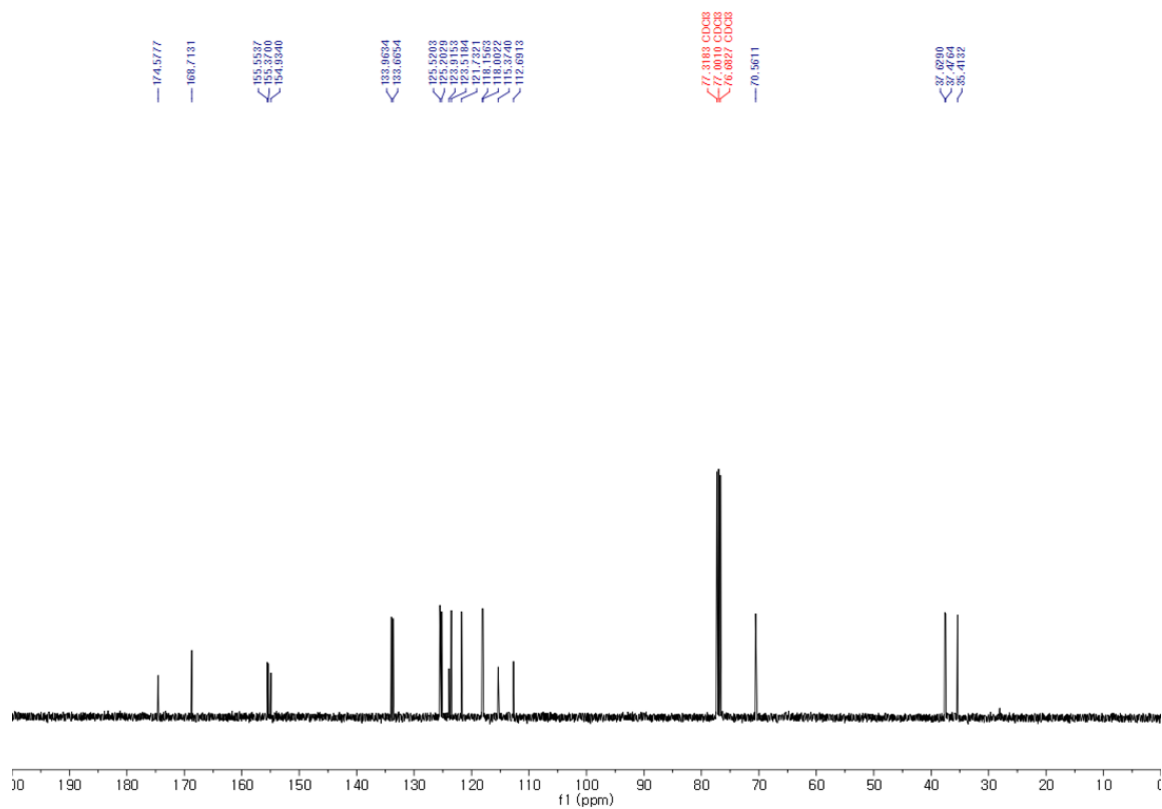


100 MHz, ^{13}C NMR in CDCl_3

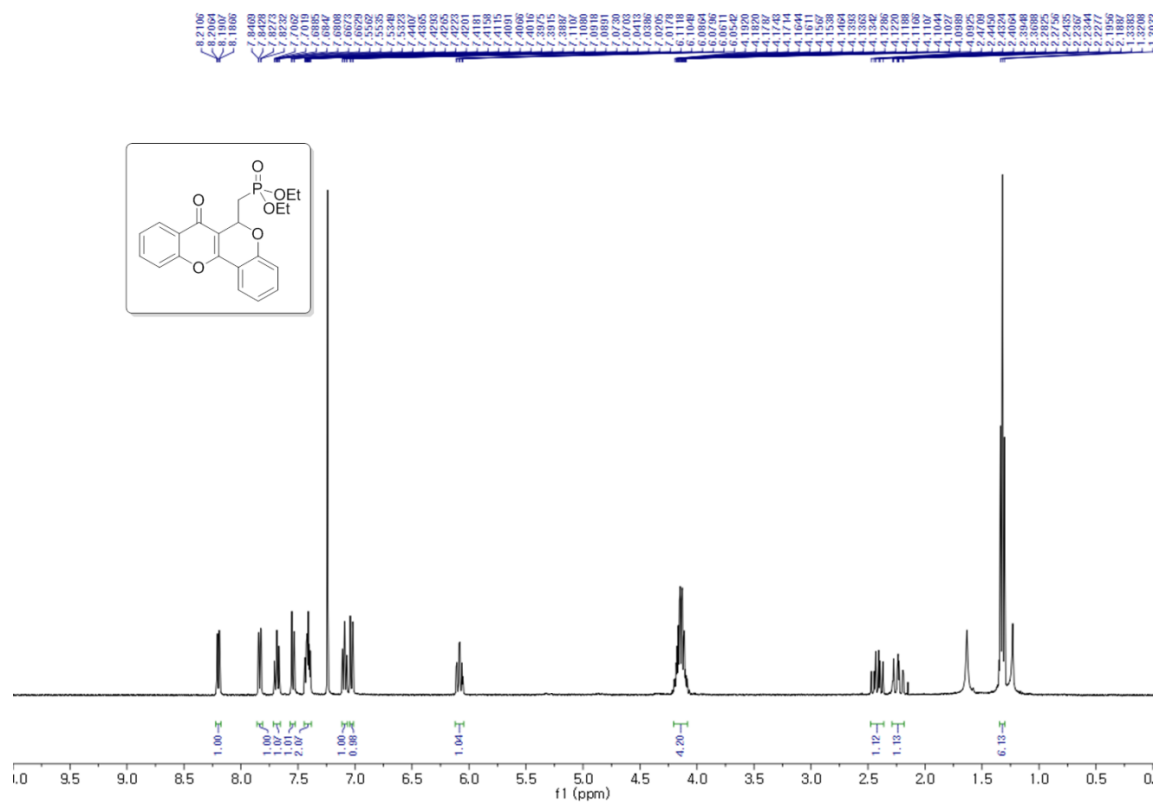
N,N-Dimethyl-2-(7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetamide (3f)



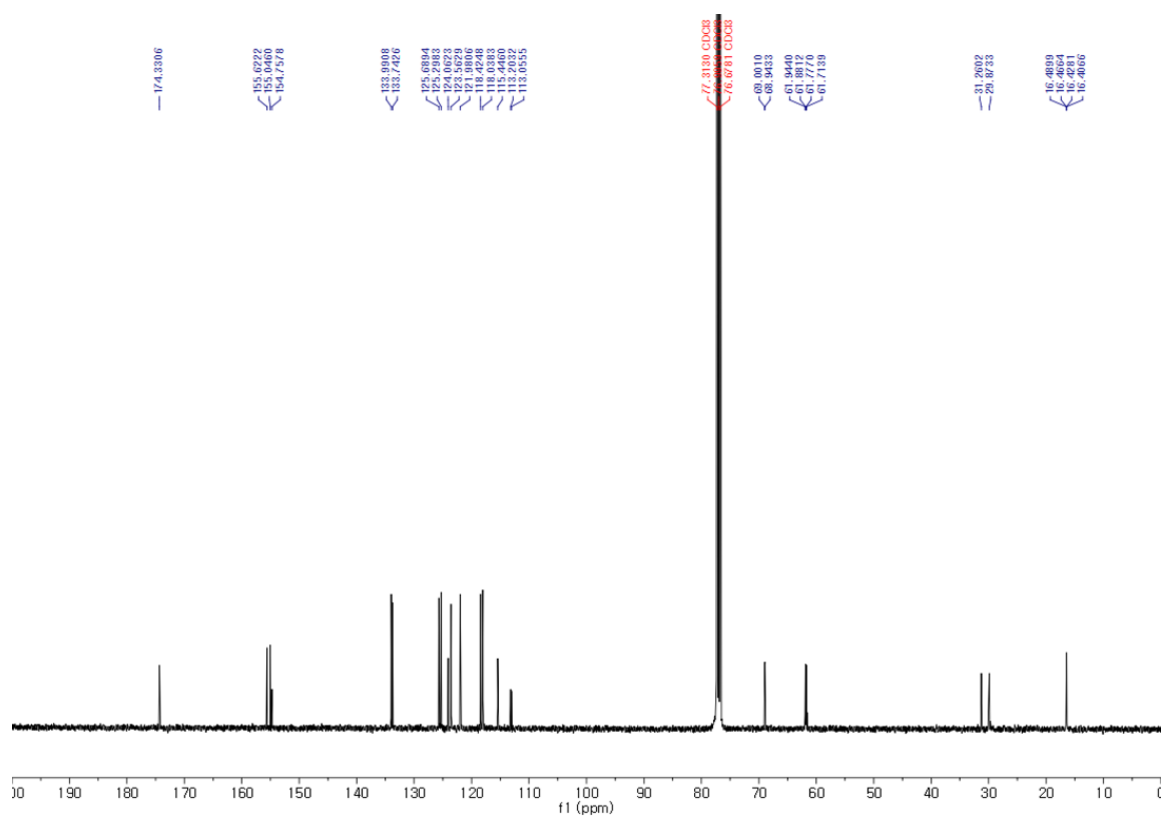
400 MHz, ^1H NMR in CDCl_3



Diethyl ((7-Oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)methyl)phosphonate (3g)

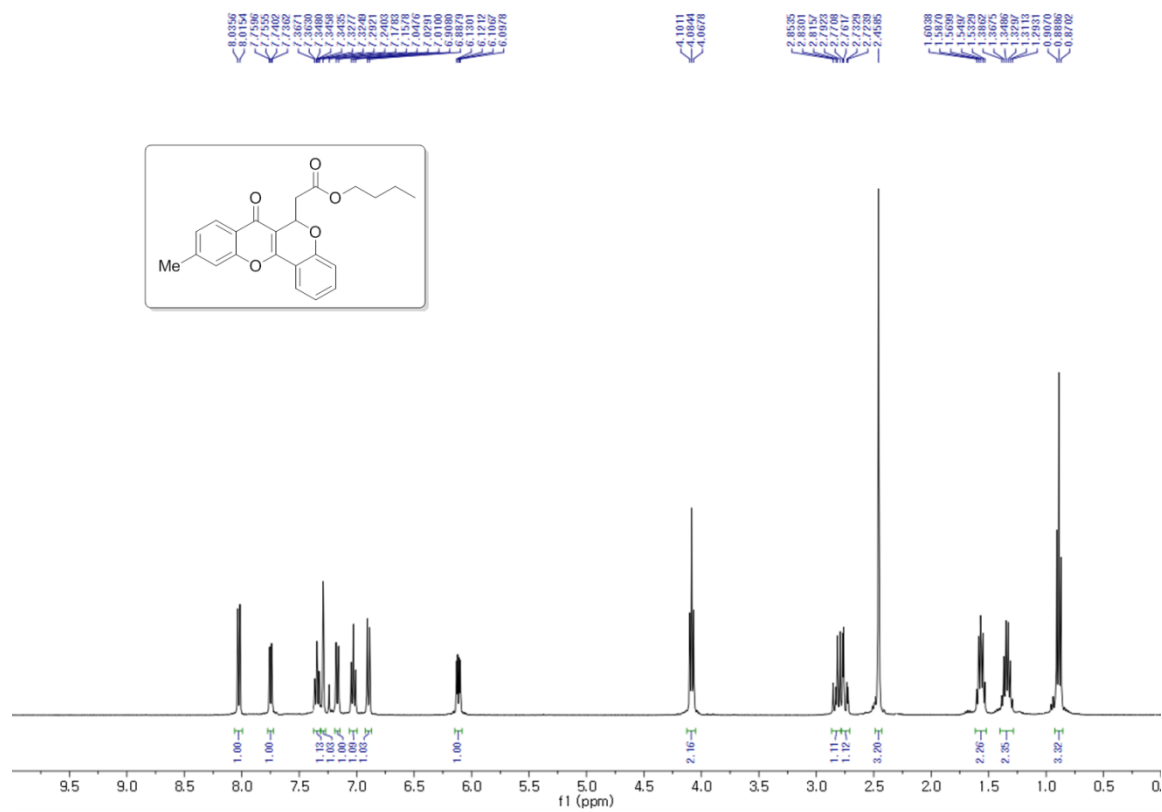


400 MHz, ^1H NMR in CDCl_3

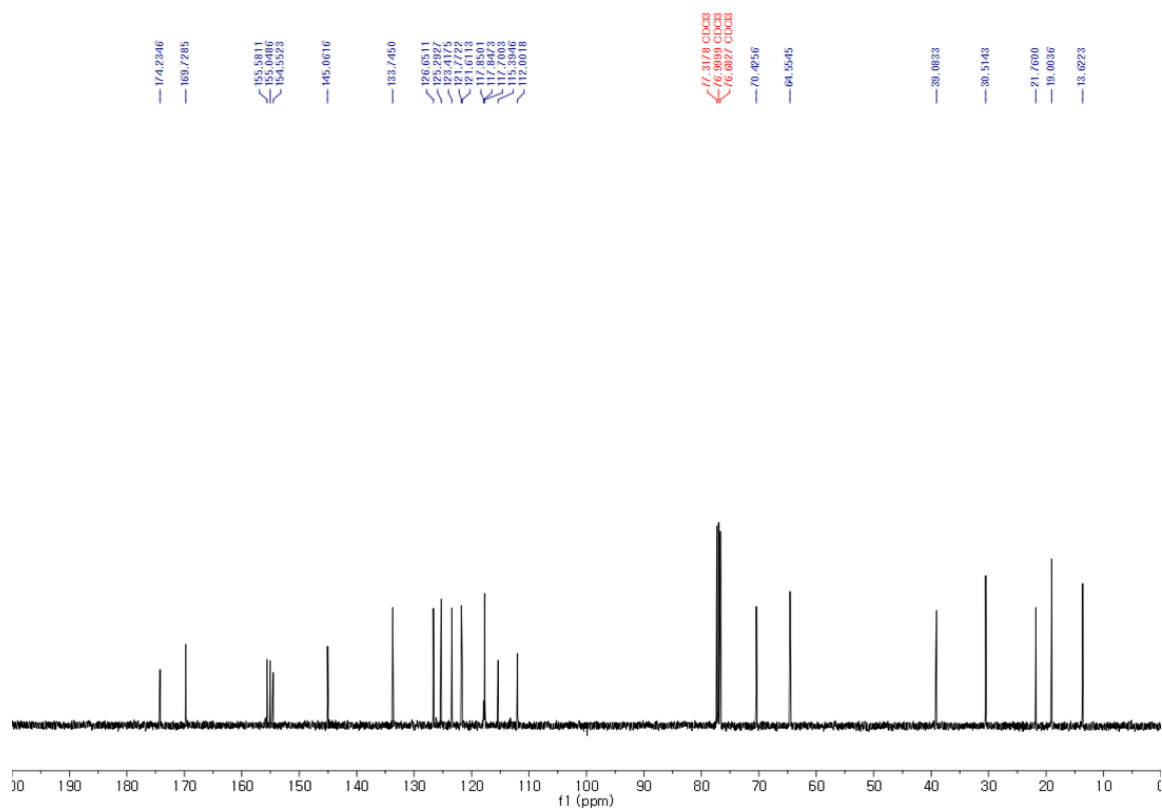


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(10-Methyl-7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3h)

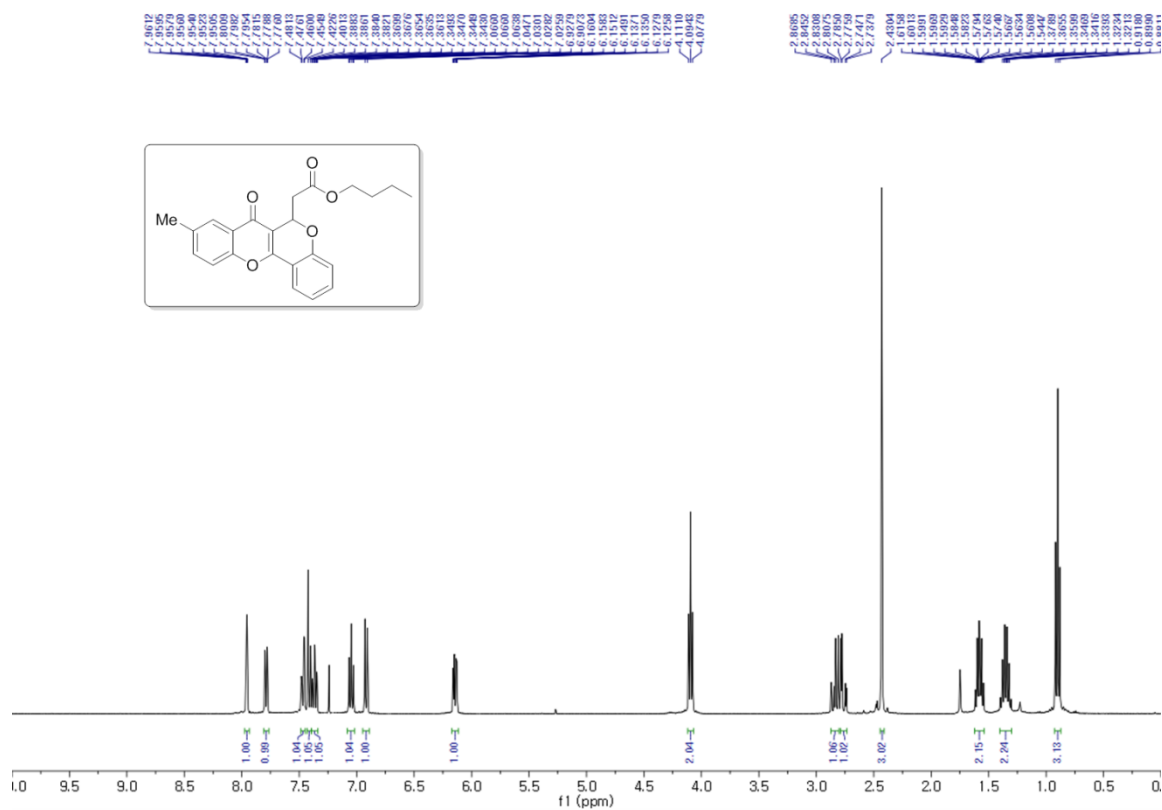


400 MHz, ¹H NMR in CDCl₃

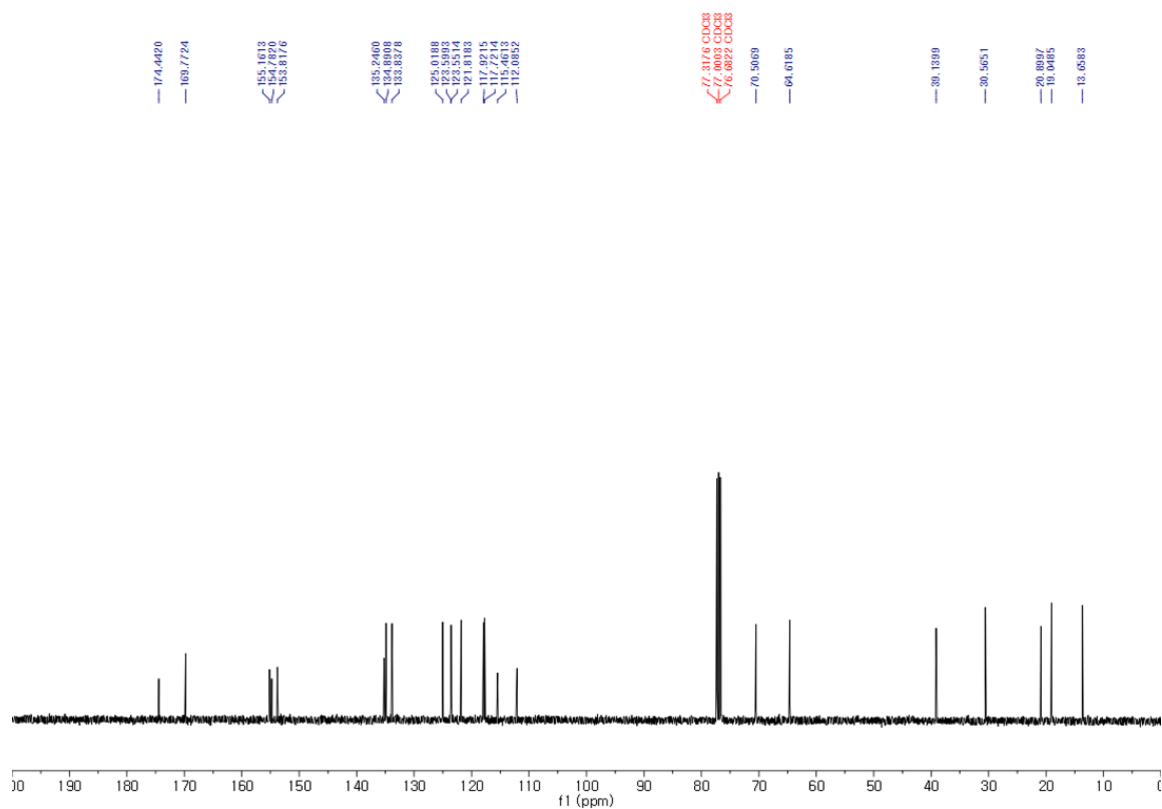


100 MHz, ¹³C NMR in CDCl₃

Butyl 2-(9-Methyl-7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3i)

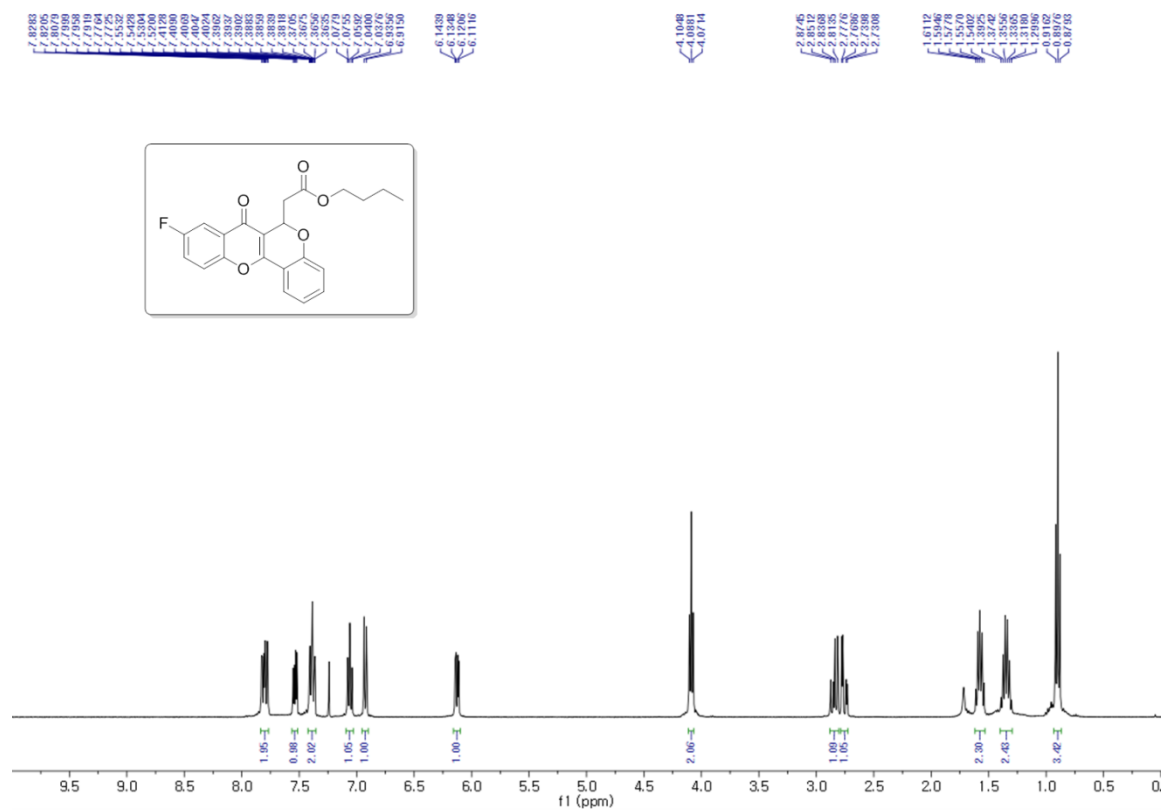


400 MHz, ¹H NMR in CDCl₃

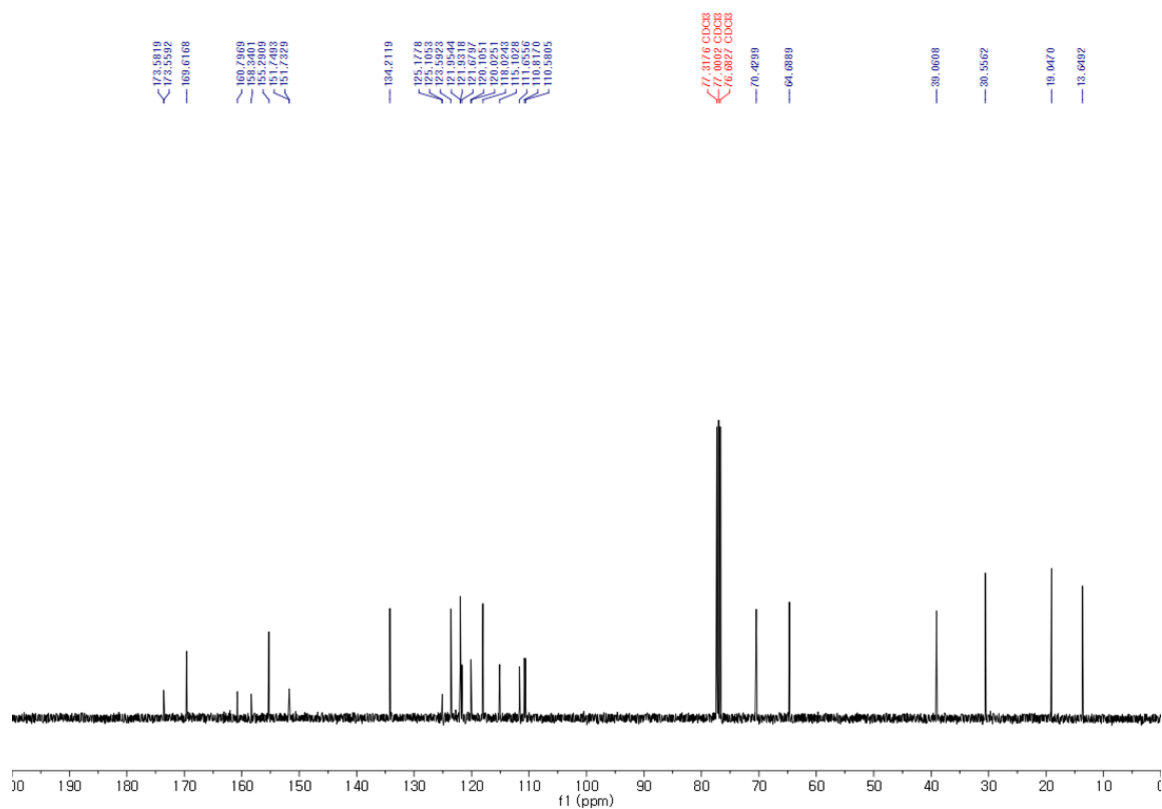


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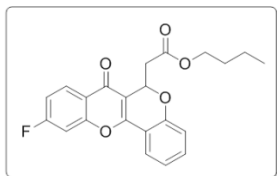
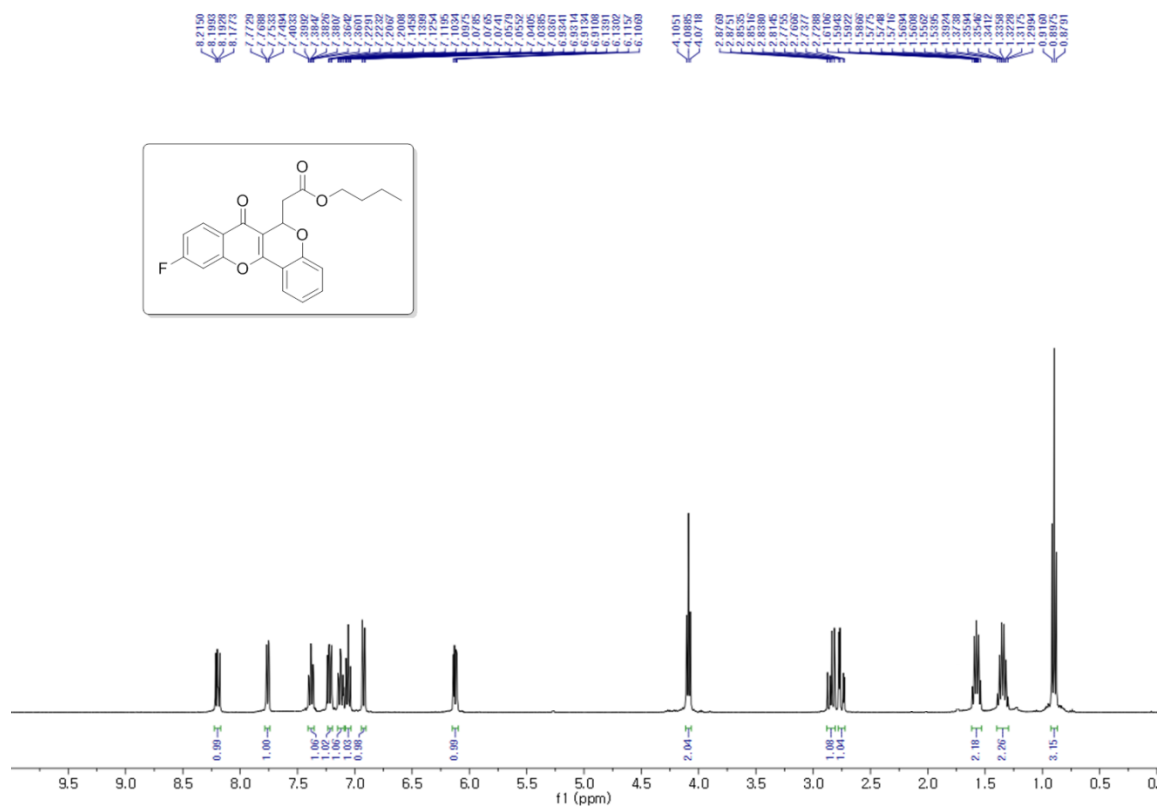


400 MHz, ¹H NMR in CDCl₃

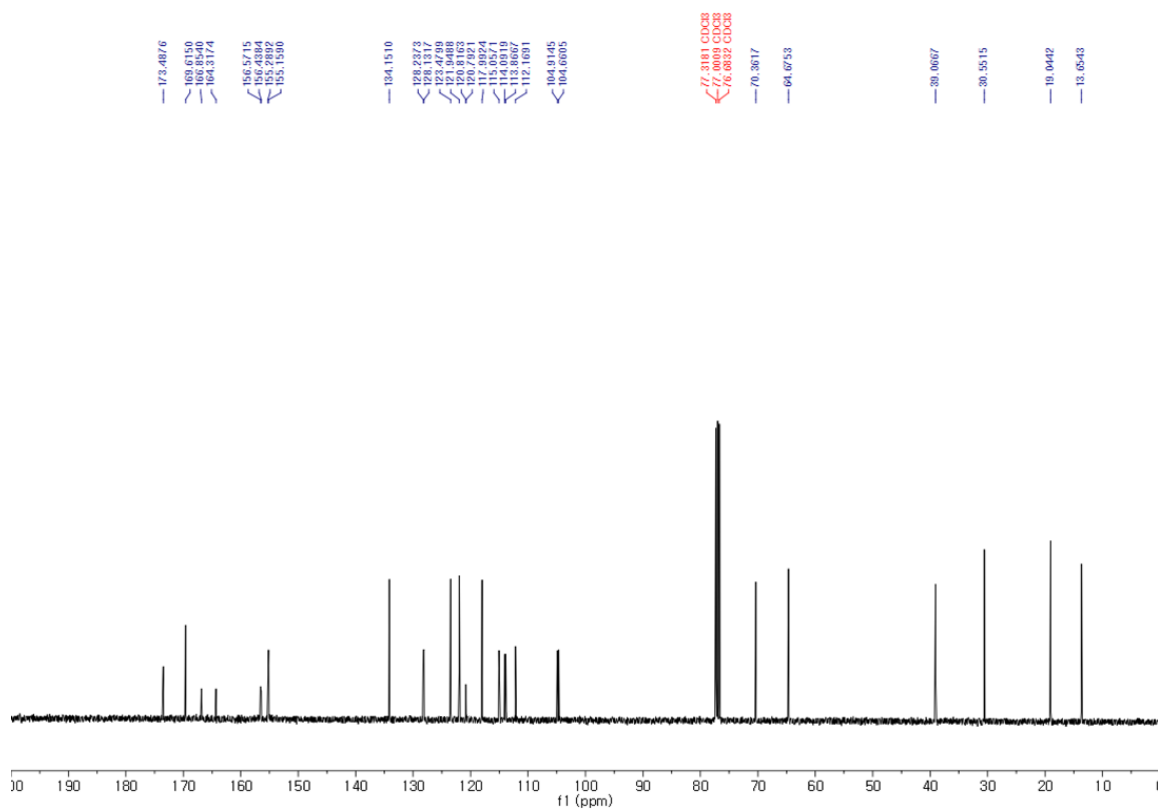


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Butyl 2-(10-Fluoro-7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3k)

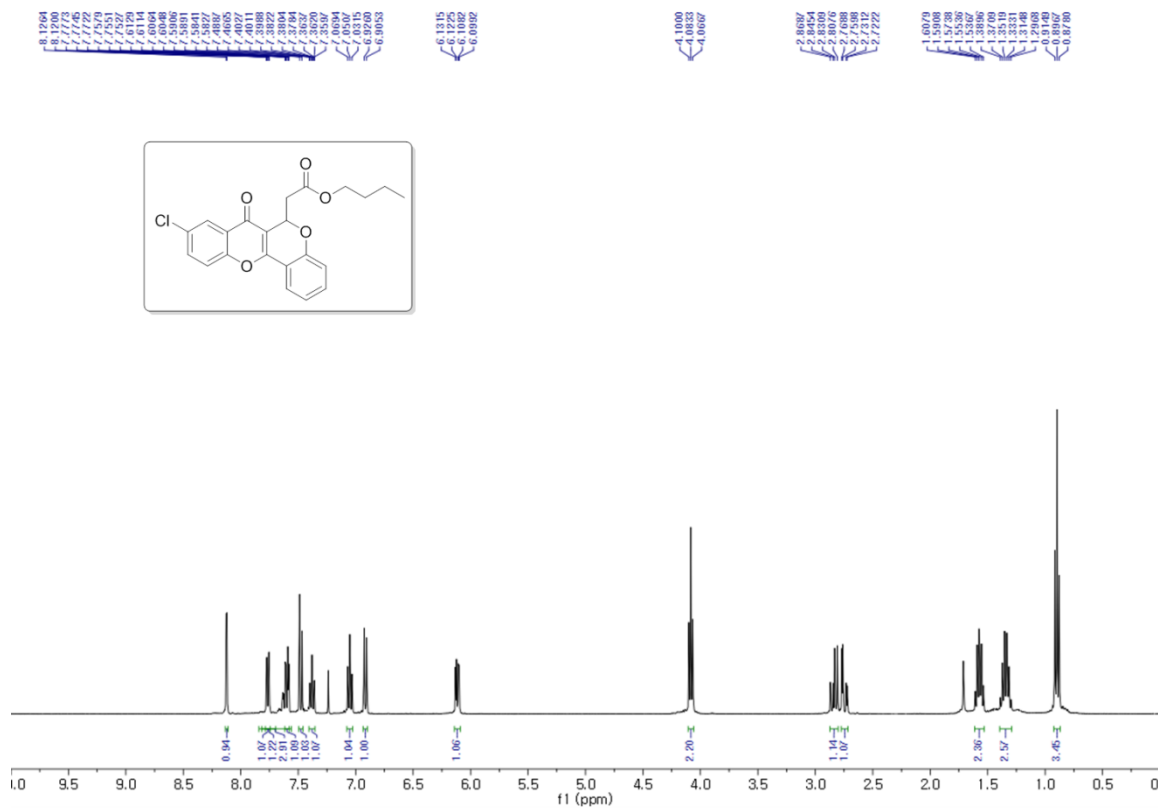


400 MHz, ^1H NMR in CDCl_3

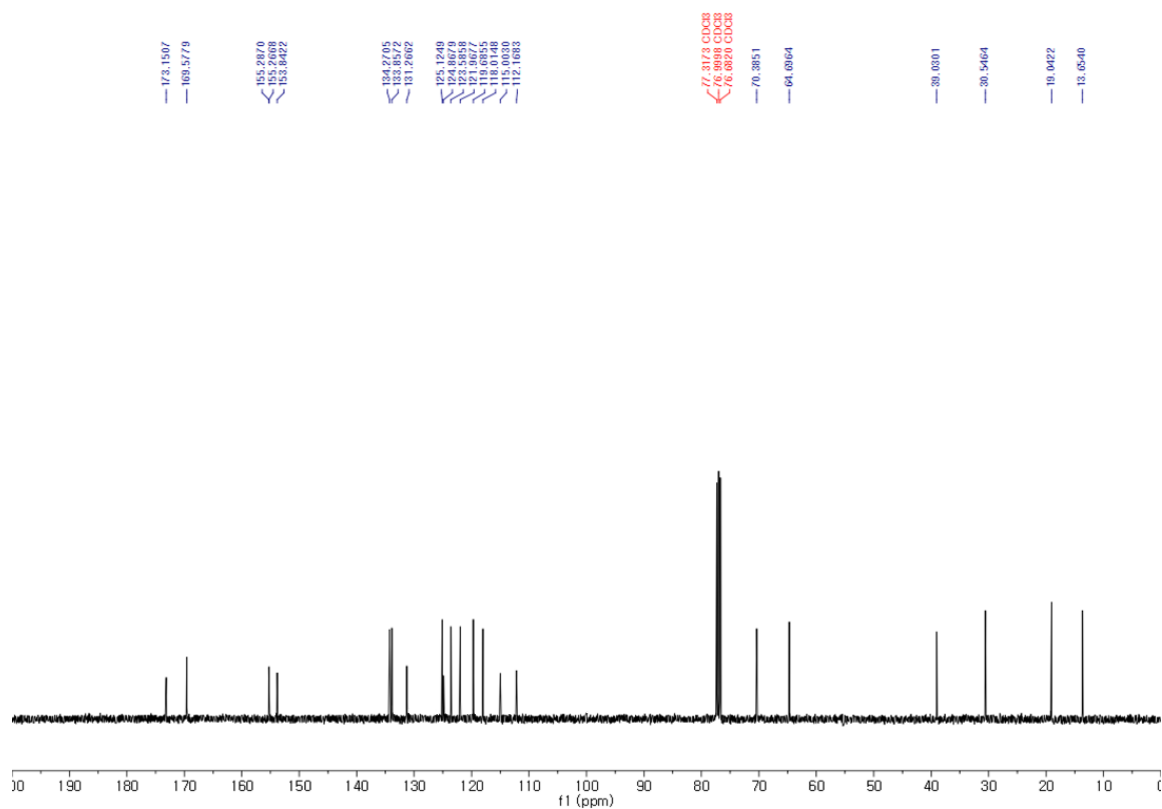


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(9-Chloro-7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3l)

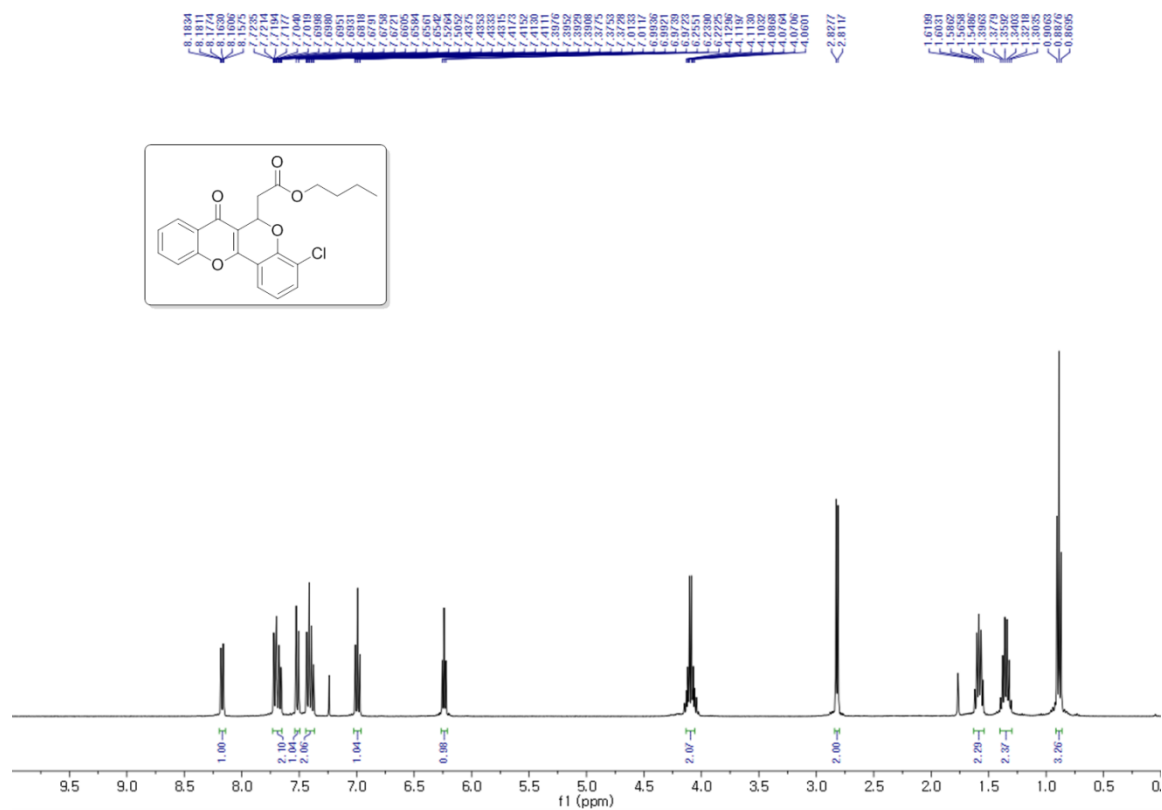


400 MHz, ¹H NMR in CDCl₃

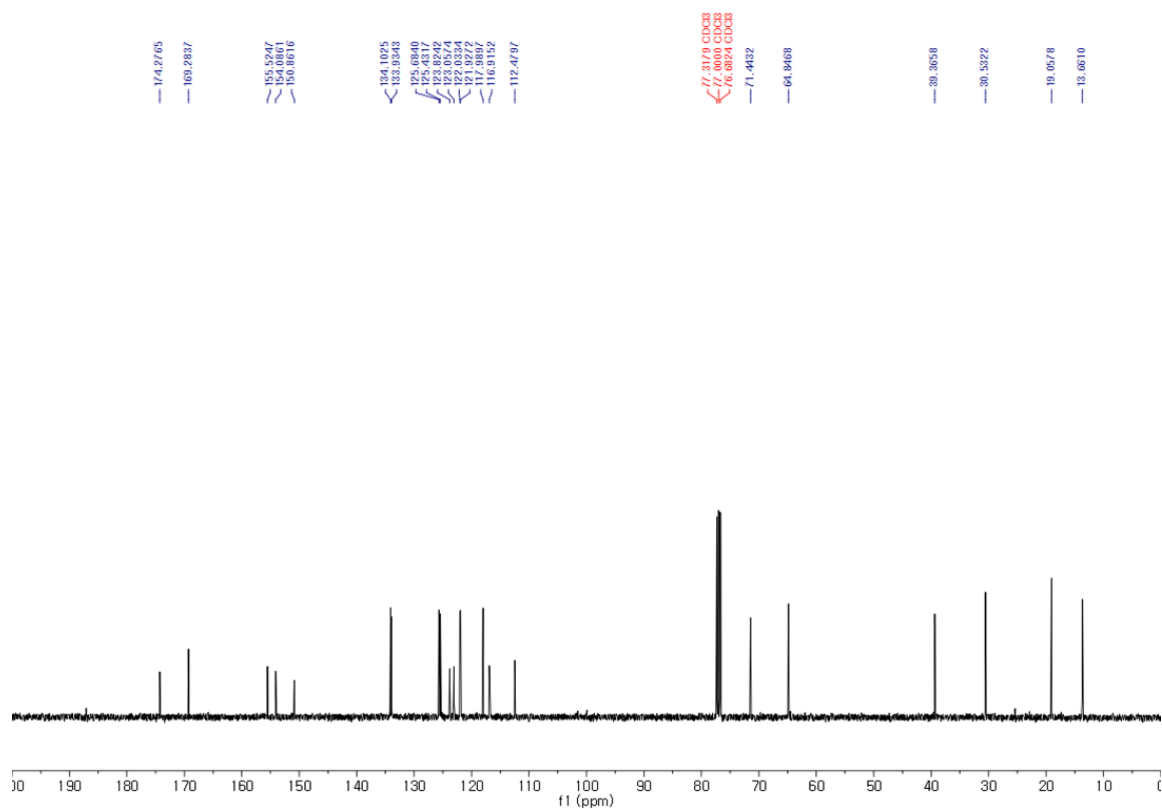


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(4-Chloro-7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3m)

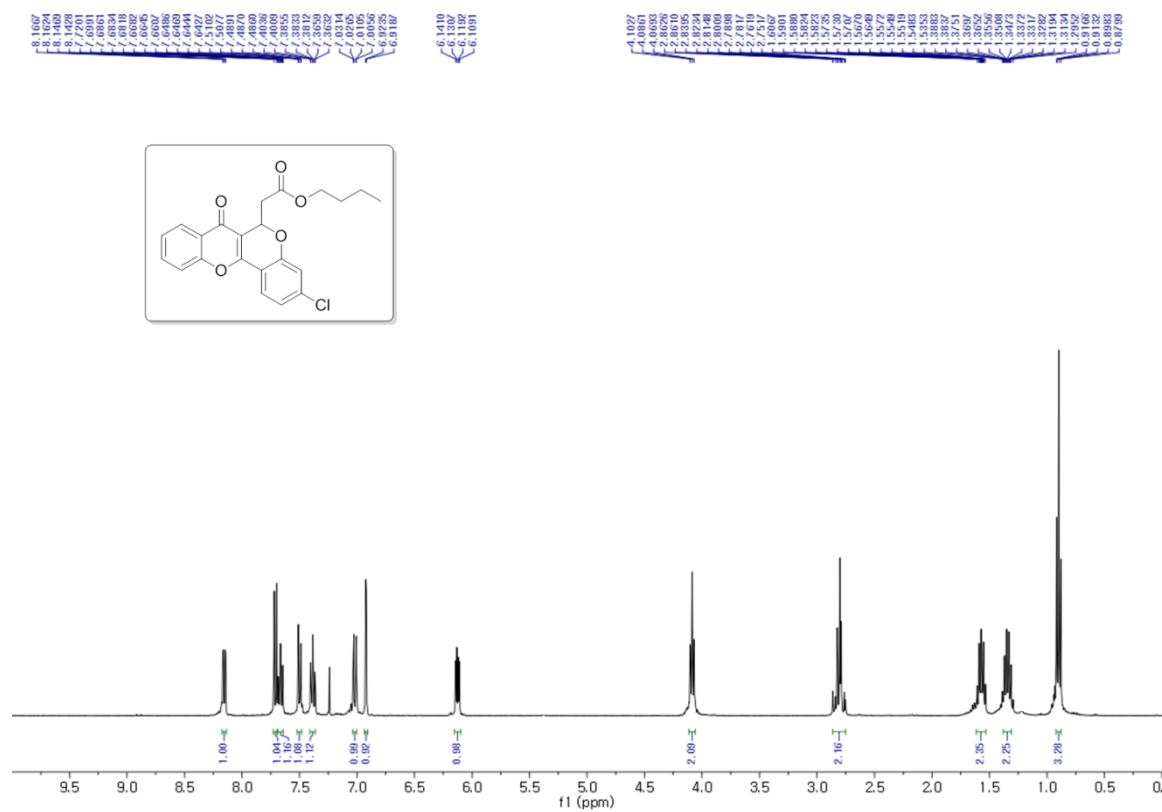


400 MHz, ¹H NMR in CDCl₃

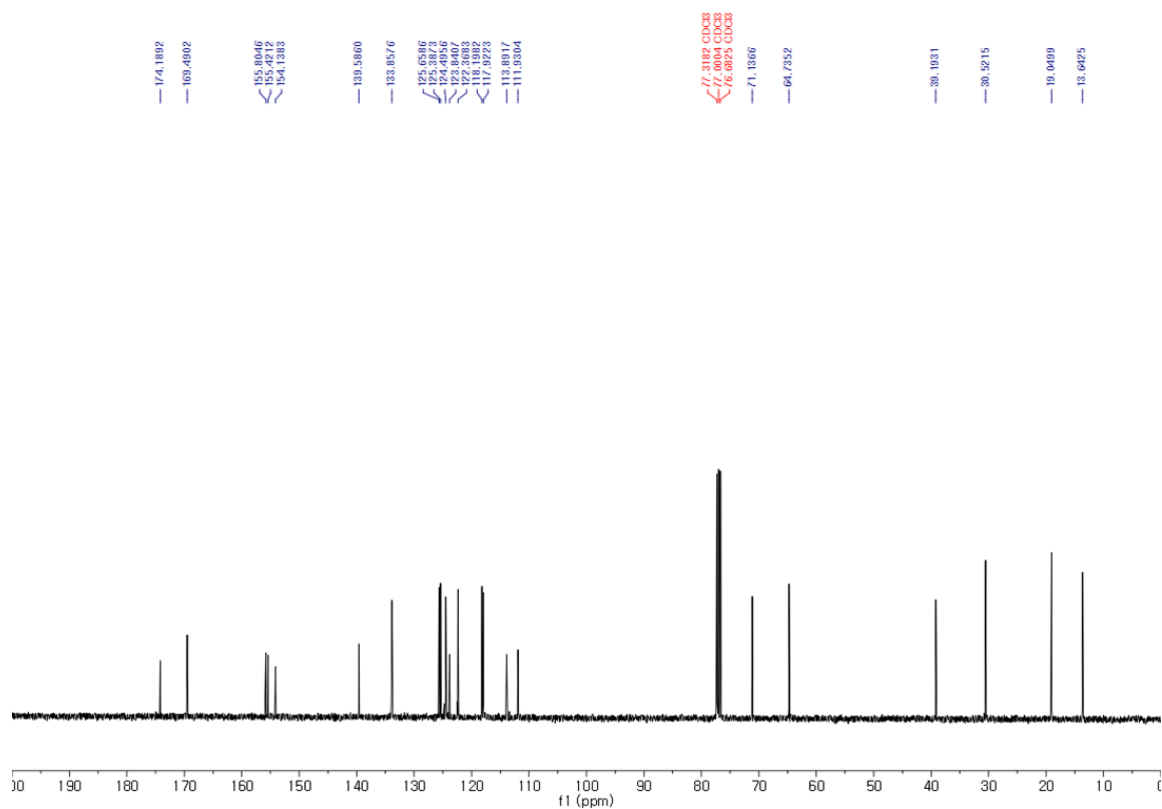


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(3-Chloro-7-oxo-6,7-dihydrochromeno[4,3-b]chromen-6-yl)acetate (3n)

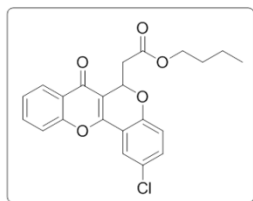
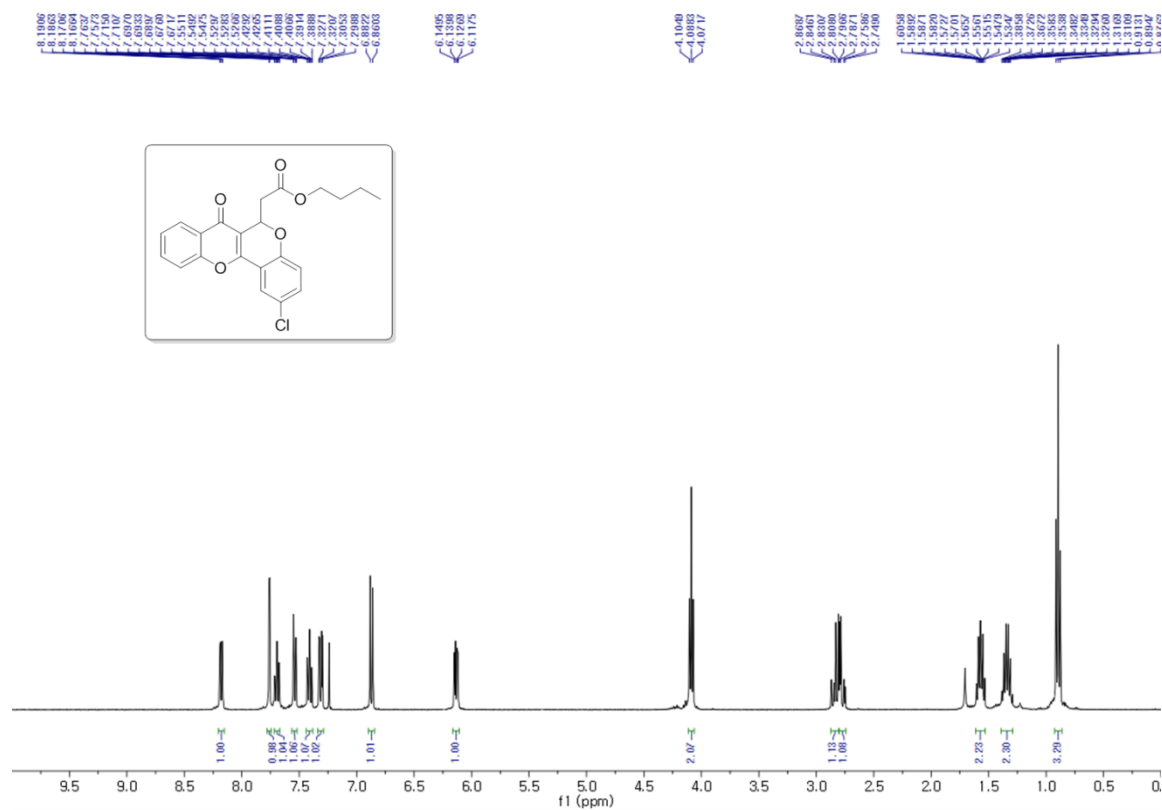


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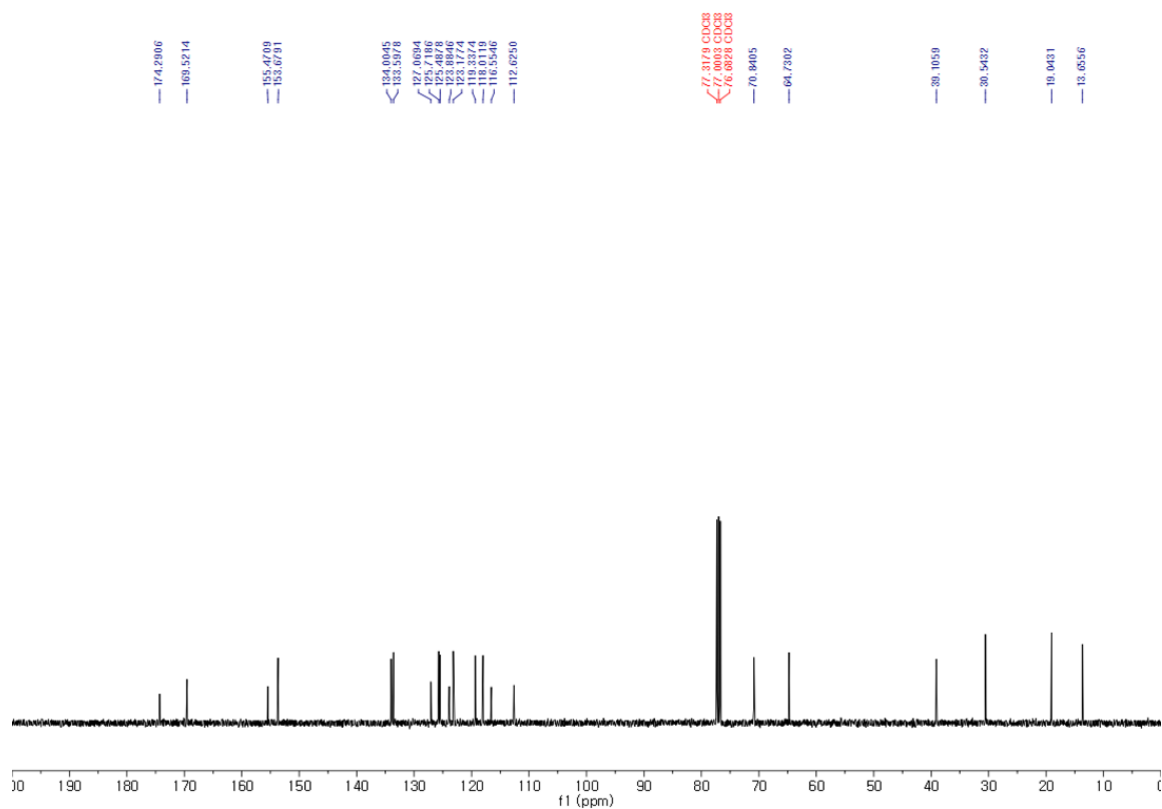


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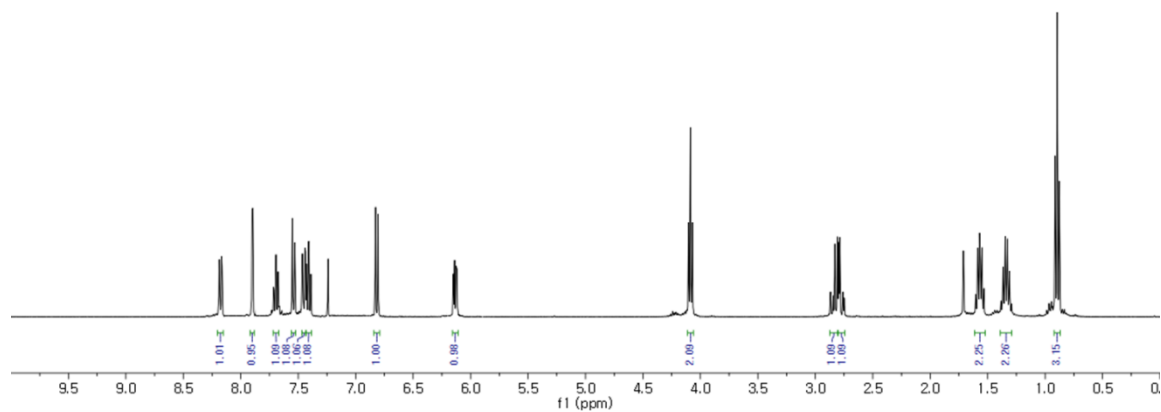
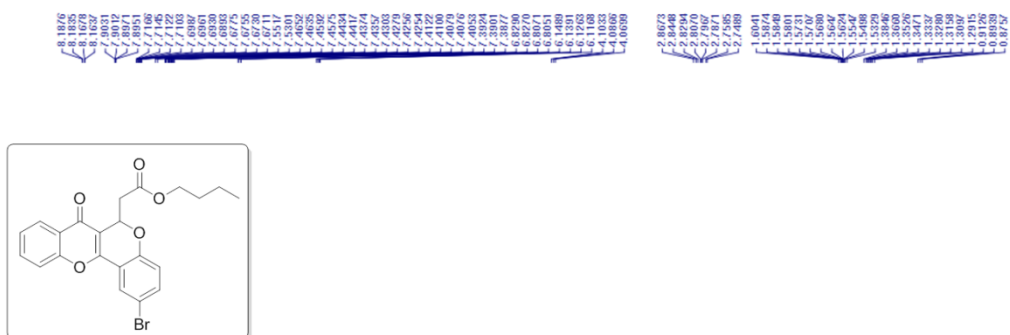


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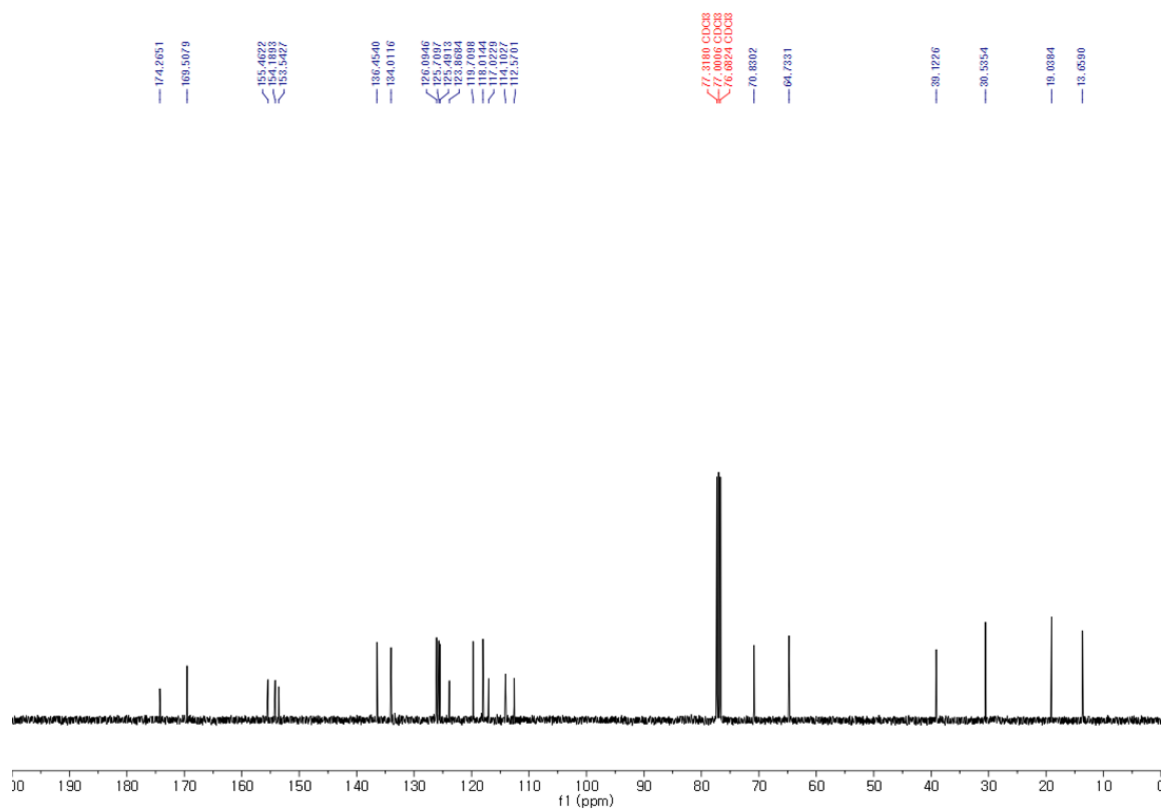


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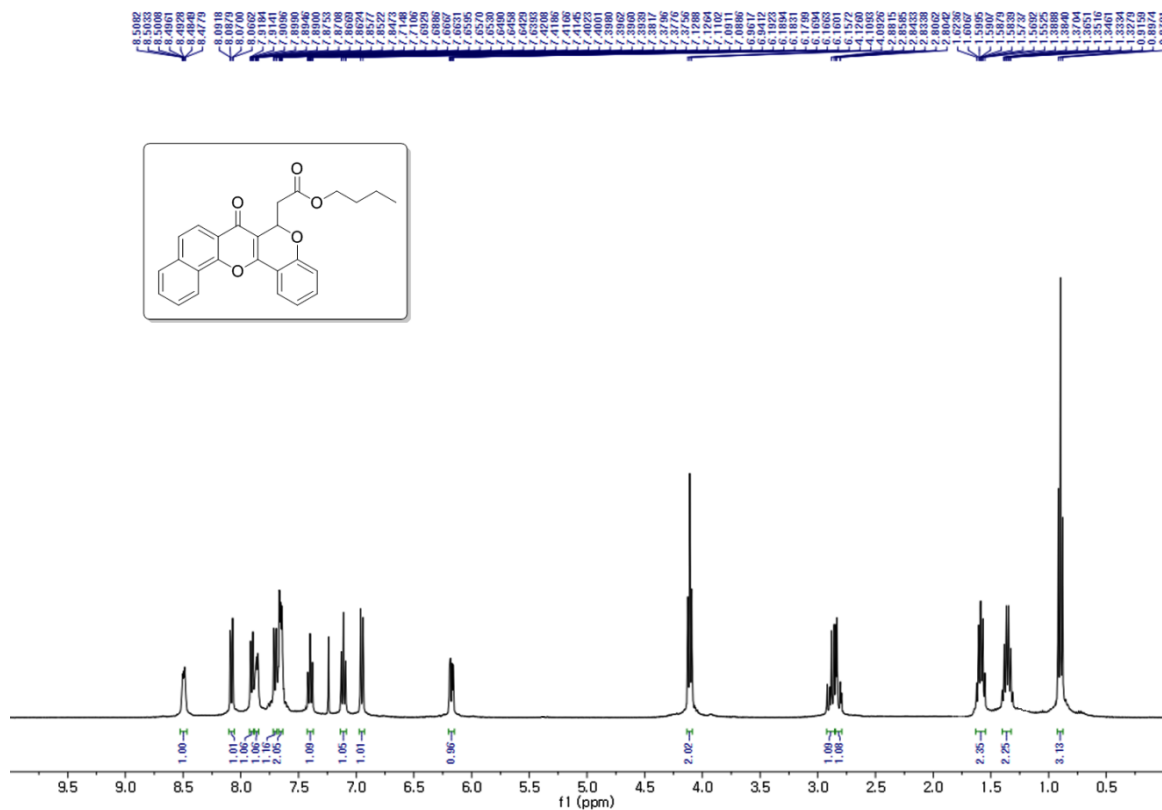


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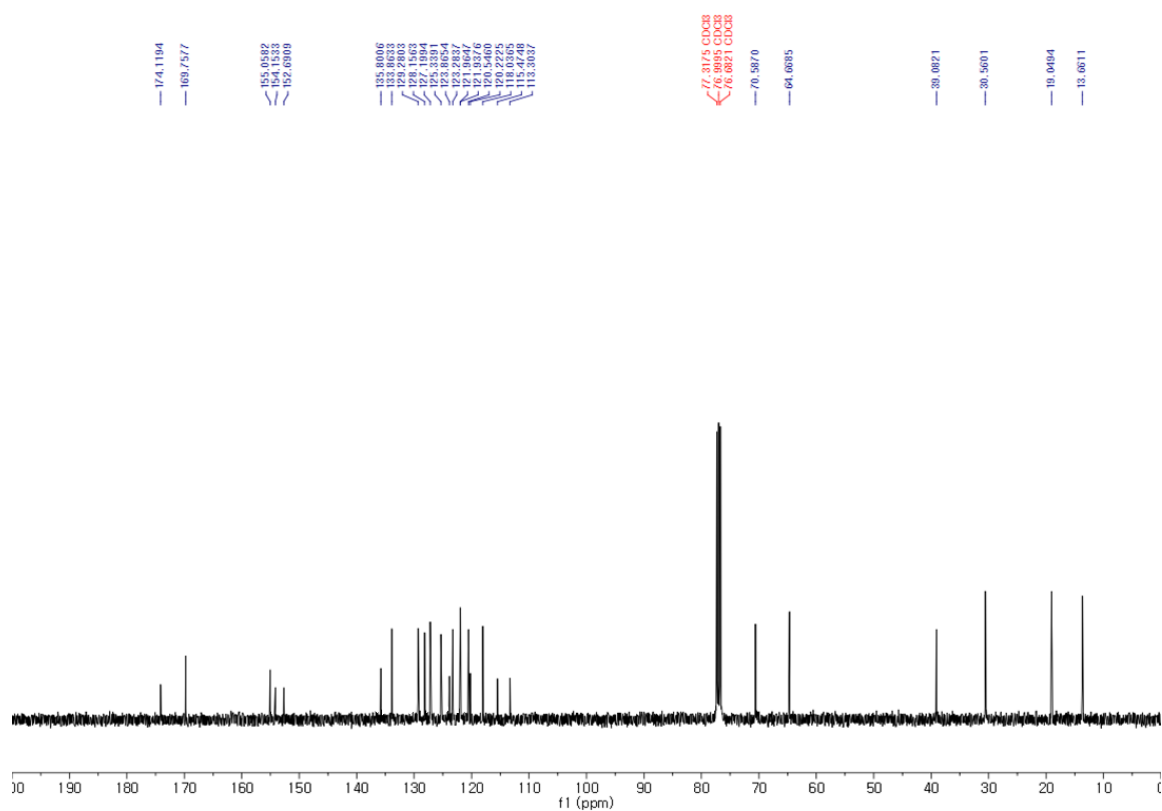


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Butyl 2-(7-Oxo-6,7-dihydrobenzo[h]chromeno[4,3-b]chromen-6-yl)acetate (3q)

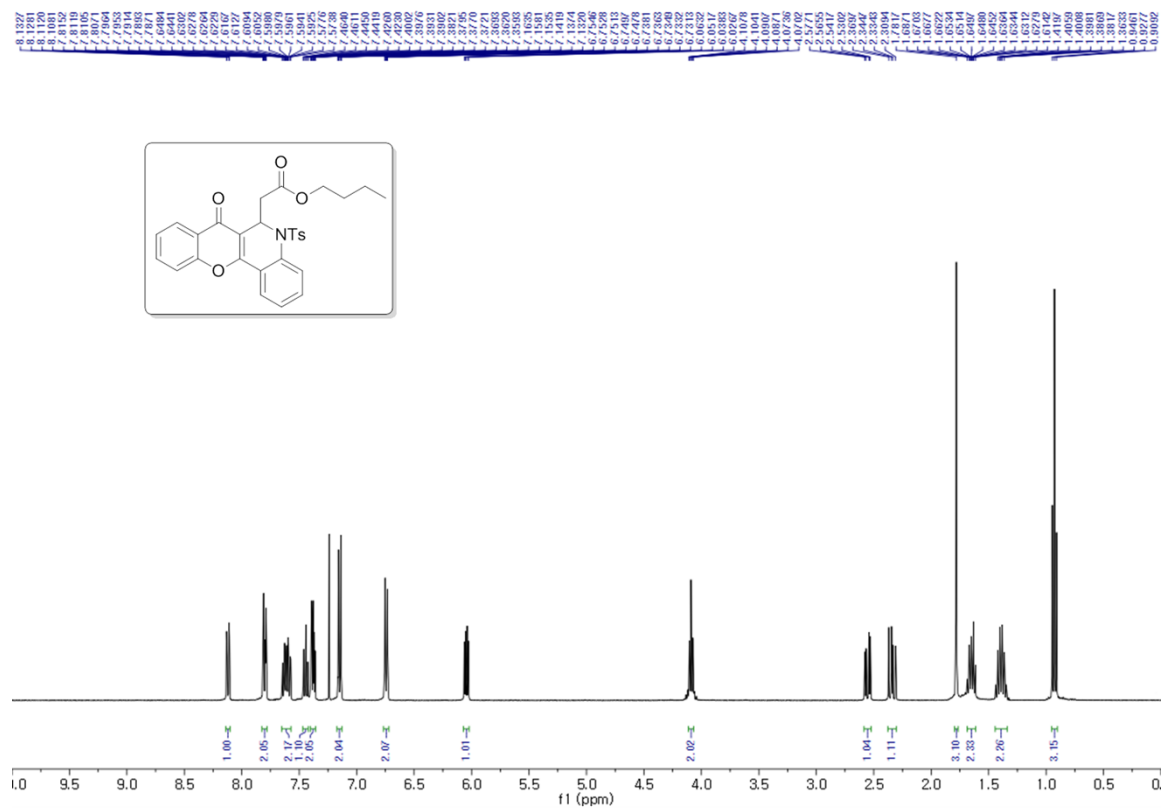


400 MHz, ^1H NMR in CDCl_3

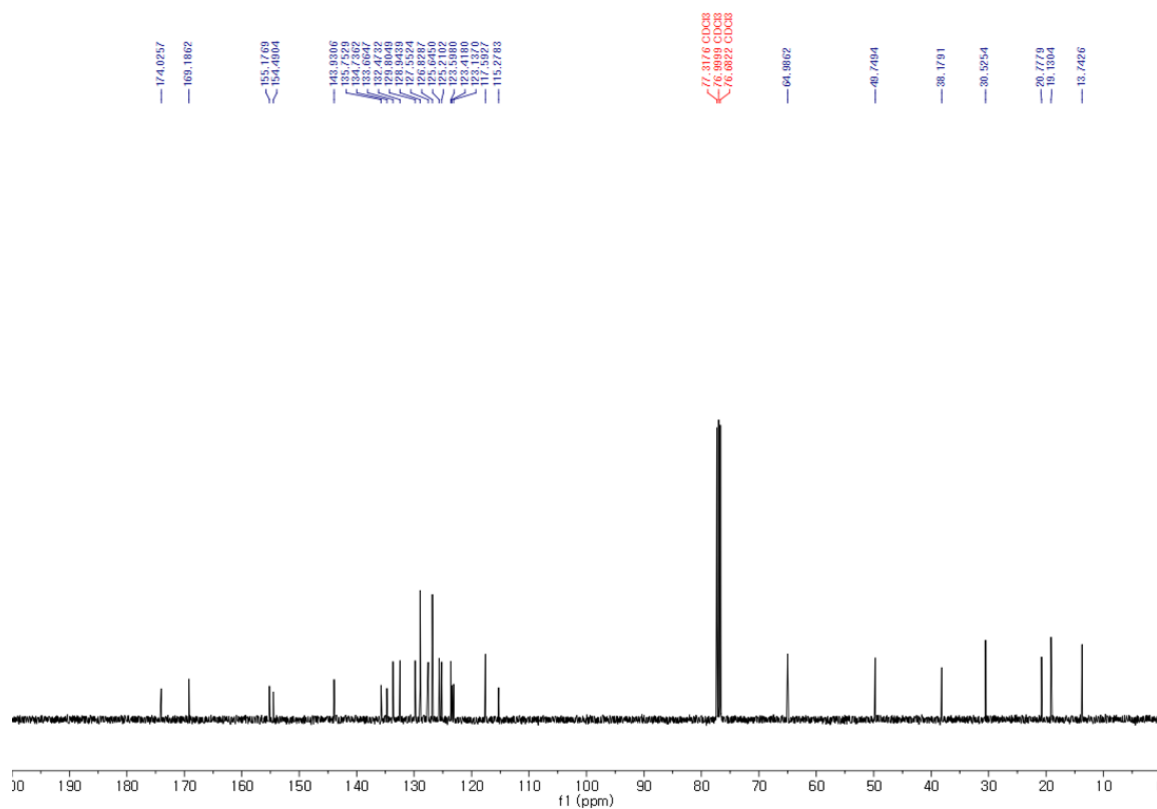


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Butyl 2-(7-Oxo-5-tosyl-6,7-dihydro-5H-chromeno[3,2-c]quinolin-6-yl)acetate (3r)

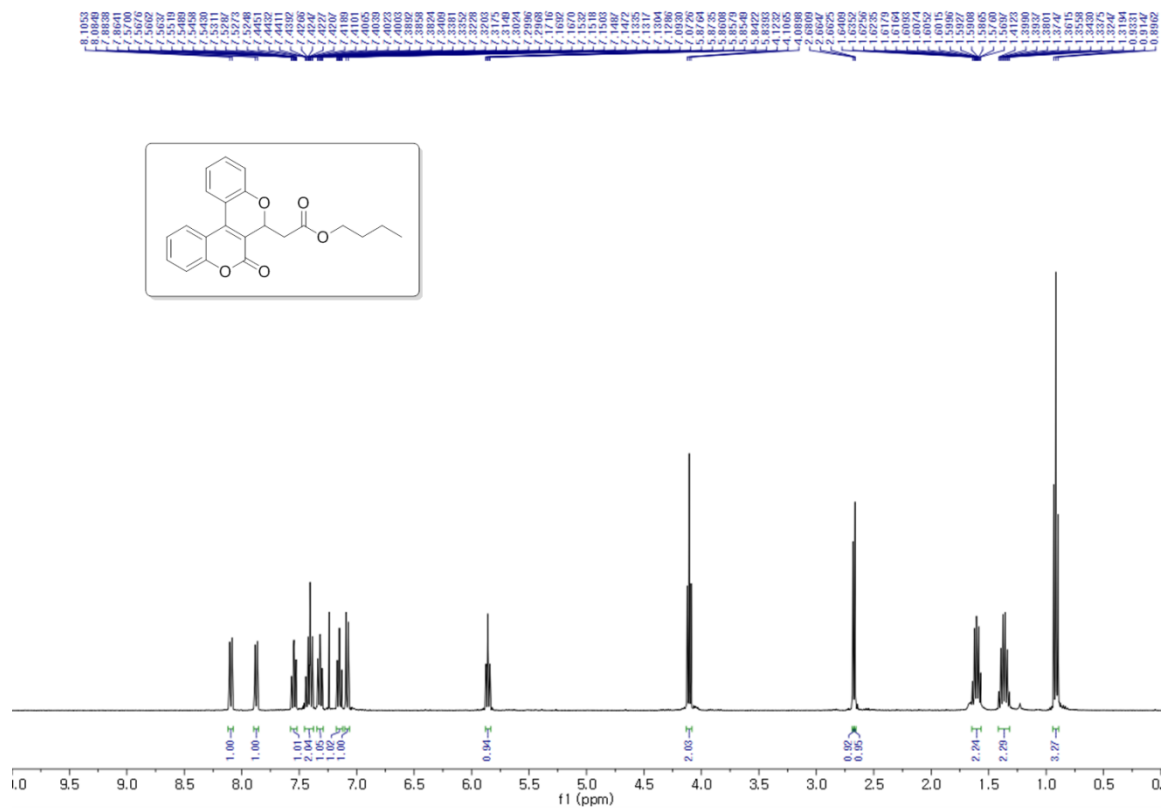


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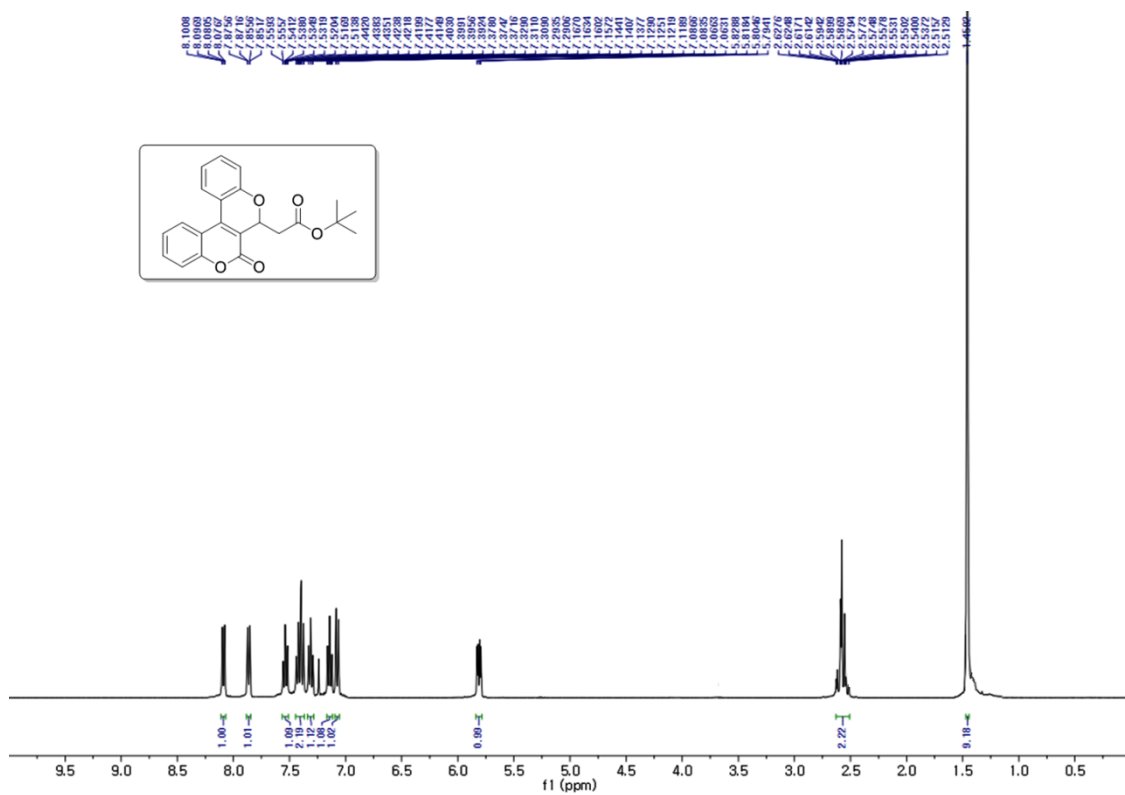
100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(7-Oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5a)

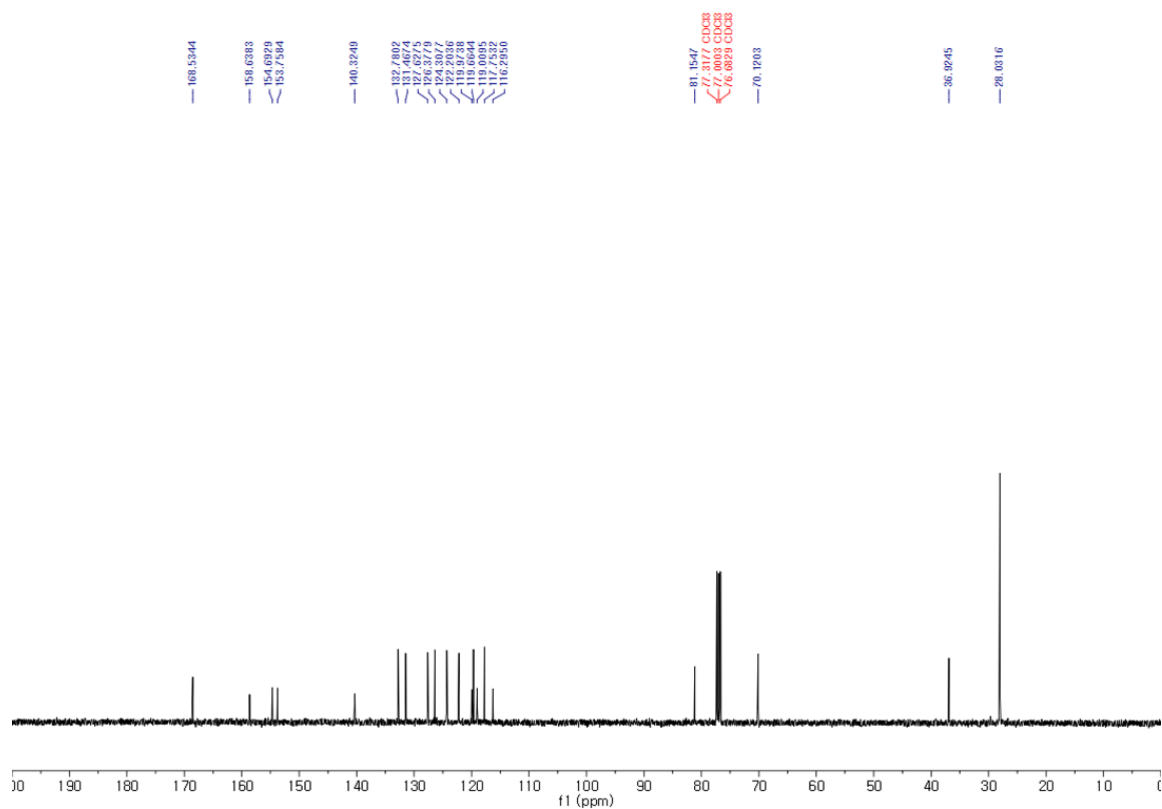


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tert-Butyl 2-(7-Oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5b)

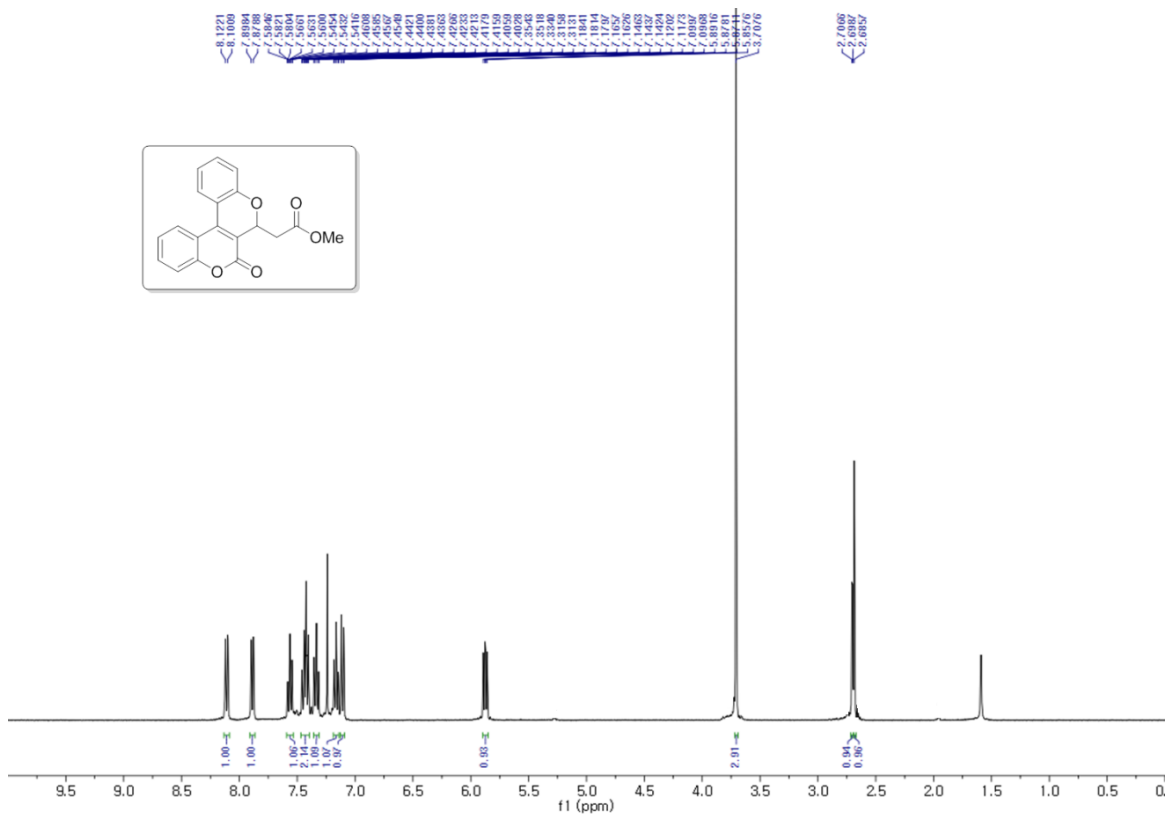


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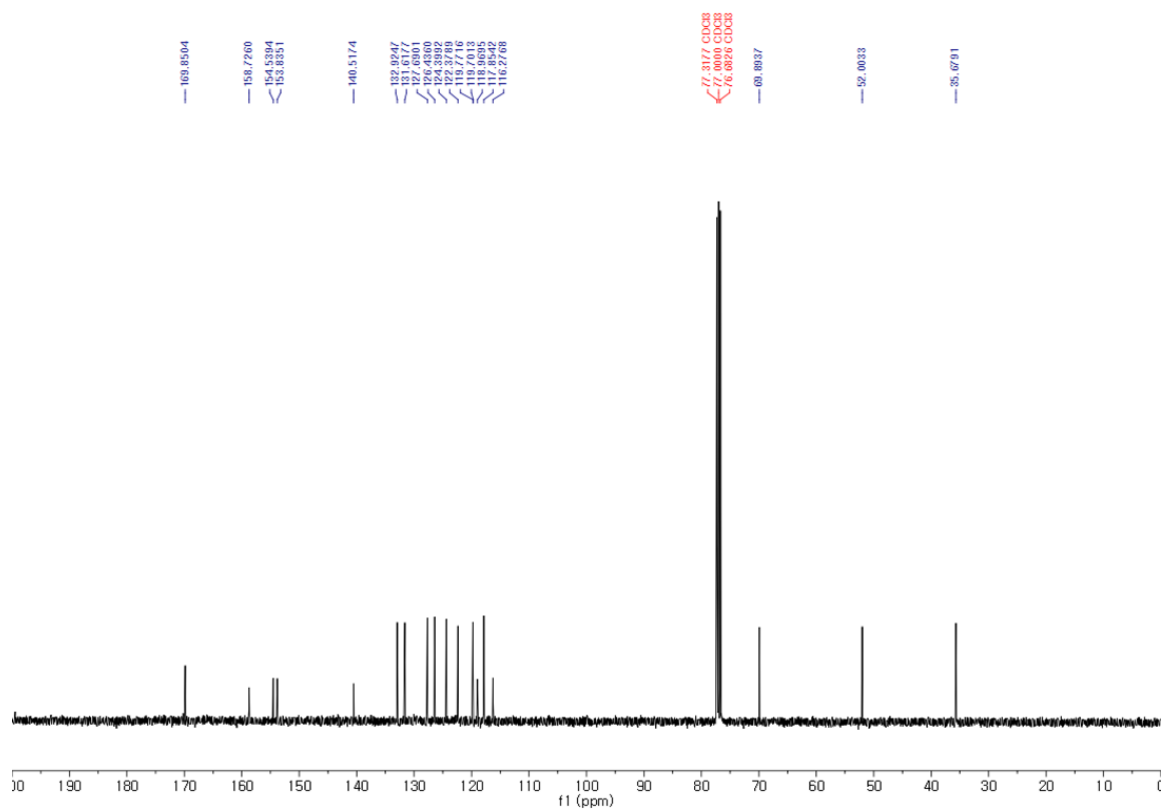


100 MHz, ^{13}C NMR in CDCl_3

Methyl 2-(7-Oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5c)

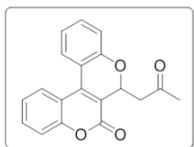
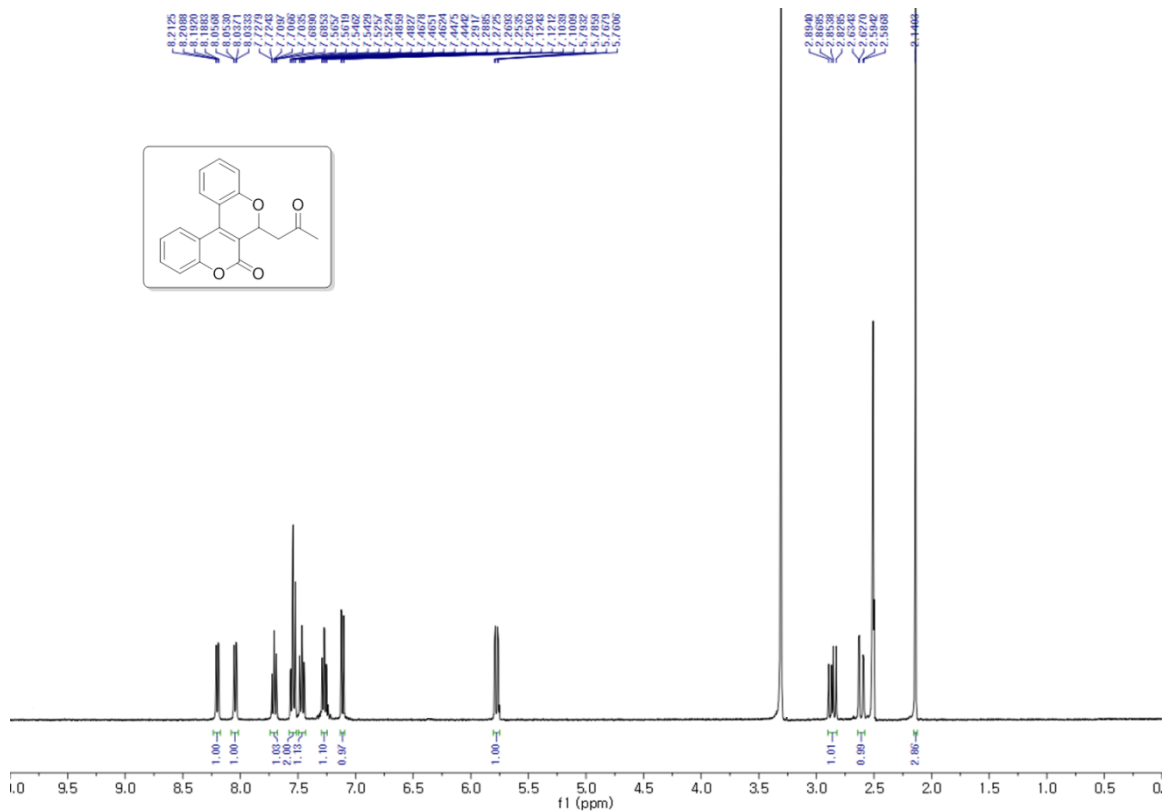


400 MHz, ^1H NMR in CDCl_3



100 MHz, ^{13}C NMR in CDCl_3

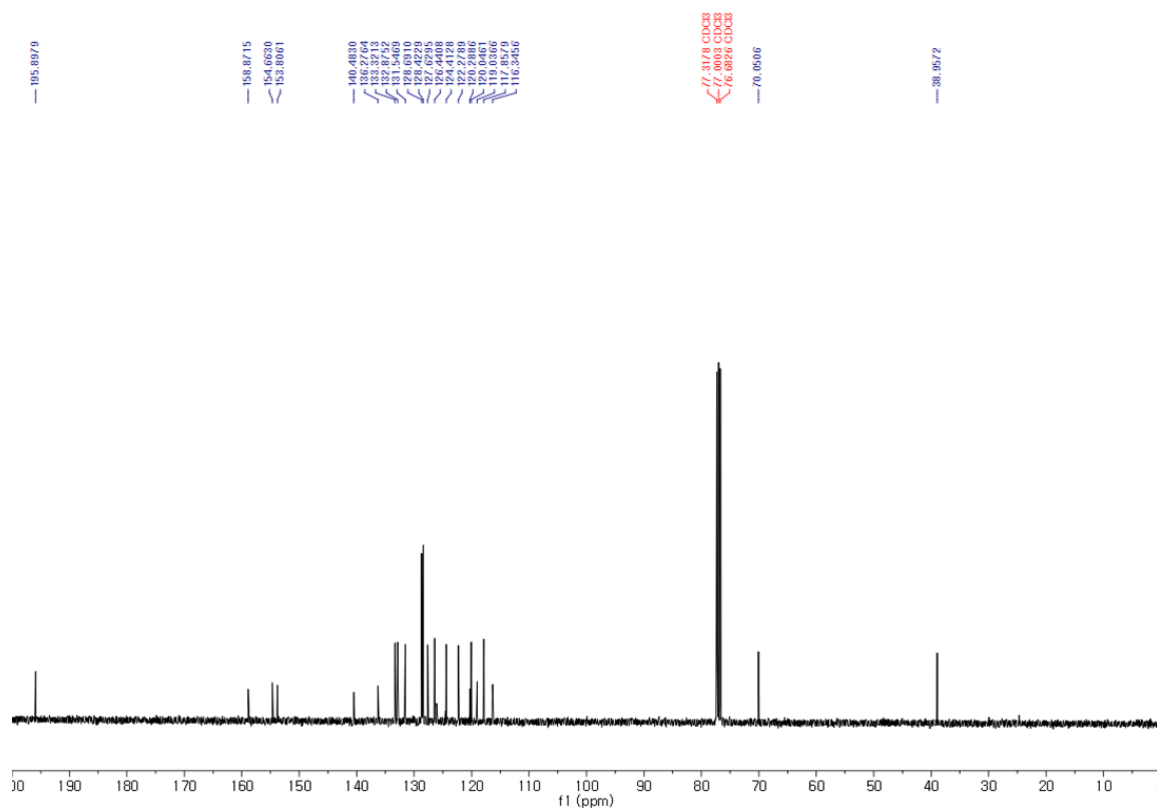
7-(2-Oxopropyl)chromeno[3,4-c]chromen-6(7H)-one (5d)



100 MHz, ¹³C NMR in CDCl₃

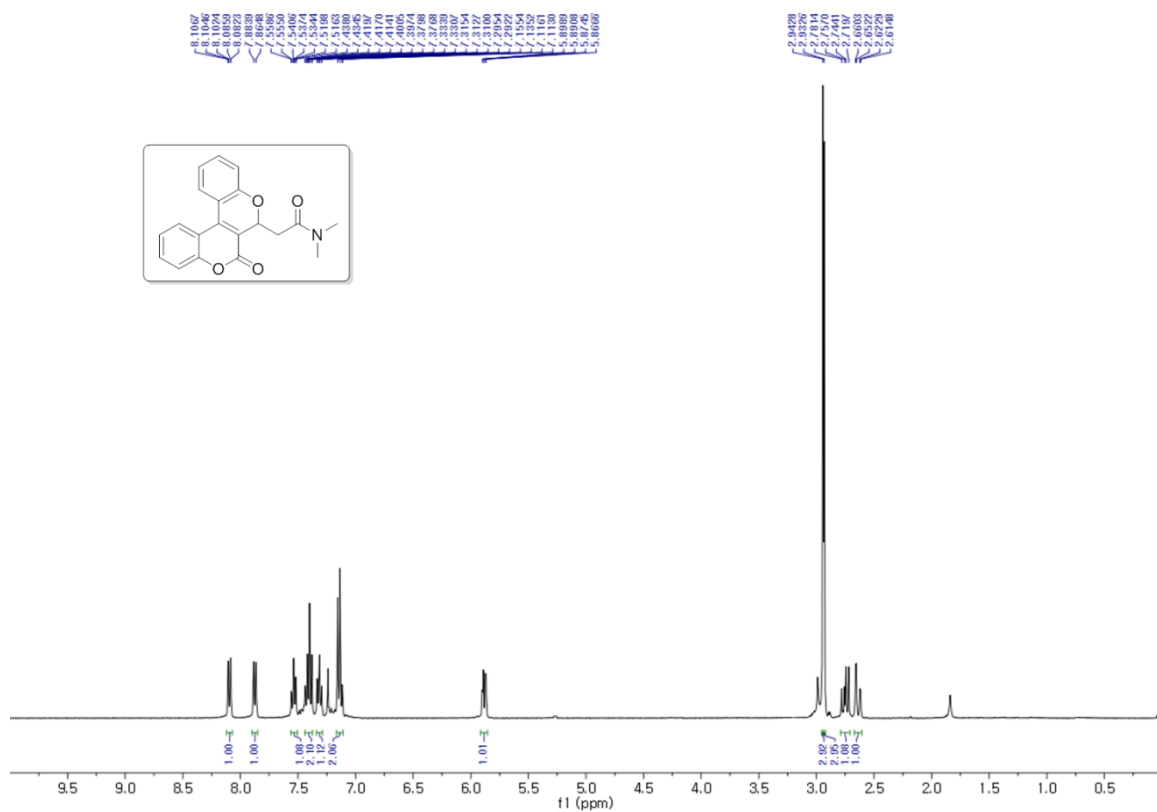


400 MHz, ¹H NMR in CDCl₃

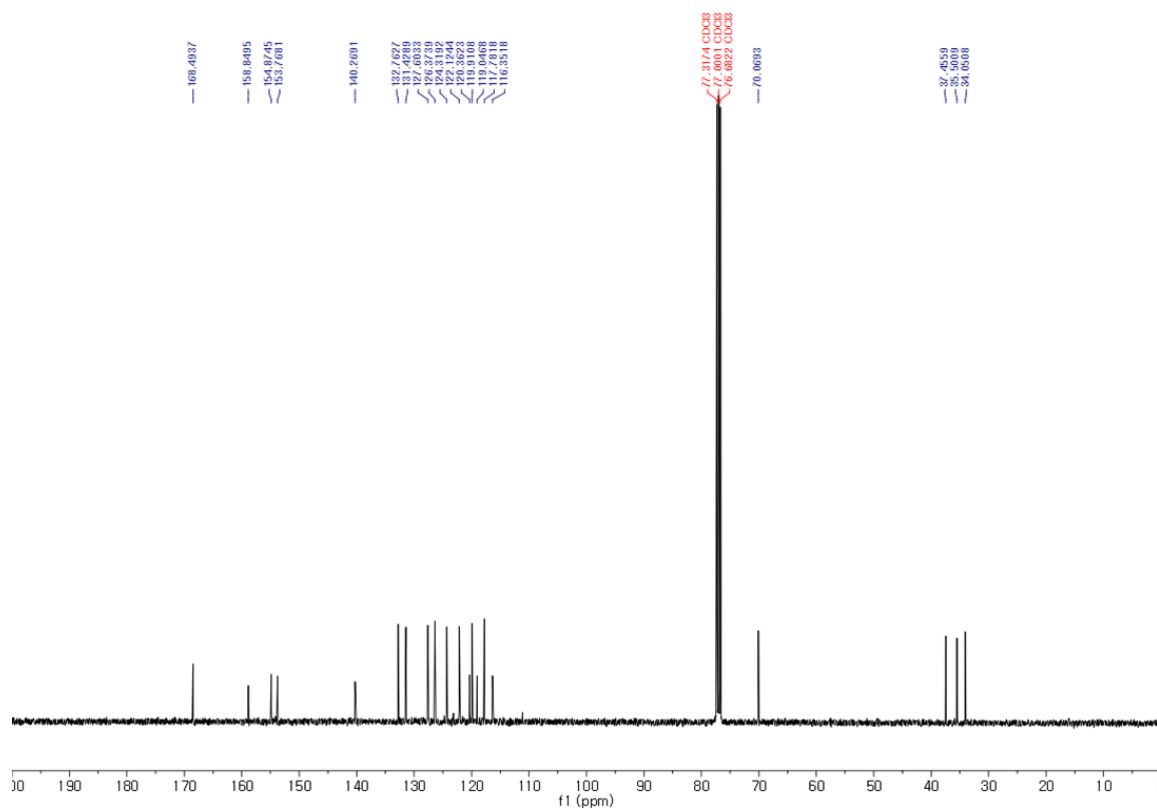


100 MHz, ¹³C NMR in CDCl₃

N,N-Dimethyl-2-(7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetamide (5f)

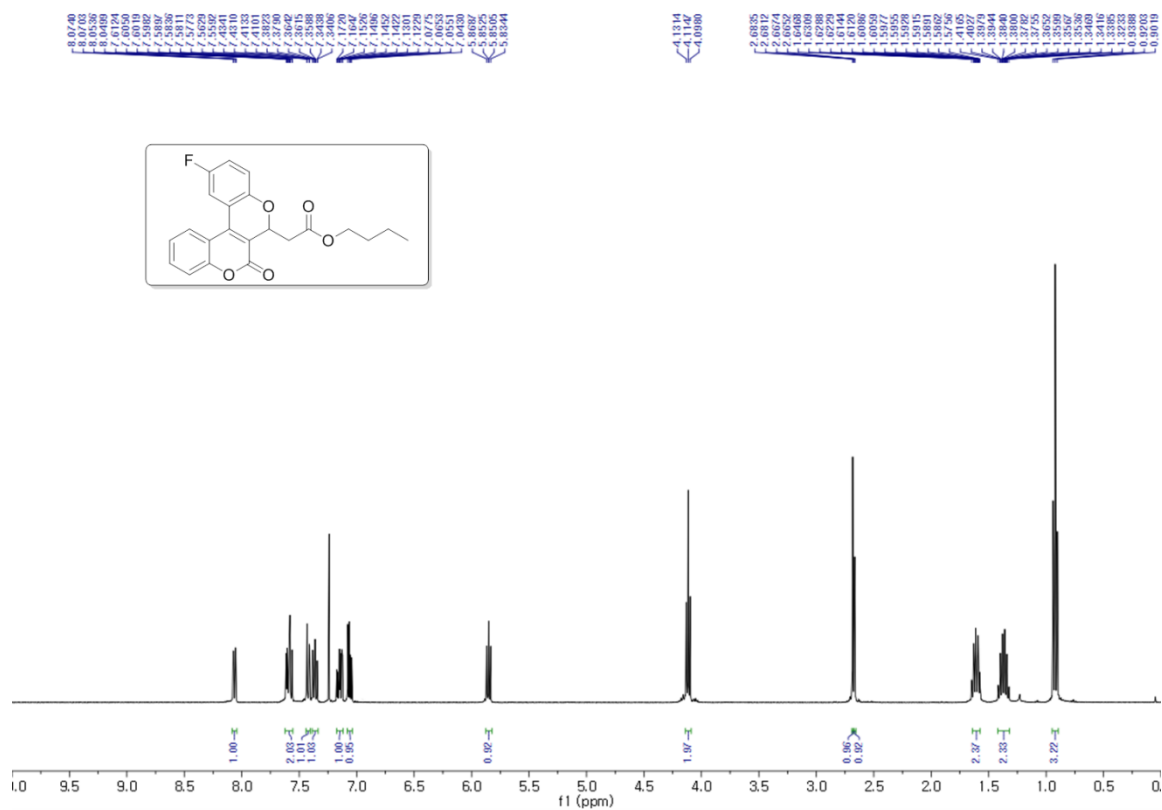


400 MHz, ^1H NMR in CDCl_3

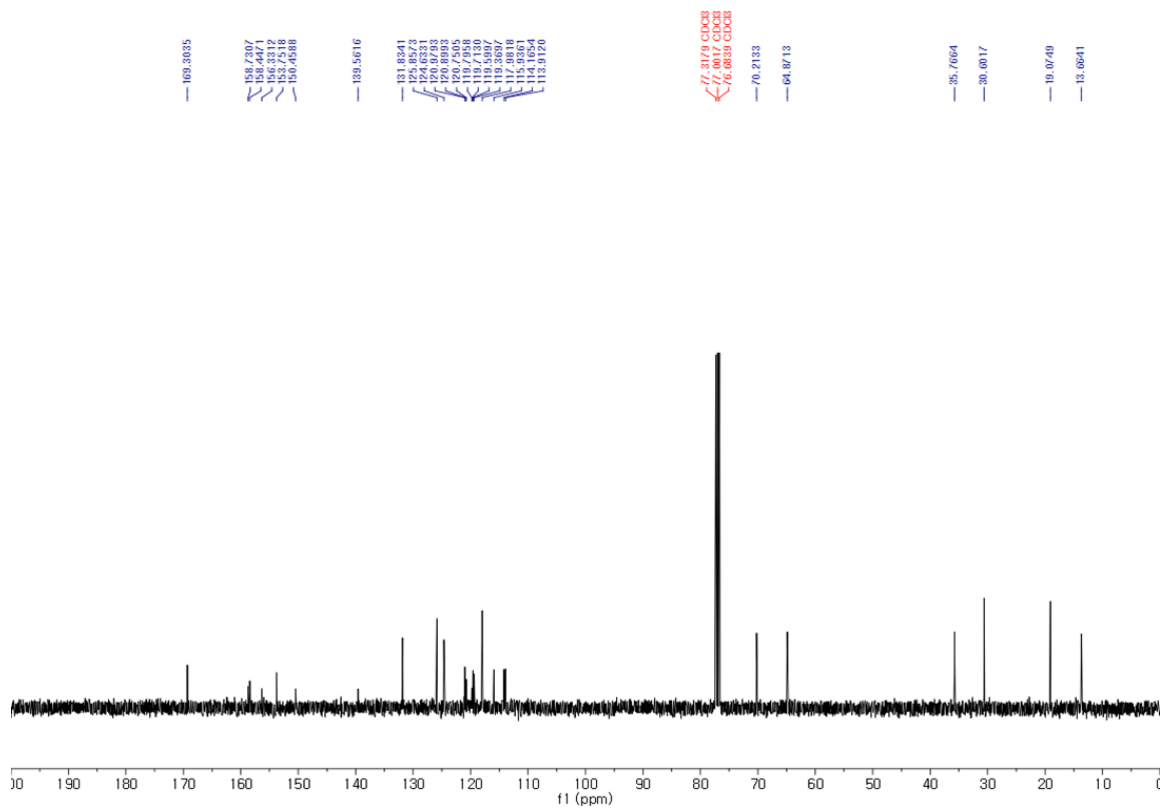


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(2-Fluoro-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5g)

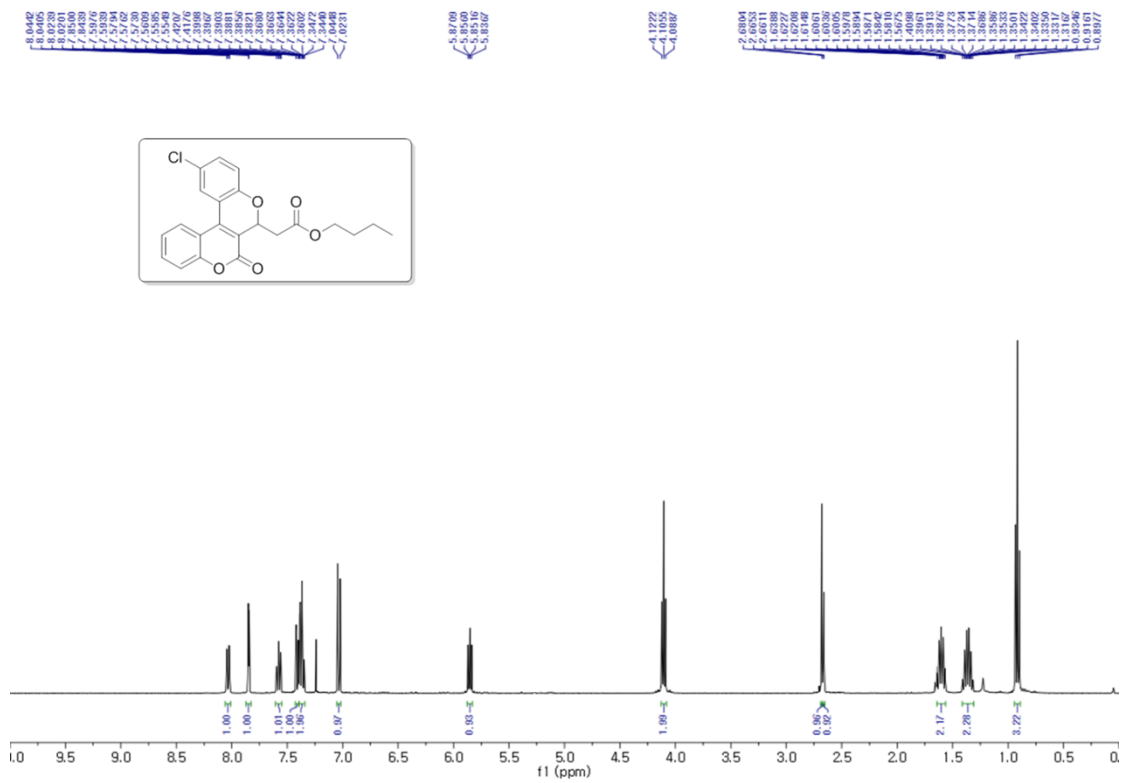


400 MHz, ^1H NMR in CDCl_3

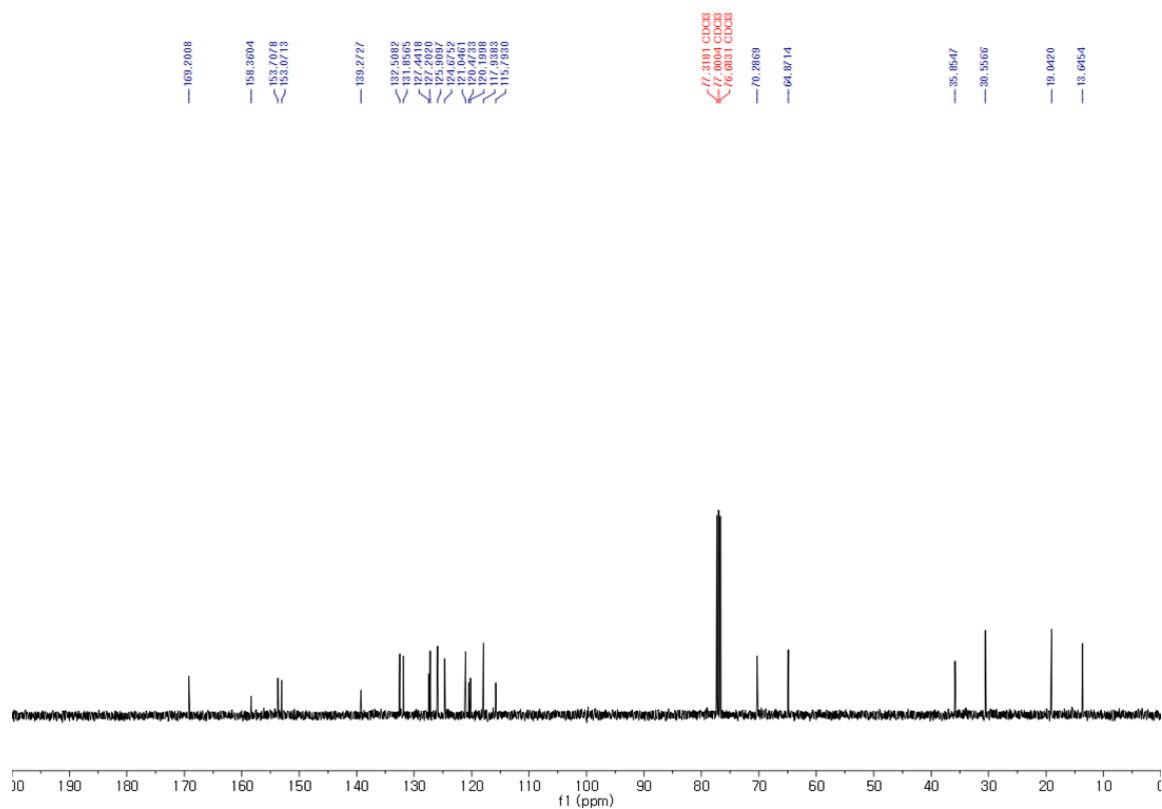


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(2-Chloro-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5h)

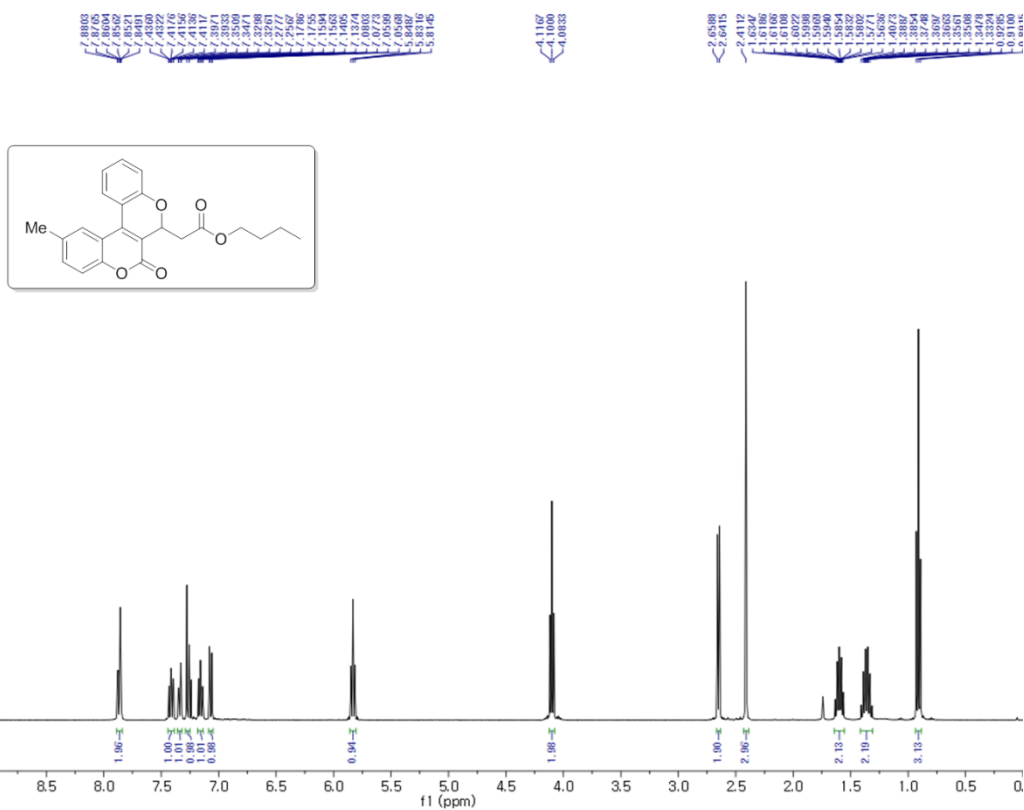


400 MHz, ¹H NMR in CDCl₃



100 MHz, ¹³C NMR in CDCl₃

Butyl 2-(11-Methyl-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5i)

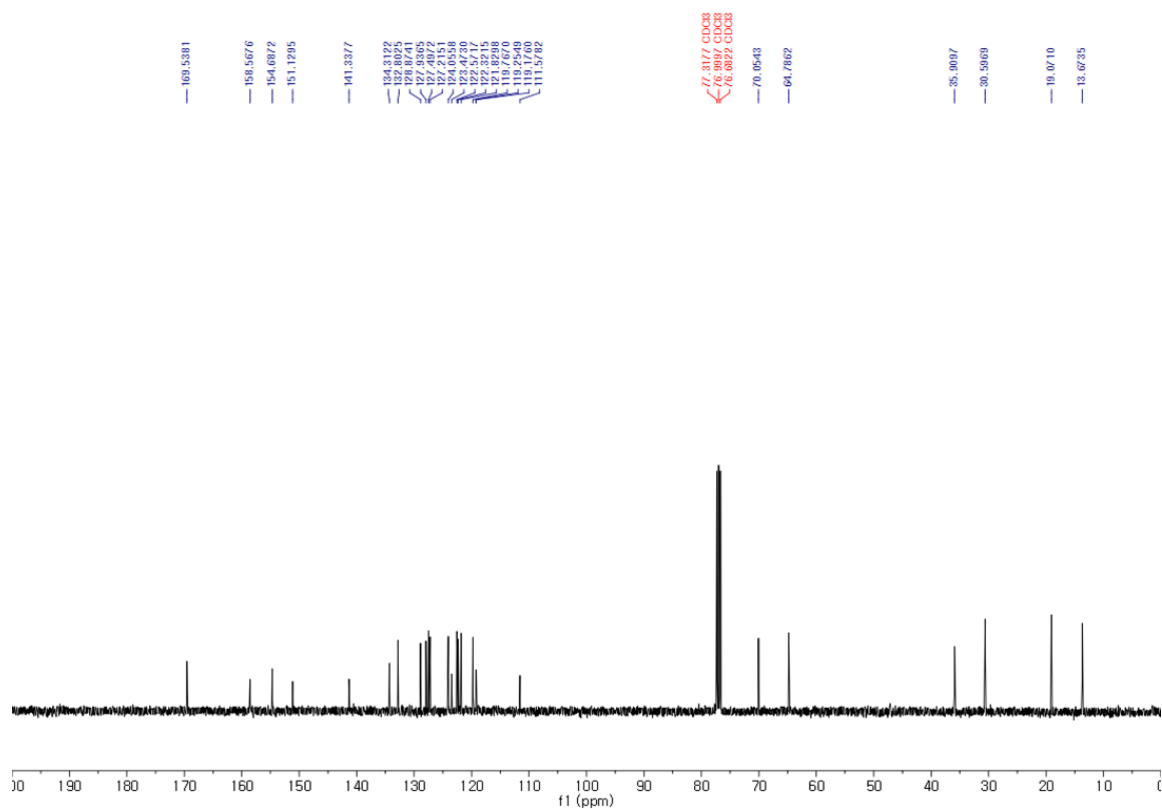


Chemical shifts (ppm):

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- 158.7788
- 154.5327
- 151.8690
- 140.2891
- 133.9981
- 132.7225
- 132.4640
- 127.6258
- 126.1428
- 122.2421
- 119.6942
- 118.6125
- 119.0348
- 117.4411
- 115.3176
- 77.3181 CDCl3
- 76.8995 CDCl3
- 76.8822 CDCl3
- 68.9600
- 64.6993
- 35.8210
- 30.5463
- 21.1342
- 18.6193
- 15.6248

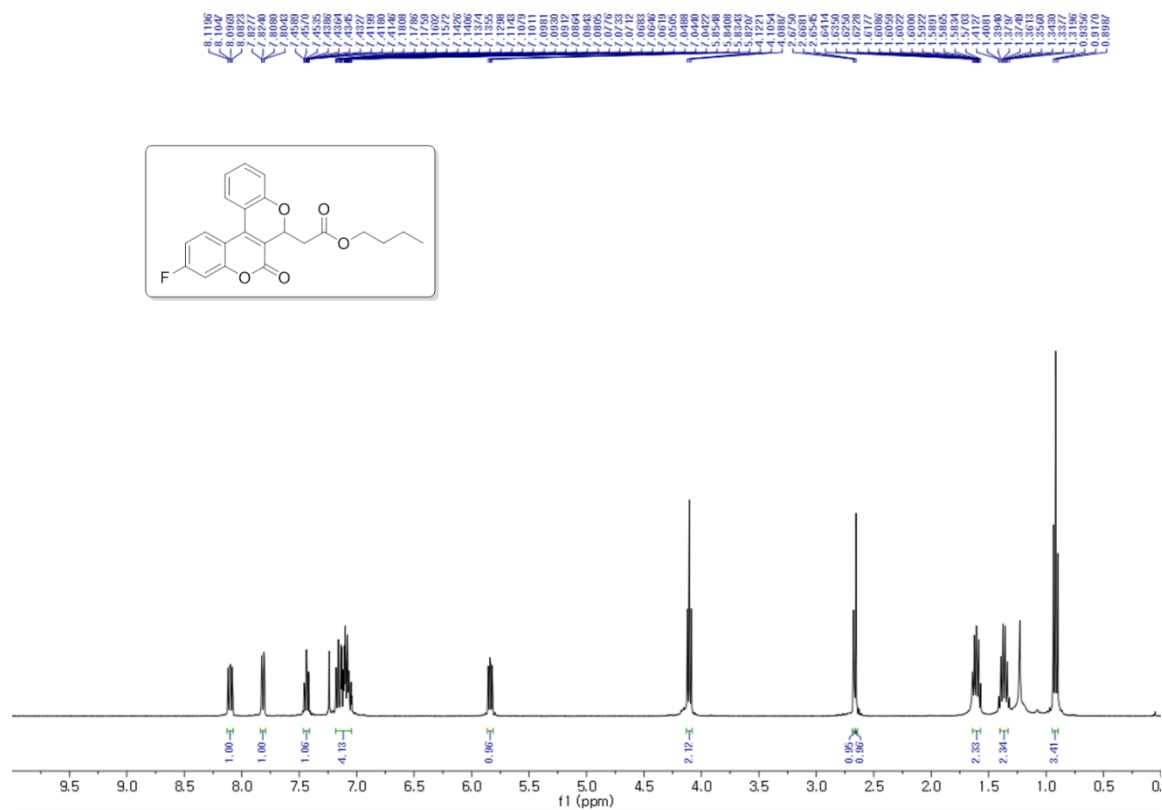
Chemical structure of 6-(benzyloxy)-2,4-dihydroxy-1-phenyl-1H-benzopyran-3-one is shown in the inset. The ¹H NMR spectrum (400 MHz, CDCl₃) displays the following peaks (ppm): 8.5575, 8.5394, 8.5271, 8.5221, 8.5211, 8.5201, 8.5191, 8.5181, 8.5171, 8.5161, 8.5151, 8.5141, 8.5131, 8.5121, 8.5111, 8.5101, 8.5091, 8.5081, 8.5071, 8.5061, 8.5051, 8.5041, 8.5031, 8.5021, 8.5011, 8.5001, 8.4991, 8.4981, 8.4971, 8.4961, 8.4951, 8.4941, 8.4931, 8.4921, 8.4911, 8.4901, 8.4891, 8.4881, 8.4871, 8.4861, 8.4851, 8.4841, 8.4831, 8.4821, 8.4811, 8.4801, 8.4791, 8.4781, 8.4771, 8.4761, 8.4751, 8.4741, 8.4731, 8.4721, 8.4711, 8.4701, 8.4691, 8.4681, 8.4671, 8.4661, 8.4651, 8.4641, 8.4631, 8.4621, 8.4611, 8.4601, 8.4591, 8.4581, 8.4571, 8.4561, 8.4551, 8.4541, 8.4531, 8.4521, 8.4511, 8.4501, 8.4491, 8.4481, 8.4471, 8.4461, 8.4451, 8.4441, 8.4431, 8.4421, 8.4411, 8.4401, 8.4391, 8.4381, 8.4371, 8.4361, 8.4351, 8.4341, 8.4331, 8.4321, 8.4311, 8.4301, 8.4291, 8.4281, 8.4271, 8.4261, 8.4251, 8.4241, 8.4231, 8.4221, 8.4211, 8.4201, 8.4191, 8.4181, 8.4171, 8.4161, 8.4151, 8.4141, 8.4131, 8.4121, 8.4111, 8.4101, 8.4091, 8.4081, 8.4071, 8.4061, 8.4051, 8.4041, 8.4031, 8.4021, 8.4011, 8.4001, 8.3991, 8.3981, 8.3971, 8.3961, 8.3951, 8.3941, 8.3931, 8.3921, 8.3911, 8.3901, 8.3891, 8.3881, 8.3871, 8.3861, 8.3851, 8.3841, 8.3831, 8.3821, 8.3811, 8.3801, 8.3791, 8.3781, 8.3771, 8.3761, 8.3751, 8.3741, 8.3731, 8.3721, 8.3711, 8.3701, 8.3691, 8.3681, 8.3671, 8.3661, 8.3651, 8.3641, 8.3631, 8.3621, 8.3611, 8.3601, 8.3591, 8.3581, 8.3571, 8.3561, 8.3551, 8.3541, 8.3531, 8.3521, 8.3511, 8.3501, 8.3491, 8.3481, 8.3471, 8.3461, 8.3451, 8.3441, 8.3431, 8.3421, 8.3411, 8.3401, 8.3391, 8.3381, 8.3371, 8.3361, 8.3351, 8.3341, 8.3331, 8.3321, 8.3311, 8.3301, 8.3291, 8.3281, 8.3271, 8.3261, 8.3251, 8.3241, 8.3231, 8.3221, 8.3211, 8.3201, 8.3191, 8.3181, 8.3171, 8.3161, 8.3151, 8.3141, 8.3131, 8.3121, 8.3111, 8.3101, 8.3091, 8.3081, 8.3071, 8.3061, 8.3051, 8.3041, 8.3031, 8.3021, 8.3011, 8.3001, 8.2991, 8.2981, 8.2971, 8.2961, 8.2951, 8.2941, 8.2931, 8.2921, 8.2911, 8.2901, 8.2891, 8.2881, 8.2871, 8.2861, 8.2851, 8.2841, 8.2831, 8.2821, 8.2811, 8.2801, 8.2791, 8.2781, 8.2771, 8.2761, 8.2751, 8.2741, 8.2731, 8.2721, 8.2711, 8.2701, 8.2691, 8.2681, 8.2671, 8.2661, 8.2651, 8.2641, 8.2631, 8.2621, 8.2611, 8.2601, 8.2591, 8.2581, 8.2571, 8.2561, 8.2551, 8.2541, 8.2531, 8.2521, 8.2511, 8.2501, 8.2491, 8.2481, 8.2471, 8.2461, 8.2451, 8.2441, 8.2431, 8.2421, 8.2411, 8.2401, 8.2391, 8.2381, 8.2371, 8.2361, 8.2351, 8.2341, 8.2331, 8.2321, 8.2311, 8.2301, 8.2291, 8.2281, 8.2271, 8.2261, 8.2251, 8.2241, 8.2231, 8.2221, 8.2211, 8.2201, 8.2191, 8.2181, 8.2171, 8.2161, 8.2151, 8.2141, 8.2131, 8.2121, 8.2111, 8.2101, 8.2091, 8.2081, 8.2071, 8.2061, 8.2051, 8.2041, 8.2031, 8.2021, 8.2011, 8.2001, 8.1991, 8.1981, 8.1971, 8.1961, 8.1951, 8.1941, 8.1931, 8.1921, 8.1911, 8.1901, 8.1891, 8.1881, 8.1871, 8.1861, 8.1851, 8.1841, 8.1831, 8.1821, 8.1811, 8.1801, 8.1791, 8.1781, 8.1771, 8.1761, 8.1751, 8.1741, 8.1731, 8.1721, 8.1711, 8.1701, 8.1691, 8.1681, 8.1671, 8.1661, 8.1651, 8.1641, 8.1631, 8.1621, 8.1611, 8.1601, 8.1591, 8.1581, 8.1571, 8.1561, 8.1551, 8.1541, 8.1531, 8.1521, 8.1511, 8.1501, 8.1491, 8.1481, 8.1471, 8.1461, 8.1451, 8.1441, 8.1431, 8.1421, 8.1411, 8.1401, 8.1391, 8.1381, 8.1371, 8.1361, 8.1351, 8.1341, 8.1331, 8.1321, 8.1311, 8.1301, 8.1291, 8.1281, 8.1271, 8.1261, 8.1251, 8.1241, 8.1231, 8.1221, 8.1211, 8.1201, 8.1191, 8.1181, 8.1171, 8.1161, 8.1151, 8.1141, 8.1131, 8.1121, 8.1111, 8.1101, 8.1091, 8.1081, 8.1071, 8.1061, 8.1051, 8.1041, 8.1031, 8.1021, 8.1011, 8.1001, 7.9991, 7.9981, 7.9971, 7.9961, 7.9951, 7.9941, 7.9931, 7.9921, 7.9911, 7.9901, 7.9891, 7.9881, 7.9871, 7.9861, 7.9851, 7.9841, 7.9831, 7.9821, 7.9811, 7.9801, 7.9791, 7.9781, 7.9771, 7.9761, 7.9751, 7.9741, 7.9731, 7.9721, 7.9711, 7.9701, 7.9691, 7.9681, 7.9671, 7.9661, 7.9651, 7.9641, 7.9631, 7.9621, 7.9611, 7.9601, 7.9591, 7.9581, 7.9571, 7.9561, 7.9551, 7.9541, 7.9531, 7.9521, 7.9511, 7.9501, 7.9491, 7.9481, 7.9471, 7.9461, 7.9451, 7.9441, 7.9431, 7.9421, 7.9411, 7.9401, 7.9391, 7.9381, 7.9371, 7.9361, 7.9351, 7.9341, 7.

400 MHz, ¹H NMR in CDCl₃

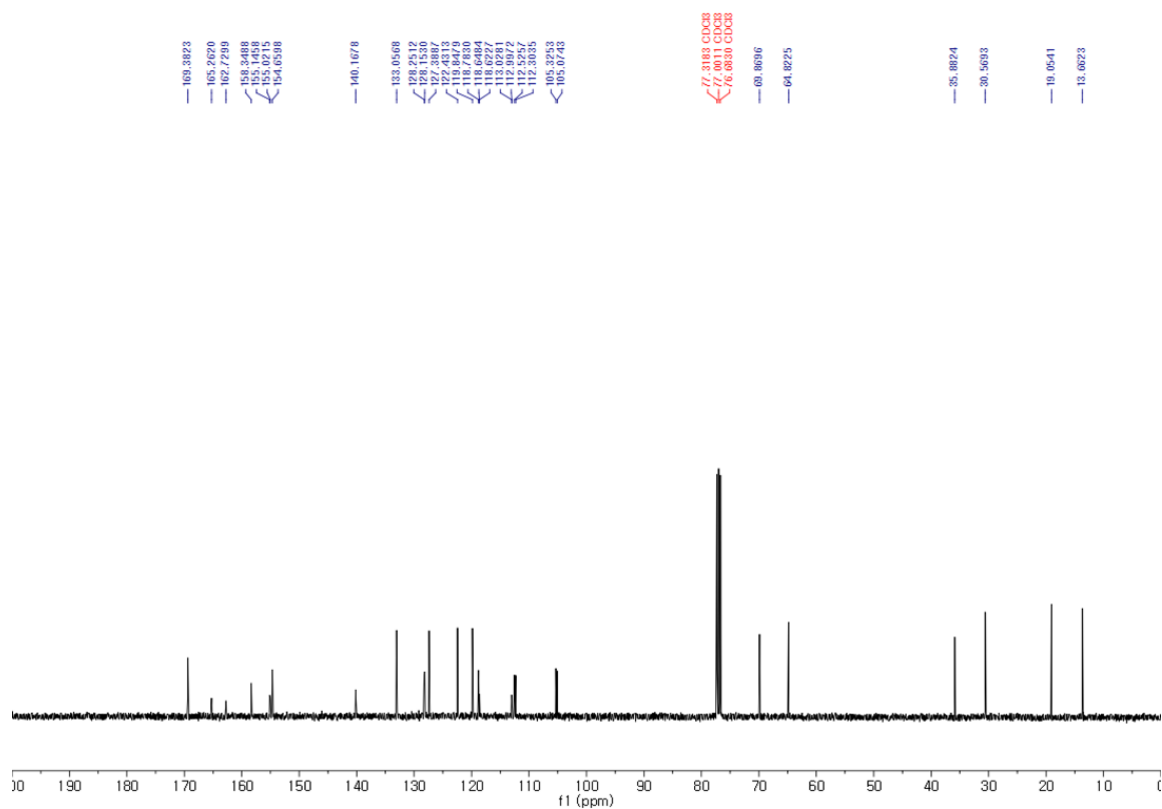


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(10-Fluoro-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5k)

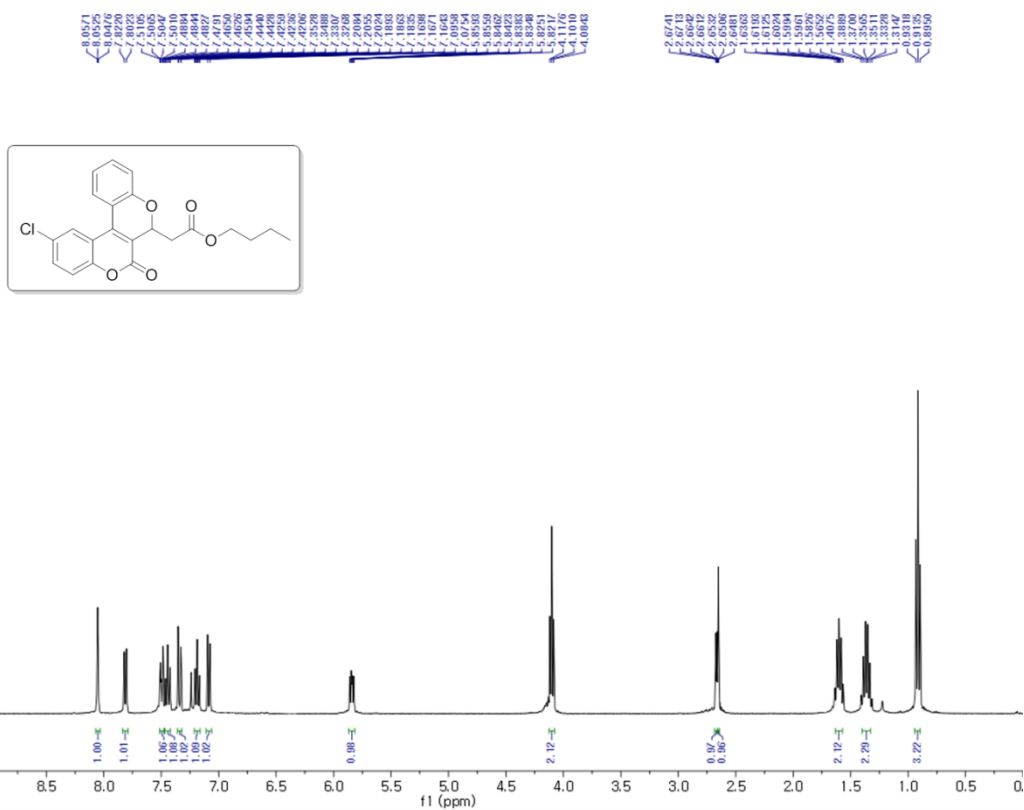


400 MHz, ^1H NMR in CDCl_3

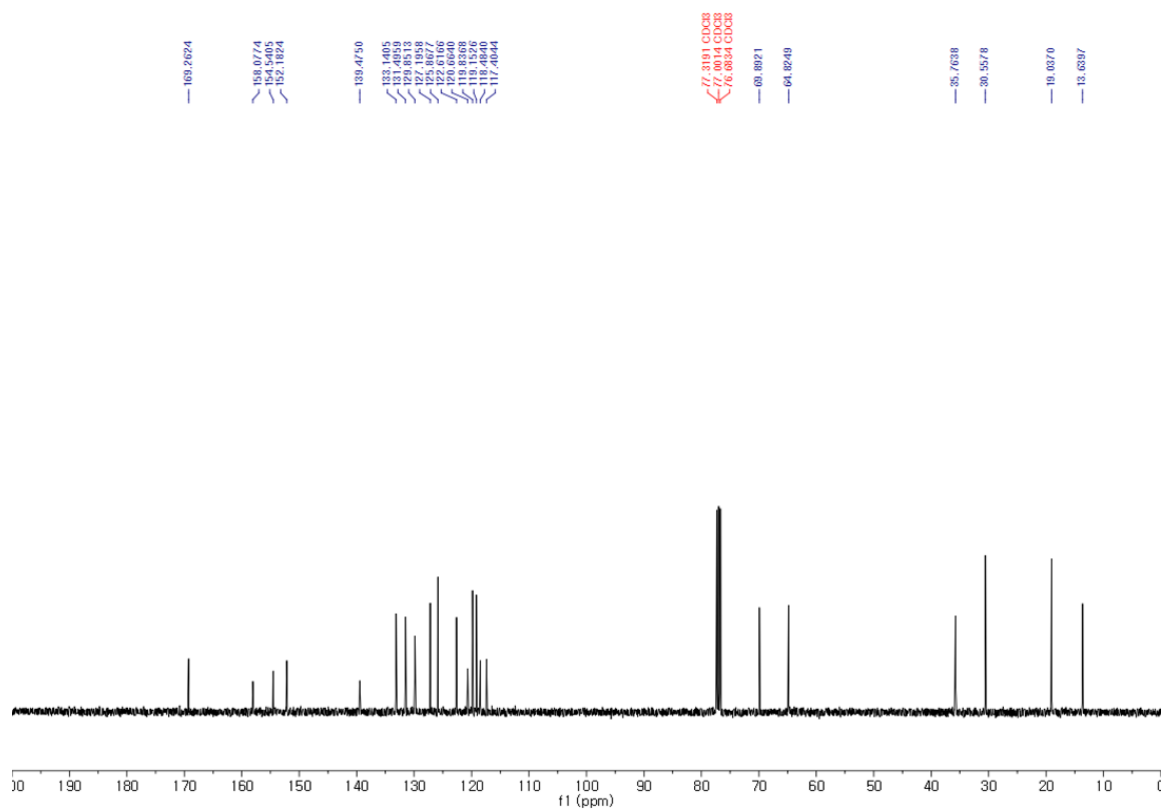


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(11-Chloro-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5l)

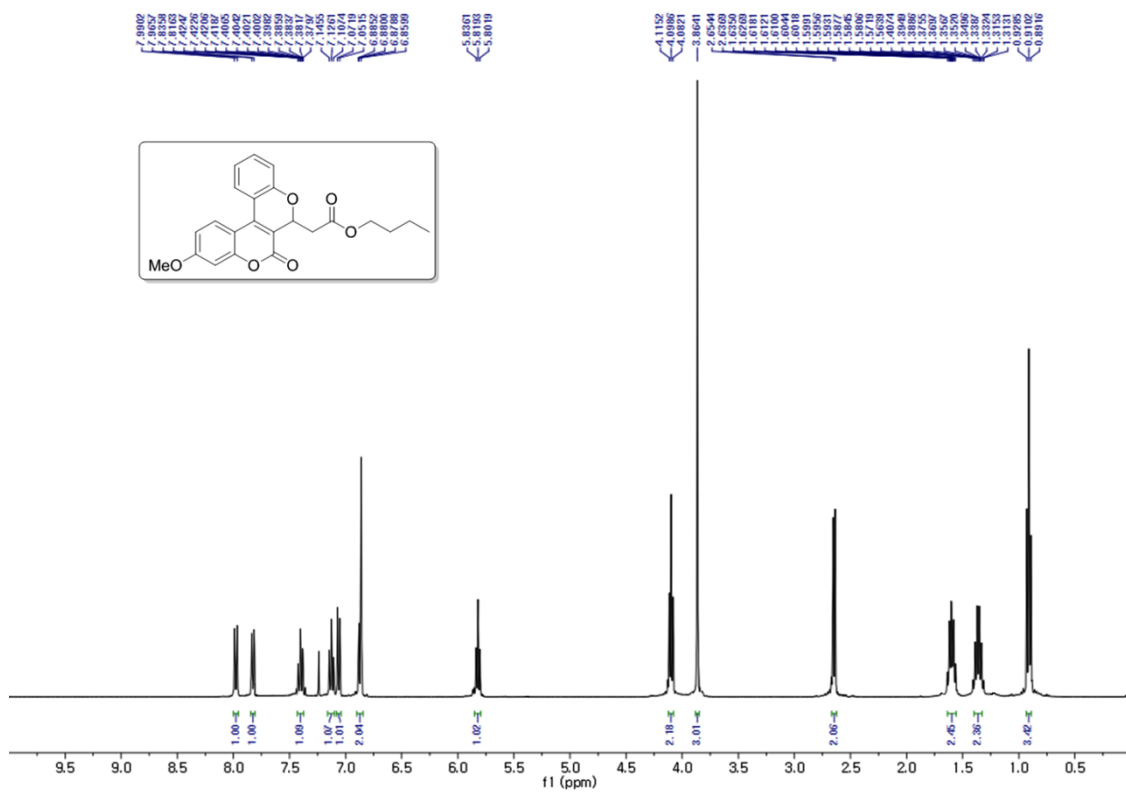


400 MHz, ^1H NMR in CDCl_3

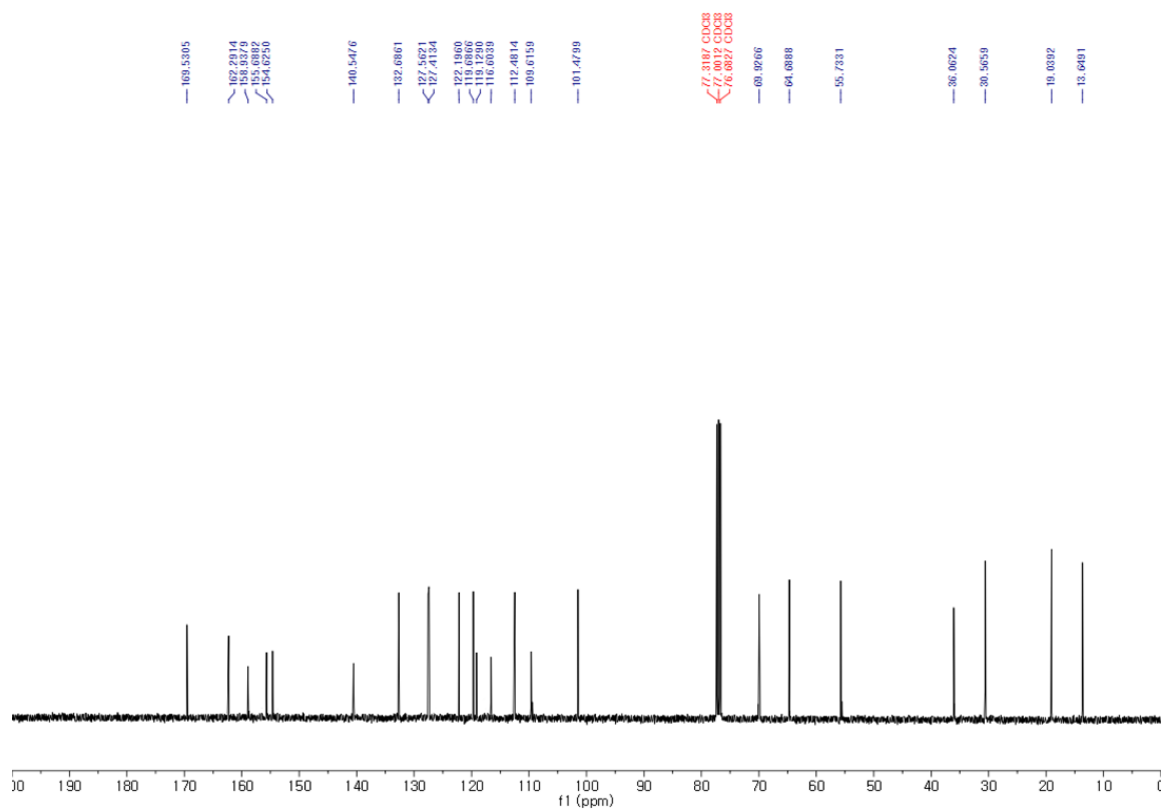


100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(10-Methoxy-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5m)

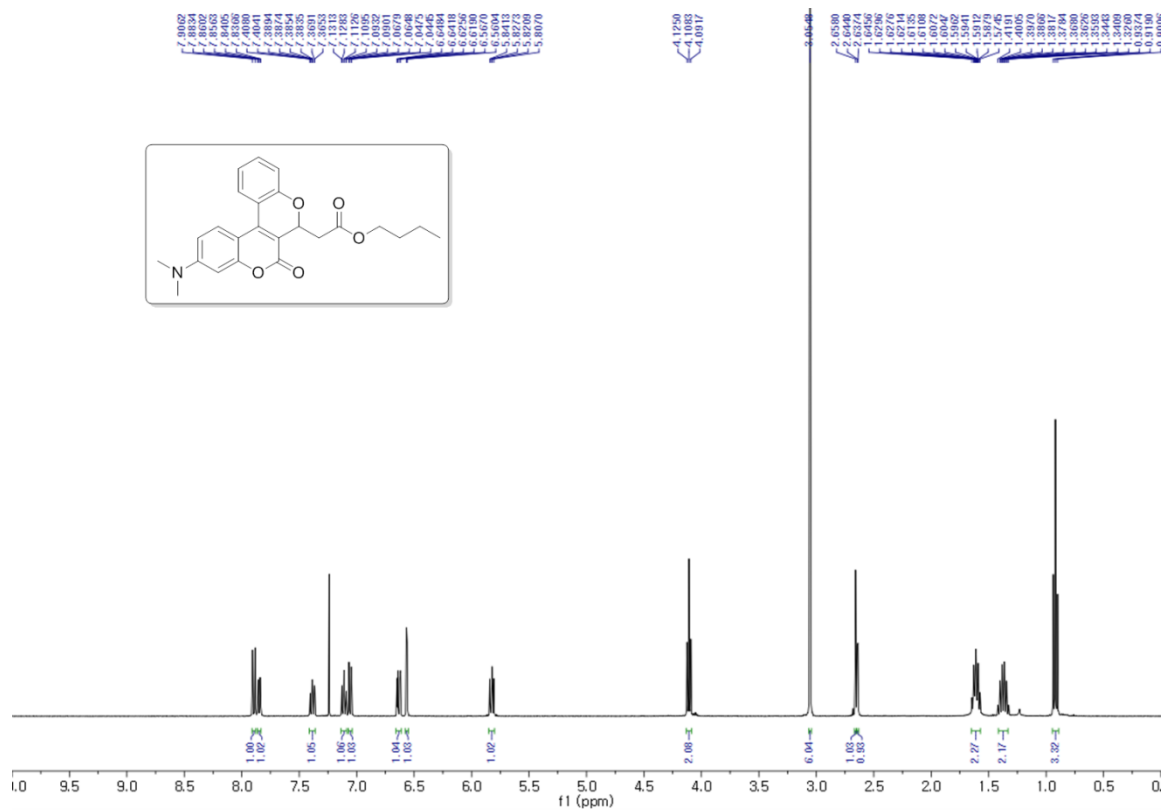


400 MHz, ^1H NMR in CDCl_3



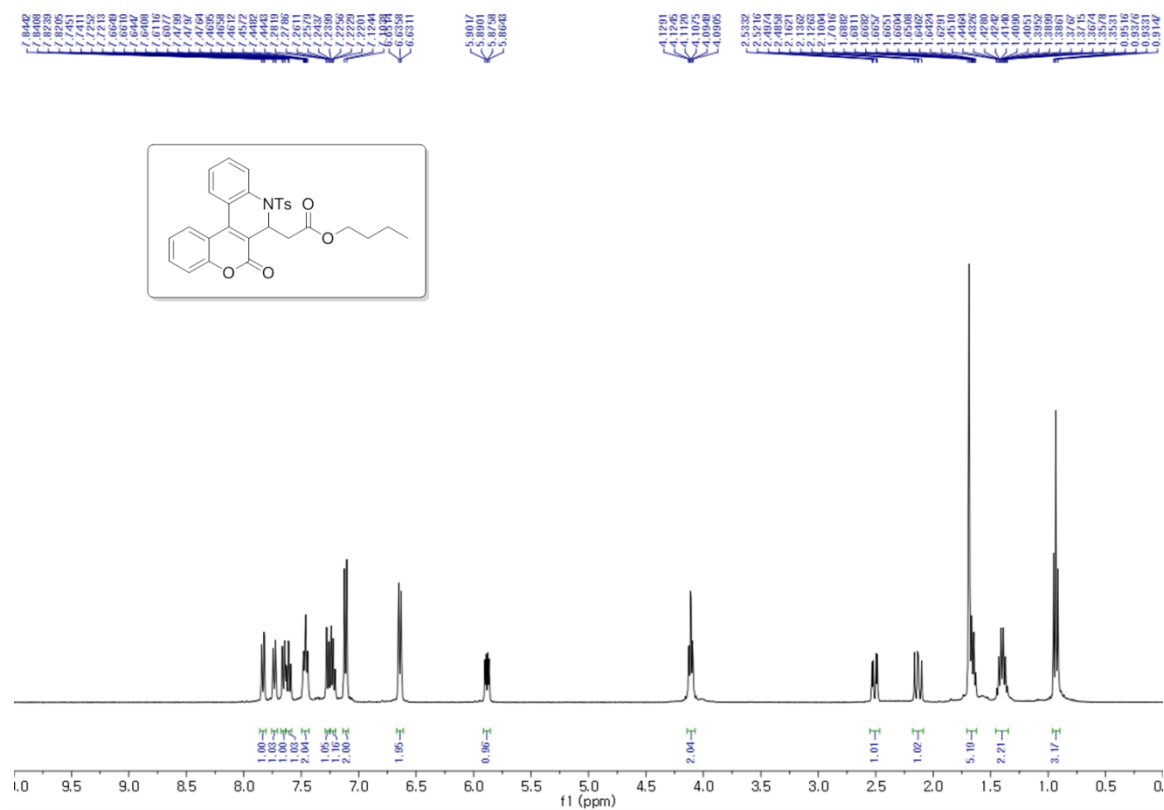
100 MHz, ^{13}C NMR in CDCl_3

Butyl 2-(10-(Dimethylamino)-7-oxo-6,7-dihydrochromeno[3,4-c]chromen-6-yl)acetate (5n)

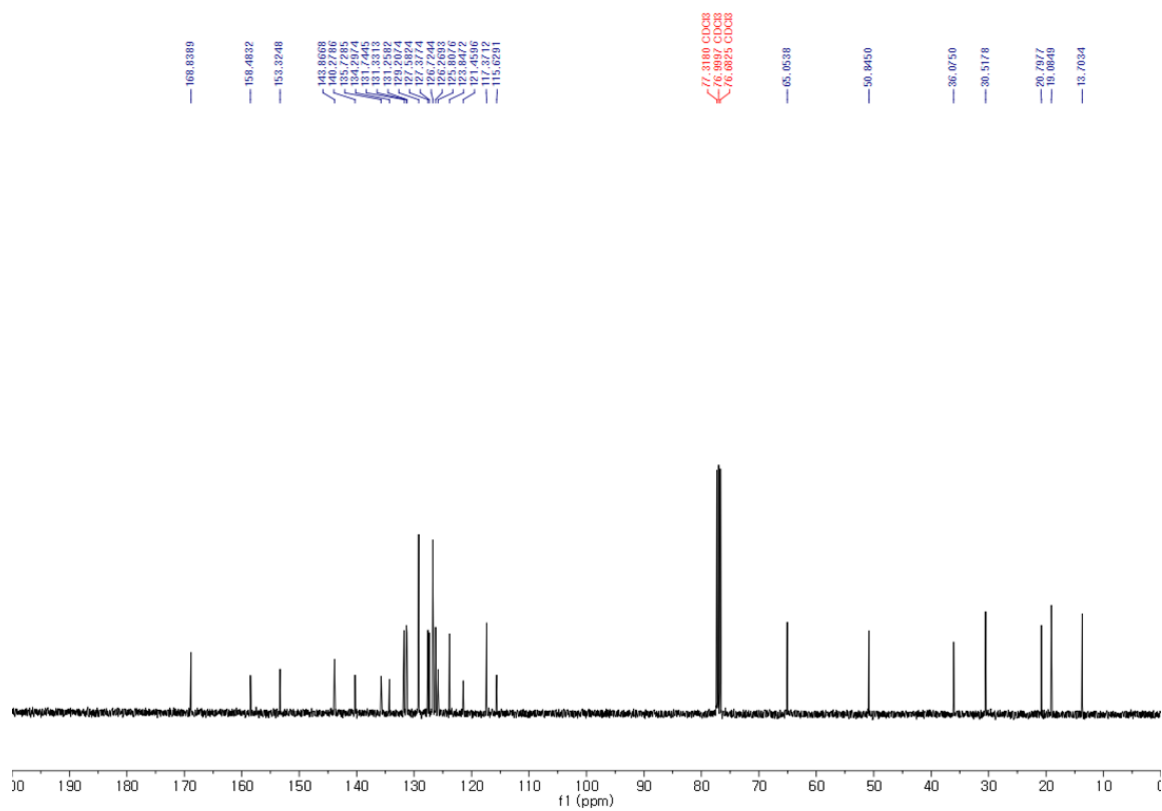


13C NMR spectrum of compound 10b in CDCl₃. The x-axis is labeled 'f1 (ppm)' and ranges from 0 to 200. The spectrum shows several peaks, with the most prominent ones at 77.015, 76.819, and 76.622 ppm, which are labeled as CDCl₃. Other peaks are labeled with their chemical shifts: 169.8106, 159.6179, 156.1354, 154.7855, 152.3882, 140.8658, 132.3356, 127.7197, 127.1887, 124.9730, 119.6533, 119.6068, 113.7753, 109.0510, 105.4554, 88.7594, 77.015 CDCl₃, 76.819 CDCl₃, 76.622 CDCl₃, 70.0949, 64.0426, 40.0086, 36.4260, 30.6222, 19.0030, and 13.6882.

Butyl 2-(6-Oxo-8-tosyl-7,8-dihydro-6H-chromeno[3,4-c]quinolin-7-yl)acetate (5o)



400 MHz, ^1H NMR in CDCl_3



100 MHz, ^{13}C NMR in CDCl_3