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Electrochemical techniques have long been heralded for their innate sustainability as efficient methods for achieving redox reactions. Carbonyl desaturation, as a fundamental organic oxidation, is an oft-employed transformation to unlock adjacent reactivity. To date, the most reliable methods for achieving it have relied on transition metals (Pd/Cu) or stoichiometric reagents based on I, Br, Se, or S. Herein we report an operationally simple pathway to such structures from enol silanes and phosphates using electrons as the primary reagent. This electrochemically driven desaturation exhibits a broad scope across an array of carbonyl derivatives, is easily scalable (1-100g), and can be predictably implemented into synthetic pathways using experimentally or computationally derived NMR shifts. Mechanistic interrogation suggests a radical-based reaction pathway.

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Electrochemically Driven Desaturation of Carbonyl Compounds

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ABSTRACT: Electrochemical techniques have long been heralded for their innate sustainability as efficient methods for achieving redox reactions. Carbonyl desaturation, as a fundamental organic oxidation, is an oft-employed transformation to unlock adjacent reactivity. To date, the most reliable methods for achieving it have relied on transition metals (Pd/Cu) or stoichiometric reagents based on I, Br, Se, or S. Herein we report an operationally simple pathway to such structures from enol silanes and phosphates using electrons as the primary reagent. This electrochemically driven desaturation exhibits a broad scope across an array of carbonyl derivatives, is easily scalable (1-100g), and can be predictably implemented into synthetic pathways using experimentally or computationally derived NMR shifts. Mechanistic interrogation suggests a radical-based reaction pathway.

The removal of one molecule of hydrogen adjacent to a carbonyl compound is one of the simplest organic oxidation reactions known and is a widely employed tactic in synthesis.¹⁻³ Classic methods for accomplishing this transformation involve indirect α -functionalization approaches traversing through halide, sulfur, and selenium derivatives.⁴⁻⁸ Chemoselective methods that directly afford enones from ketones are indeed more desirable and have been extensively explored (**Figure 1**). Amongst them, the Saegusa-Ito reaction, discovered in 1978, remains the most oft-applied method for such applications.⁹ In its canonical implementation, formation of a silyl enol ether, followed by exposure to stoichiometric (from 0.5–1.0 equiv) quantities of Pd delivers the desired α,β -desaturated product.⁹ Variants that employ a co-oxidant (e.g. O₂, quinone or [Cu]) to lower the [Pd]-levels have also been reported.^{10,11} Another popular approach involves the use of stoichiometric IBX through an SET-based process.^{12,13} Recently, two new methods have also appeared from the Newhouse and Dong groups that allow the use of catalytic amounts of palladium and copper, respectively.¹⁴⁻²⁰ These methods expand the scope of available desaturation methods to nitriles, esters, lactones, and lactams and do not require the preparation of enol ethers. Since the essence of this reaction involves a formal 2-electron oxidation, it stands to reason that even simpler redox approaches might be developed. Indeed, in 1973, the Shono group demonstrated that enol acetates can undergo anodic oxidation in AcOH as solvent to afford the corresponding enone. In order to deliver synthetically useful yields of product, α -substitution was required with simple cyclohexanone-substrates providing <10% enone.^{21,22} Similar reactivity was also observed by Moeller and co-workers in their studies of silyl enol ether alkylation where

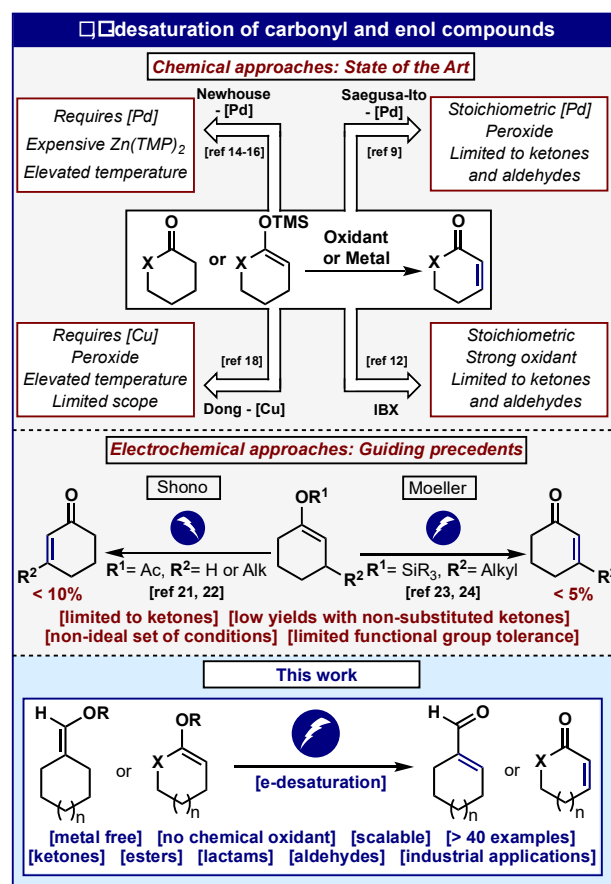


Figure 1. Desaturation of carbonyl and enol compounds: State-of-the-art, electrochemical precedents, and Electrochemically Driven Desaturation (EDD).

trace amounts of enone were isolated as a by-product (<5% yield).²³⁻²⁵ Building on these encouraging studies, we report herein an electrochemically driven approach to elicit desaturation that requires no metals or chemical oxidants and features a broad substrate scope with inherent scalability. The utility of this method is placed in the context of the most popular and recently disclosed methods, and a simple method for predicting reactivity is also described.

The TMS-enol ether of cyclododecanone **1** was chosen for initial optimization of electrochemically driven desaturation (EDD); an abbreviated summary is depicted in **Table 1** (see SI for more extensive tabulation). Trial runs using the literature

EDD Reaction optimization		
entry	deviation from above	yield (%) ^a
1	none	22 (17)
2	TEAOTs, AcOK in acetic acid (<i>Shono, enol acetate, ref 21</i>)	n.d.
3	LiClO ₄ , 3.5% lutidine in MeCN/PrOH (1:1) (<i>Moeller, ref 23/25</i>)	8
4	TBAPF ₆ instead of LiClO ₄	n.d.
5	LiBF ₄ instead of LiClO ₄	12
6	NaOTs instead of LiClO ₄	14
7	NaSbF ₆ instead of LiClO ₄	30
8	RVC anode, NaSbF ₆ instead of LiClO ₄	< 5%
9	Platinum anode, NaSbF ₆ instead of LiClO ₄	n.d.
10	Nickel foam anode, NaSbF ₆ instead of LiClO ₄	19
11	RVC cathode, NaSbF ₆ instead of LiClO ₄	12
12	Acetone instead of MeCN, NaSbF ₆ instead of LiClO ₄	14
13	DMF instead of MeCN, NaSbF ₆ instead of LiClO ₄	11
14	DMA instead of MeCN, NaSbF ₆ instead of LiClO ₄	18
15	TEA instead of lutidine, NaSbF ₆ instead of LiClO ₄	n.d.
16	Collidine instead of lutidine, NaSbF ₆ instead of LiClO ₄	45 (39)
17	20% collidine, , NaSbF ₆ instead of LiClO ₄	55
18	30% collidine, NaSbF ₆ instead of LiClO ₄	70 (62)
19	50% collidine, NaSbF ₆ instead of LiClO ₄	68
20	under air	65
21	non-anhydrous MeCN	64
22	no 2,4,6-collidine	n.d.
23	no NaSbF ₆	n.d.
24	no electrolysis	n.d.

Table 1. Optimization of the EDD reaction. ^aIsolated yield. n.d.: not detected

conditions noted above provided only trace quantities of product. Our prior experiences for electrochemical reaction development served as a template for this study.²⁶⁻³³ A myriad of electrolytes, electrodes, and solvents were evaluated. First, an electrolyte screen revealed that inorganic non-nucleophilic salts proved optimal (entries 4-7) with NaSbF₆ (\$0.56/gram) delivering the highest conversion. The use of a graphite anode was found to be essential whereas several materials were suitable for the cathode (entries 8-11). Ultimately the low cost (ca. \$0.1/cm²) and efficiency of graphite motivated its selection for both electrode materials. Of all solvents screened, MeCN, acetone, DMA, and DMF could be employed but MeCN gave the highest yield across a broad range of substrates. A variety of bases were also tested with heteroaromatic amines proving most promising (entries 15-16). 2,4,6-Collidine (30% v/v – entry 18) emerged as optimum providing the desired product **2** in 62% isolated yield. The final set of EDD conditions tolerates exogenous air and moisture, lead to completion in 90 minutes or less, and can be setup in minutes, using a simple undivided cell and a commercial potentiostat.

EDD could be applied to a diverse set of carbonyl derivatives as illustrated in **Table 2**. As there are numerous desaturation methods available to the practitioner all of the results are placed into context with direct comparison to the powerful Pd, Cu, and hypervalent iodine-based systems. With regards to ketone substrates, both cyclic (from 5-15 membered rings) and acyclic derivatives could be employed (**2-17**). This stands in contrast to recently developed catalytic methods that operate smoothly on cyclic systems but fail on acyclic ones (**14** and **15**).^{15,18} As EDD of ketones is reliant on formation of a silyl enol ether, regioselective desaturation is possible simply by tuning conditions (i.e. **7** vs. **8**). Substituents at the α -, β -, and γ -position are all tolerated as well as Lewis-basic heteroatoms (**16**), alkynes (**10**), proximal cyclopropanes (**15**), esters (**16** and **17**), TBS protected alcohols (**11**), and acid-labile ketals (**6**). A two-step *in situ* EDD protocol was also developed to afford enones

6, **12** and **17** in decent yields directly from the respective ketone starting material. Esters and lactones, substrate classes that have only recently succumbed to direct dehydrogenation,^{14,17,18} can also be subjected to EDD using the corresponding diphenylphosphate ester derivatives (**18-31**). Such enol derivatives are easily prepared and hydrolytically stable unlike the corresponding silyl ketene acetals. Simple lactones and benzolactones, which are outside the substrate scope of IBX and Saegusa methodologies can be smoothly dehydrogenated. As with EDD of ketones, the functional group tolerance here is also broad including aryl halides (**22** and **24**), CF₃ (**30**), oxidizable anisoles (**23**), tosyl protected amines (**29**), and alkenes (**32**). In addition, α -aryl lactones also afforded the desired products in satisfactory yields (**21-23** and **25**). The difficulty of desaturating such substrates has been documented by Dong. They are often alternatively accessed through cross-coupling on the corresponding vinyl halide derivatives or through α -bromination/elimination sequences.^{34,35} It worth noting that while comparing EDD with other precedented methods, the set of conditions reported by the Newhouse group was found to provide the desaturated α -aryl lactones in moderate yields. Next, the particularly difficult class of aldehydes were investigated (**32-34**, silyl enol ethers employed). Due to the instability of such desaturated products the yields observed were moderate (and accompanied by 5-11% of recovered parent aldehyde). Other direct catalytic methods for this dehydrogenation are not applicable, with the Saegusa protocol being the only other option. Lactams, a similarly challenging class of carbonyls, were surveyed as diphenylphosphate-ketenimine acetals, and in select cases (**35-37**) were viable.

The scalability of the method was evaluated using cyclopentadecanone-derived silyl enol ether **38** on a 4-gram scale (**Scheme 1A**) to afford enone **12**, a key intermediate in the synthesis of (*R*)-muscone **39**, a valuable ingredient in the fragrance industry.³⁶ A simple increase of current (from 10 mA to 300 mA) and the use of alternating polarity (to avoid any accumulation of material at the anode) enabled the standard EDD reaction to smoothly deliver compound **12** in 66% yield. To increase scale further, the design and assembly of a flow apparatus containing six reaction cells was undertaken (**Scheme 1A**). After optimization, 100 grams of **38** were successfully converted to compound **12** by increasing the current value to 3.6 A (compared to 300 mA in batch) to obtain 61% isolated yield and 27% recovered starting material **38**.

From a mechanistic standpoint, the EDD reaction accomplishes the formal removal of two electrons and one proton from the corresponding silyl enol ether. The electrochemical oxidation of silyl enol ethers has been previously disclosed by Moeller and studied mechanistically by Wright.²⁵ These studies demonstrated that initial anodic oxidation leads to the formation of an enol ether radical cation intermediate by using a cyclopropyl ring-opening clock. A similar conclusion was made by Moeller and co-workers when they oxidized various alkyl-enol ethers and thio-enol ethers.³⁷ It is therefore postulated that EDD proceeds through three elementary steps: (1) formation of the radical cation intermediate **40**; (2) deprotonation to afford **41**; (3) a second oxidation to form oxonium **42** which affords the desired enone product **5** (**Scheme 1B**, panel A). To provide empirical support for the proposed mechanism, three control experiments were designed and tested (**Scheme 1B**, panel B to D). First, the standard reaction conditions under air revealed the formation of the 1,2-diketone side product **44** in 9% yield. The amount of this by-product decreases to 4% when the reaction performed under inert atmosphere. In addition,

Scope of the EDD reaction

NaSbF₆ (0.15 M)
 MeCN/2,4,6-collidine (7:3)
 10 mA, rt, 1.5 to 4.0 h
 [e-desaturation]
 R = TMS, P(O)(OPh)₂; X = CH₂, O, N

Comparison to State-of-the-Art:

[Pd1] = Saegusa-Ito (cat. [Pd] with oxidant)
 [Pd2] = Newhouse (cat. [Pd] with Zn(TMP)₂ or LiTMP)
 [Cu] = Dong (cat. [Cu] with (O^tBu)₂)
 [IBX] = Nicolaou (stoichiometric IBX in DMSO)

Ketones (via TMS-enol ethers)

[EDD]: 62% [Pd1]: 52% [Pd2]: 6% [Cu]: n.d. [IBX]: 51%	[EDD]: 62% [Pd1]: 85% [Pd2]: 71% [Cu]: n/a [IBX]: 70%	[EDD]: 81% ^a [Pd1]: 46% [Pd2]: 75% [Cu]: traces [IBX]: n.d.	[EDD]: 67% [Pd1]: 87% [Pd2]: 63% [Cu]: 7% [IBX]: 60%	[EDD]: 64%, 35% ^b [Pd1]: 92% [Pd2]: 68% [Cu]: n.d. [IBX]: 53%	[EDD]: 78% [Pd1]: n.d. [Pd2]: n/a [Cu]: n/a [IBX]: 9%	[EDD]: 72% [Pd1]: 45% [Pd2]: 71% [Cu]: 52% [IBX]: 19%	[EDD]: 33% ^a [Pd1]: 88% [Pd2]: 74% [Cu]: 13% [IBX]: 85%	[EDD]: 50% [Pd1]: n.d. [Pd2]: 19% [Cu]: 39% [IBX]: 30%	[EDD]: 67% [Pd1]: 72% [Pd2]: 75% [Cu]: 46% [IBX]: 31%
[EDD]: 44%, 54% ^b [Pd1]: 65% [Pd2]: traces [Cu]: n.d. [IBX]: 83%	[EDD]: 88% [Pd1]: 81% [Pd2]: 31% [Cu]: n/a [IBX]: 58%	[EDD]: 46% [Pd1]: 56% [Pd2]: n/a [Cu]: n.d. [IBX]: 34%	[EDD]: 38% [Pd1]: 56% [Pd2]: n/a [Cu]: n/a [IBX]: 31%	[EDD]: 50% ^c [Pd1]: 55% [Pd2]: 67% [Cu]: n.d. [IBX]: 38%	[EDD]: 27, 24% ^b [Pd1]: 51% [Pd2]: 94% [Cu]: 45% [IBX]: n.d.				

Esters (via diphenylphosphate-ketene acetals)

[EDD]: 41% [Pd1]: n/a [Pd2]: n/a [Cu]: 73% [IBX]: n/a	[EDD]: 55% [Pd1]: n/a [Pd2]: n/a [Cu]: n/a [IBX]: n/a	[EDD]: 53% [Pd1]: n/a [Pd2]: 47% [Cu]: n/a [IBX]: n/a	[EDD]: 54% [Pd1]: n/a [Pd2]: 31% [Cu]: n/a [IBX]: n/a	[EDD]: 36% [Pd1]: n/a [Pd2]: 39% [Cu]: n/a [IBX]: n/a	[EDD]: 41% [Pd1]: n/a [Pd2]: 13% [Cu]: n/a [IBX]: n/a	[EDD]: 58% [Pd1]: n/a [Pd2]: 15% [Cu]: traces [IBX]: n/a
[EDD]: 64% [Pd1]: n/a [Pd2]: 44% [Cu]: n/a [IBX]: n/a	[EDD]: 54% [Pd1]: n/a [Pd2]: 81% [Cu]: n.d. [IBX]: n/a	[EDD]: 71% [Pd1]: n/a [Pd2]: 72% [Cu]: n.d. [IBX]: n/a	[EDD]: 81% [Pd1]: n/a [Pd2]: 44% [Cu]: n.d. [IBX]: n/a	[EDD]: 54% [Pd1]: n/a [Pd2]: 62% [Cu]: n.d. [IBX]: n/a	[EDD]: 52% [Pd1]: n/a [Pd2]: n/a [Cu]: n/a [IBX]: n/a	[EDD]: 34% [Pd1]: n/a [Pd2]: n/a [Cu]: 41% [IBX]: n/a

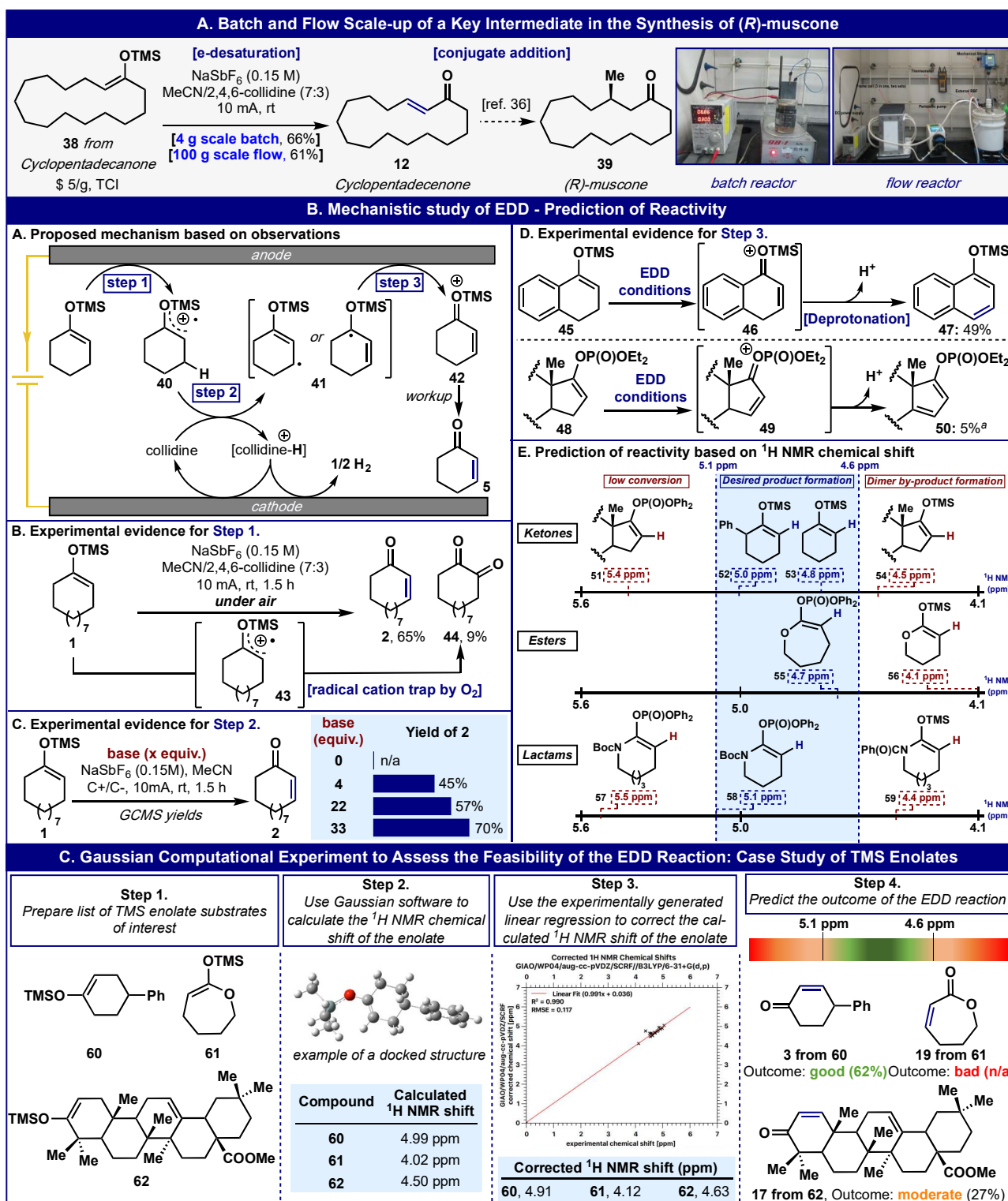
Lactams (via diphenylphosphate-keteniminyl acetals) and Aldehydes (via TMS-enol ethers)

[EDD]: 38% ^b [Pd1]: 74% [Pd2]: n/a [Cu]: n/a [IBX]: 11%	[EDD]: 37% ^c [Pd1]: 61% [Pd2]: n/a [Cu]: n/a [IBX]: 7%	[EDD]: 50% [Pd1]: 55% [Pd2]: n/a [Cu]: n/a [IBX]: n.d.	[EDD]: 58% ^d [Pd1]: n/a [Pd2]: n/a [Cu]: 48% [IBX]: n.a.	[EDD]: 69% [Pd1]: n/a [Pd2]: n/a [Cu]: 32% [IBX]: n/a	[EDD]: 24% [Pd1]: n/a [Pd2]: n/a [Cu]: 30% [IBX]: n/a

Table 2. Scope of the EDD reaction. ^aYield based on GCMS conversion. ^bUsing in-situ protocol. ^cYield based on NMR conversion. ^dPrepared from phenyl acetate-keteniminyl acetals. n/a: not applicable. n.d.: not detected.

the parent ketone is the only product observed when water is added to the reaction. These results suggest that formation of compound **44** derived from molecular oxygen via a radical type mechanism. Next, to support the crucial role of the base in the deprotonation event, the EDD reaction conditions were applied to compound **1** with various amounts of 2,4,6-collidine

(**Scheme 1B**, panel C). No desired product was obtained when base was excluded, reinforcing the importance of the base for the EDD reaction and its implication in the deprotonation step 2 (**Scheme 1**, panel A). Furthermore, a noticeable improvement was observed between the reaction efficiency and the base



Scheme 1. (A) Batch and flow scale-up of a key intermediate in the synthesis of (*R*)-muscone. (B) Mechanistic study of the EDD reaction. (C) Gaussian computational experiment to assess the feasibility of the EDD reaction: Case study of TMS enolates. ^aYield based on LCMS conversion.

concentration. Finally, a third experiment was conducted to explore the formation of an oxonium intermediate (Scheme 1B, panel D). Compound 45 was subjected to the reaction conditions affording naphthalene 47 in 49% yield. The formation of this product is in accordance with the formation of intermediate (46), which after elimination would deliver 47. Similarly,

when the diethylphosphate 48 derived from dehydroepiandrosterone was subjected to EDD, diene 50 was also observed as a side-product.

During these studies it was empirically noted that ketone, lactam and lactone substrates whose vinylic proton shifts registered between 4.6 and 5.1 ppm showed good conversion to the

desaturated product. However, compounds with NMR shifts lower than 4.6 ppm led to the formation of dimer, hydrolysis, and other by-products. Compounds with NMR shifts higher than 5.1 ppm showed low reactivity toward oxidation. Based on these findings and Moeller's reports,³⁷ it is possible to identify a trend between the oxidation potential of the enol ether (to form a radical cation intermediate similar to **40**) and the electron density of the pi-system (see SI, figure S10 for details). Compounds such as dehydroepiandrosterone-phosphate **51** and the 8-membered lactam **57** cannot be oxidized under the EDD reaction conditions due to the deshielded vinylic proton correlating to a higher oxidation potential (CV = 2.06 to 2.47 V). When the vinylic proton is shielded, the oxidation potential becomes lower and reactivity toward EDD is observed (CV = 1.54 to 1.72 V). On the other hand, compounds such as dehydroepiandrosterone-TMS **54**, lactone-TMS **56**, and lactam-TMS **59** whose vinylic protons that are too shielded, afforded low amounts of the desaturated product (CV = 1.32 to 1.4 V). In this case, the enol derivatives react as nucleophilic radicals rather than electrophilic radical cations due to greater cationic stabilization, which renders the EDD pathway less favorable.^{38,39} Accordingly, this explains why electron withdrawing enol-phosphates are required for esters and lactams in EDD rather than the corresponding silyl enol ethers.

Based on these observations, one could imagine predicting the outcome of the EDD reaction by calculating the NMR shift of the TMS enol ethers of interest (**Scheme 1C**, Step 1). With this idea in mind, a simple protocol using GAUSSIAN16, a quantum chemical calculation software, was developed. This protocol gives access to a calculated NMR shift based on the shielding constants using the gauge-including atomic orbital (GIAO) method in the WP04 database (functional) with an aug-cc-pVDZ basis set using tetramethylsilane as a reference (**Scheme 1C**, Step 2). Next, to obtain a more accurate value, the NMR shift value was corrected using an experimentally generated linear regression (**Scheme 1C**, Step 3 and see SI for detailed graphical step-by-step guide). Finally, the corrected NMR shift can be used to predict the efficiency of the EDD reaction (**Scheme 1C**, Step 4). To our knowledge, this is a rare example of using calculated NMR shift to predict the scope of an organic methodology.⁴⁰

The desaturation of carbonyl derivatives is a basic reaction of utmost utility in organic chemistry as it unlocks a variety of useful downstream transformations. Studies in this area continue to the present day; the contribution reported herein affords a potentially simple solution to this problem. Drawing from early studies in electrosynthesis and more recent mechanistic studies of anodic enol-oxidation, a useful protocol for EDD has been uncovered. This oxidation protocol can be performed in an undivided cell, on multiple scales, without strict removal of air or water, and in the absence of expensive metals, ligands, or stoichiometric organic oxidants. As with the oxidation of alcohols, for which numerous methods are available, this desaturation study has been placed into context with the most powerful methods currently available to aid the practitioner. Finally, a simple ¹H NMR-based rubric was created to allow users to experimentally or computationally predict which substrates are suitable for EDD, which should facilitate its rapid adoption.

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Electrochemically Driven Desaturation of Carbonyl Compounds

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GENERAL METHODS

Reagents were purchased at the highest commercial quality and used without further purification unless otherwise stated. Isolated yields refer to chromatographically and spectroscopically (^1H NMR) homogeneous material, unless otherwise stated. Acetonitrile (MeCN), methyl tert-butyl ether (MTBE), dichloromethane (DCM), *N,N*-dimethylformamide (DMF), and tetrahydrofuran (THF) were obtained by passing the previously degassed solvents through an activated alumina column. For determination of ^1H NMR yields, cyclohexanecarboxaldehyde, 1,4-bis(trifluoromethyl)benzene or 1,3,5-trimethoxybenzene were used as internal standards (automatic baseline correction was applied). Reactions were monitored by thin layer chromatography (TLC) carried out on 0.25 mm E. Merck silica plates (60 F₂₅₄), using short-wave UV light (254 nm) for visualization, and *p*-anisaldehyde or potassium permanganate as developing agents. Flash column chromatography was performed using E. Merck silica gel (60, particle size 0.043–0.063 mm) or basic Al₂O₃. NMR spectra were recorded on Bruker DRX-600, DRX-500, and AMX-400 instruments, and chemical shifts for ^1H and ^{13}C NMR are reported relative to the solvent peaks (7.26 ppm for ^1H NMR in CDCl₃, 77.16 ppm for ^{13}C NMR in CDCl₃). $^{19}\text{F}\{^1\text{H}\}$ NMR data were calibrated using trichlorofluoromethane as an external reference (0.0 ppm). $^{31}\text{P}\{^1\text{H}\}$ NMR data were calibrated using 85% H₃PO₄ as an external reference (0.0 ppm). The following abbreviations were used to explain NMR peak multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, m = multiplet, br = broad. High-resolution mass spectra (HRMS) were recorded on an Agilent LC/MSD TOF mass spectrometer using ESI ion source, a Waters LC-TOF (I-Class and G2-XS) mass spectrometer using ESI or APCI ion sources, and a Thermo Fisher Scientific LTQ Orbitrap XL mass spectrometer using ESI ion source. GC-MS (EI) was recorded on Agilent 7820A GC systems and 5975 Series MSD using *n*-decane as an internal standard.

SOURCE OF REAGENTS:

NaSbF₆ (technical grade) was purchased from Sigma-Aldrich [CAS 16925-25-0, cat# 237981] and was ground carefully prior to use. 2,4,6-collidine (99%) was purchased from Sigma-Aldrich [108-75-8, cat# 142387] or Alfa Aesar [cat# 10218070]. Commercial chemicals were obtained from suppliers and used as received unless otherwise specified.

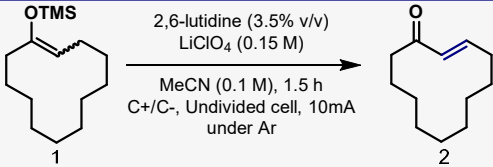
ELECTRODE MATERIALS/DIMENSIONS:

The graphite electrodes used in this work were bought from IKA (for 0.1–0.2 mmol scale). The reticulated vitreous carbon (RVC) electrodes were prepared from commercial RVC foam (pore size of 80 ppi, purchased from Ultramet). Other electrodes used or tested in this work were obtained from IKA (<https://www.ika.com/en>). For experiments using an ElectraSyn vial, the dimensions of the electrodes were approximately W7 × D1.5 × H55 mm (with the submerged exterior surface of the electrode approximately W7 × D1.5 × H20 mm), unless otherwise stated. For experiments on larger scales, dimensions of electrodes have been specified in the relevant experimental section.

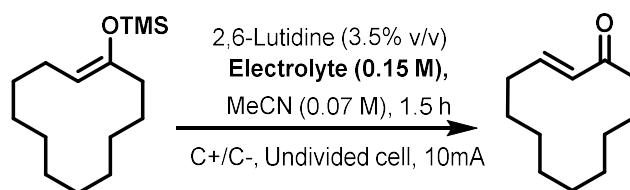
OPTIMIZATION OF REACTION PARAMETERS FOR ELECTROCHEMICAL DESATURATION

All optimization reactions were carried out on 0.05-0.30 mmol scale. The crude reaction mixture was analyzed by GC/FID using *n*-decane as internal standard.

OPTIMIZATION TABLE PRESENTED IN THE MANUSCRIPT

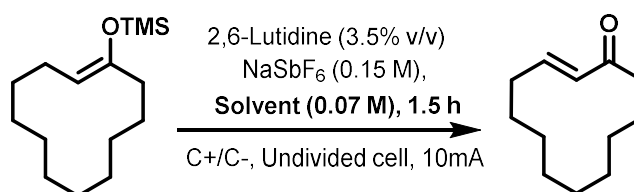
EDD Reaction optimization		
		
entry	deviation from above	yield (%)
1	none	22 (17)
2	TEAOTs, AcOK in acetic acid (<i>Shono, enol acetate</i>)	n.d.
3	LiClO ₄ , 3.5% lutidine in MeCN/PrOH (1:1) (<i>Moeller</i>)	8
4	TBABF ₄ instead of LiClO ₄	n.d.
5	LiBF ₄ instead of LiClO ₄	12
6	NaOTs instead of LiClO ₄	14
7	NaSbF ₆ instead of LiClO ₄	30
8	RVC anode, NaSbF ₆ instead of LiClO ₄	< 5%
9	Platinum anode, NaSbF ₆ instead of LiClO ₄	n.d.
10	Nickel foam anode, NaSbF ₆ instead of LiClO ₄	19
11	RVC cathode, NaSbF ₆ instead of LiClO ₄	12
12	Acetone instead of MeCN, NaSbF ₆ instead of LiClO ₄	14
13	DMF instead of MeCN, NaSbF ₆ instead of LiClO ₄	11
14	DMA instead of MeCN, NaSbF ₆ instead of LiClO ₄	18
15	TEA instead of lutidine, NaSbF ₆ instead of LiClO ₄	n.d.
16	Collidine instead of lutidine, NaSbF ₆ instead of LiClO ₄	45 (39)
17	20% collidine, , NaSbF ₆ instead of LiClO ₄	55
18	30% collidine, NaSbF ₆ instead of LiClO ₄	70 (62)
19	50% collidine, NaSbF ₆ instead of LiClO ₄	68
20	under air	65
21	non-anhydrous MeCN	64
22	no 2,4,6-collidine	n.d.
23	no NaSbF ₆	n.d.
24	no electrolysis	n.d.

EVALUATION OF ELECTROLYTES (TABLE S1)



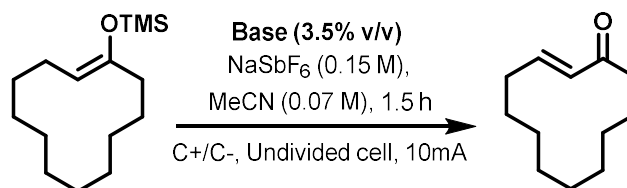
Entry	Electrolyte	Product yield
1	LiClO ₄	22%
2	LiBF ₄	12%
3	TBABF ₄	No product
4	TBAPF ₆	No product
5	TEAOTs	No product
6	EMIM-OTf	No product
7	EMIM-BF ₄	No product
8	EMIM-PF ₆	No product
9	LiOTf	11%
10	NaOTs	12%
11	AgOTs	8%
12	NaNO ₂	No product
13	NaBF ₄	No product
14	NaNO ₃	No product
15	NaSbF ₆	30%
16	LiSbF ₆	No product

EVALUATION OF SOLVENTS (TABLE S2)



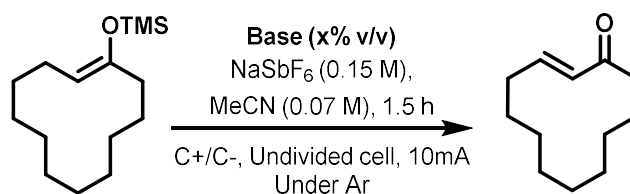
Entry	Solvent	Product yield
1	MeCN:DCM	19%
2	MeOH	No product
3	DMF	11%
4	DMA	18%
5	DMSO	No product
6	Acetone	14%

EVALUATION OF BASES (TABLE S3)



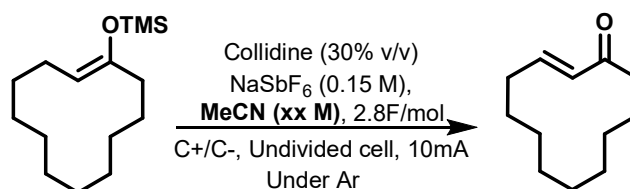
Entry	Base (X% v/v)	Additive	Product yield
1	Collidine 3.5%	Under Ar	45% (39%)
2	TEA 3.5%	Under Ar	>5%
3	DIPEA 3.5%	Under Ar	No product
4	DBU 3.5%	Under Ar	No product
5	DMAP 3.5%	Under Ar	No product
6	MeO-pyr 3.5%	Under Ar	No product

EVALUATION OF THE BASE AMOUNT (TABLE S4)



Entry	Base (X% v/v)	Product yield
1	Collidine 50%	68%
2	Lutidine 50%	15%
3	Collidine 90%	39%
4	Lutidine 90%	11%
5	Collidine 10%	51%
6	Collididne 20%	57%
7	Collidine 30%	70% (62% isolated)
8	Collidine 40%	67%

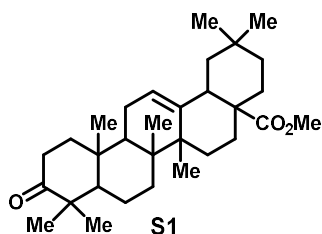
EVALUATION OF CONCENTRATION (TABLE S5)



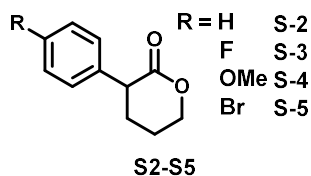
Entry	Concentration (X M)	Product yield
1	0.017	62%
2	0.034	70%
3	0.07	70%
4	0.1	63%

KETONE, ESTER, ALDEHYDE, AND LACTAM SUBSTRATES SYNTHESIS

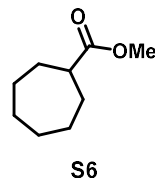
Starting materials **S1-S19** were synthesized using procedure from the literature (please see below for details). Other commercial available substrates were obtained from various suppliers and used as received. All reactions described below were carried out under an argon atmosphere, unless otherwise specified.



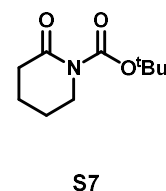
J. Asian Nat. Prod. Res., 2008, 10, 271-276
RSC Adv., 2014, 4, 10862-10874



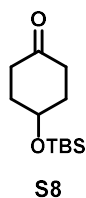
Tet. Let., 2003, 44, 365-368



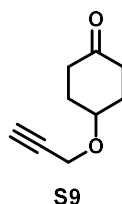
U.S. Patent No. 6,534,542



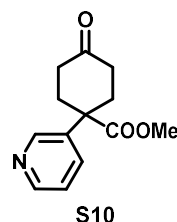
JOC, 2010, 75, 2610-2618



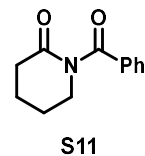
Synlett, 2011, 18, 2701-2704



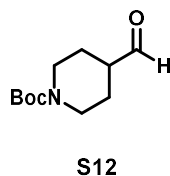
JACS, 2013, 135, 11657-11662



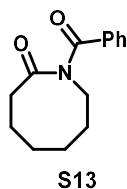
JOC, 2017, 82, 9851-9858



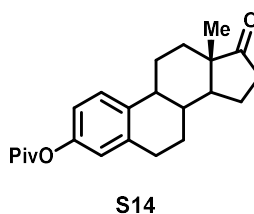
Adv. Syn. Cat., 2014, 356, 2321-2329



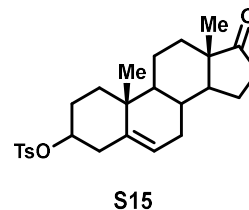
Org. Let., 2019, 21, 9188-9193



Org. Let., 2019, 21, 9188-9193

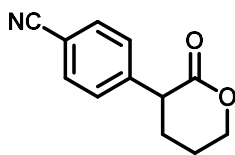


ACIE, 2014, 53, 6791-6794



Chem. Sci., 2017, 8, 6918-6923

Compound S16



Under an argon atmosphere, a culture tube was charged with **S5** (102.0 mg, 0.4 mmol, 1 equiv.), NaCN (21.6 mg, 0.44 mmol, 1.1 equiv.), Zn (1.3 mg, 0.02 mmol, 0.05 equiv.), and MeCN (1 mL). Then 0.16 mL (1.0 mol %, 0.004 mmol) of 0.025 M Pd catalyst solution containing Pd₂dba₃ (45.8 mg, 0.05 mmol, 0.12 equiv.) and *t*-Bu₃P (20.2 mg, 0.1 mmol, 0.25 equiv.) in 4 mL THF was added. The mixture was heated at 70°C for 2 h, and then cooled to r.t. Insoluble materials were removed by filtration passing through a short plug of Celite, and the filtrate was concentrated under reduced pressure. Preparative thin-layer chromatography (DCM/EtOAc, 92:8) afforded **S16** as an off-white solid (78.3 mg, 0.389 mmol, 97% yield).

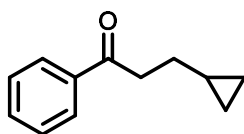
R_f = 0.3 (hexanes/EtOAc, 1:1)

¹H NMR (400 MHz, CDCl₃): δ 7.67–7.64 (m, 2H), 7.38–7.35 (m, 2H), 4.55–4.44 (m, 2H), 3.82 (dd, *J* = 10.4, 6.9 Hz, 1H), 2.35–2.29 (m, 1H), 2.10–2.0 (m, 3H).

¹³C NMR (151 MHz, CDCl₃): δ 171.4, 144.2, 132.6, 129.4, 118.7, 111.6, 69.4, 47.2, 28.1, 22.1.

HRMS (ESI): calc. for C₁₂H₁₂NO₂ [M+H]⁺ 202.0868, found 202.0871.

Compound S17



A culture tube was charged with LiCl (13 mg, 0.3 mmol, 3.0 equiv.). Next, NHPI-cyclopropane (23, mg, 0.1 mmol, 1.0 equiv.), Zn powder (13 mg, 0.2 mmol, 2.0 equiv.), and Ni(ClO₄)₂•6H₂O (7.4mg, 0.04 mmol, 0.2 equiv.) were added. A stir bar was added, and the culture tube was evacuated. The tube was backfilled with Ar from a balloon, and 1-Phenylprop-2-enone (26 mg, 0.2 mmol, 2.0 equiv.) was added with a syringe. To the reaction mixture was added 0.25 mL MeCN (0.4 M), and the mixture was stirred overnight at r.t. After at least 12 h, H₂O (distilled) and sat. aq. NH₄Cl solution (1:1 v/v) were added. The mixture was extracted with Et₂O (3 x), and the organic layer was dried over MgSO₄. The crude product was purified by silica gel flash column chromatography (Hex/EtOAc, 95:5) to afford **S17** as a colorless oil (10 mg, 0.054 mmol, 54% yield).

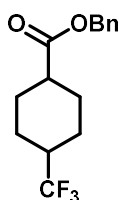
R_f = 0.3 (hexanes/EtOAc, 95:5)

¹H NMR (400 MHz, CDCl₃): δ 8.00 – 7.97 (m, 2H), 7.59 – 7.55 (m, 1H), 7.47 (t, *J* = 7.6 Hz, 2H), 3.10 (t, *J* = 7.4 Hz, 2H), 1.66 (q, *J* = 7.2 Hz, 2H), 0.81 – 0.76 (m, 1H), 0.47 – 0.45 (m, 2H), 0.09 (h, *J* = 4.5 Hz, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 200.4, 137.1, 132.9, 128.6, 128.1, 38.7, 29.6, 10.72, 4.7.

GCMS: calc. for C₁₂H₁₄O [M]⁺ 174.1, found 174.1.

Compound S18



To a solution of 4-(trifluoromethyl)benzoic acid (1.6 g, 8.9 mmol, 1 equiv.) in DMF (8 ml) was added K₂CO₃ (2.5 g, 17.8 mmol, 2 equiv.) and benzylbromide (1.7 ml, 26.7 mmol, 3 equiv.). The reaction mixture heated to 80 °C for 5 h. After completion, the solution diluted in EtOAc (200 mL) and washed with brine (100 mL). The organic layer dried over Na₂SO₄ and evaporated under reduced pressure. The crude residue purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford compound **S18** as a yellowish oil (2.19 g, 8.65 mmol, 65% yield).

R_f = 0.5 (hexanes/EtOAc, 9:1)

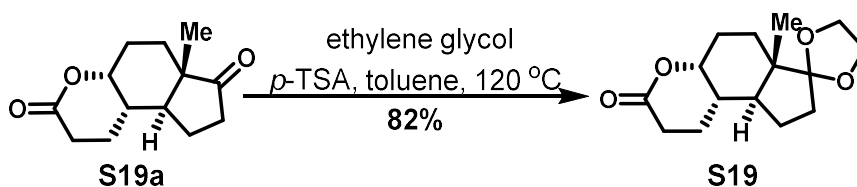
¹H NMR (400 MHz, CDCl₃): δ 7.42 – 7.35 (m, 5H), 5.17 (d, *J* = 13.9 Hz, 2H), 2.74 – 1.52 (m, 10H).

¹³C NMR (126 MHz, CDCl₃): δ 174.9, 174.2, 136.1, 136.0, 128.8, 128.6, 128.3, 128.1, 128.1, 126.6, 66.3, 66.2, 42.4, 41.3, 41.3, 41.1, 41.1, 40.9, 40.7, 38.7, 27.4, 25.7, 24.2, 24.2, 21.7, 21.7, 21.7, 21.6.

¹⁹F NMR (376 MHz, CDCl₃): δ -73.5, -74.1.

GCMS: calc. for C₁₅H₁₇F₃O₂ [M]⁺ 286.1, found 286.0.

Compound S19



Ketone **S19a** (660 mg, 3 mmol, 1 equiv.) was dissolved in toluene (10 mL). Ethylene glycol (0.26 mL, 4.5 mmol, 1.5 equiv.) and *p*-TSA (cat.) were added. The mixture was refluxed with dean-stark apparatus for 4 h. Upon completion,

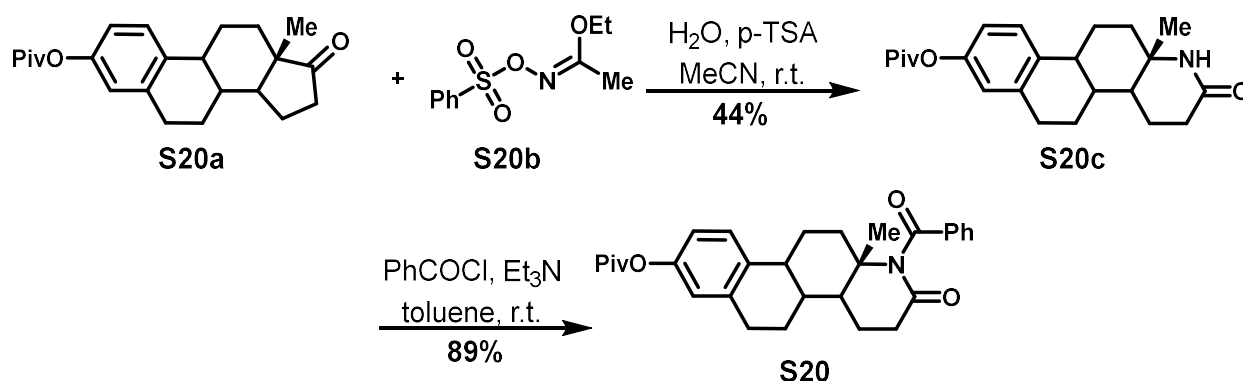
the solution was diluted in EtOAc (100 mL), washed with saturated NaHCO₃ (100 mL) and then by brine (100 mL). The organic layer dried over Na₂SO₄ and evaporated under reduced pressure. The crude residue purified by column chromatography on silica gel (Hex:EtOAc, 1:1) to afford compound **S19** as a white solid (650 mg, 2.46 mmol, 82% yield).

R_f = 0.3 (hexanes/EtOAc, 1:1)

¹H NMR (400 MHz, CDCl₃): δ 4.47 (d, *J* = 2.6 Hz, 1H), 4.93 – 3.83 (m, 5H), 2.50 – 2.44 (m, 3H), 2.03 – 1.72 (m, 12H), 1.29 – 1.21 (m, 2H), 0.89 (s, 3H).

¹³C NMR (101 MHz, CDCl₃): δ 172.3, 118.9, 78.5, 65.3, 64.6, 45.8, 39.8, 33.5, 33.0, 26.9, 26.3, 25.3, 22.0, 21.8, 13.2.

GCMS: calc. for C₁₅H₂₂O₄ [M]⁺ 266.1, found 266.1.



Compound **S20c**

To a test tube was added ketone **S20a** (1.7 g, 4.80 mmol, 1.0 equiv.), oxime **S20b** (1.5 g, 7.20 mmol, 1.2 equiv.), MeCN (5 mL) under Ar and the reaction was stirred at r.t. Then distilled water (0.11 mL, 5.04 mmol, 1.05 equiv.) and *p*-TSA (cat.) were added to the stirred reaction mixture at the r.t. After 24 h, the reaction mixture was quenched by saturated NaHCO₃ (10 mL) and extracted with ethyl acetate (3 x 50 mL). The combined organic phase was washed with brine, dried over Na₂SO₄ and evaporated under reduced pressure. The crude mixture was purified by silica gel column chromatography (MeOH/EtOAc, 2:98) to afford **S20c** as a white solid (780 mg, 2.11 mmol, 44% yield).

R_f = 0.3 (EtOAc)

¹H NMR (400 MHz, CDCl₃): δ 7.26 (d, *J* = 8.6 Hz, 1H), 7.10 (s, 1H), 6.83 (dd, *J* = 8.5, 2.6 Hz, 1H), 6.81 (d, *J* = 2.5 Hz, 1H), 2.89 – 2.85 (m, 2H), 2.50 – 2.39 (m, 4H), 2.11 – 2.02 (m, 2H), 1.90 (dt, *J* = 12.5, 3.3 Hz, 1H), 1.72 (td, *J* = 13.2, 3.7 Hz, 1H), 1.54 – 1.44 (m, 3H), 1.35 (m, 11H), 1.18 (s, 3H).

¹³C NMR (101 MHz, CDCl₃): δ 177.3, 172.1, 149.1, 137.7, 137.0, 126.2, 121.3, 118.7, 54.4, 46.5, 43.5, 39.7, 39.1, 39.0, 30.6, 29.6, 27.2, 26.5, 26.0, 22.1, 19.9.

HRMS (ESI): calc. for C₂₃H₃₂NO₃ [M+H]⁺ 370.2382, found 370.2383.

Compound **S20**

To a solution of **S20c** (500 mg, 1.35 mmol, 1 equiv.) in toluene (5 mL) was added Et₃N (0.3 mL, 2.15 mmol, 1.6 equiv.) and benzoylchloride (0.2 mL, 1.72 mmol, 1.3 equiv.). The reaction mixture stirred and heated to 50 °C for 2 h. After completion, the solution diluted in EtOAc (50 mL) and washed with saturated NH₄Cl (50 mL). The organic layer dried over Na₂SO₄ and evaporated under reduced pressure. The crude residue purified by column chromatography on silica gel (Hex/EtOAc, 1:1) to afford compound **S20** as a white solid (568 mg, 1.20 mmol, 89% yield).

R_f = 0.7 (hexanes/EtOAc, 1:1)

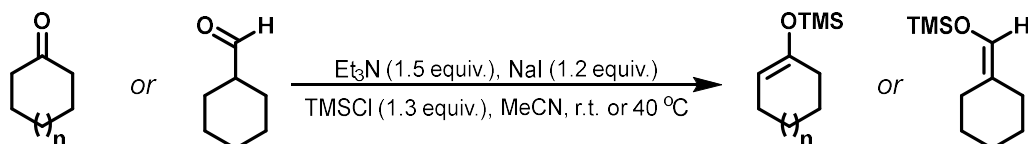
¹H NMR (600 MHz, CDCl₃): δ 7.85 (dq, *J* = 7.4, 1.2 Hz, 2H), 7.56 (ddq, *J* = 8.6, 7.0, 1.2 Hz, 1H), 7.45 (tt, *J* = 7.2, 0.9 Hz, 2H), 7.29 – 7.24 (m, 1H), 6.85 (dd, *J* = 8.4, 2.4 Hz, 1H), 6.82 (dd, *J* = 2.4, 1.0 Hz, 1H), 2.96 – 2.94 (m, 2H), 2.69 – 2.64 (m, 2H), 2.42 (td, *J* = 11.2, 3.8 Hz, 1H), 2.40 (ddt, *J* = 13.9, 7.0, 3.7 Hz, 2H), 2.23 – 2.19 (m, 2H), 1.90 (ddd, *J* = 13.4, 10.2, 3.4 Hz, 1H), 1.68 (tdd, *J* = 13.4, 10.7, 7.5 Hz, 1H), 1.61 (s, 3H), 1.57 (dd, *J* = 13.2, 4.4 Hz, 1H), 1.50 – 1.44 (m, 3H), 1.37 (s, 9H).

¹³C NMR (151 MHz, CDCl₃): δ 177.4, 176.3, 173.3, 149.2, 137.7, 136.6, 136.0, 133.0, 129.0, 128.7, 126.2, 121.3, 118.9, 61.9, 47.0, 42.8, 39.5, 39.1, 36.2, 31.8, 29.6, 27.2, 26.6, 26.1, 21.0, 20.2.

HRMS (ESI): calc. for C₃₀H₃₆NO₄ [M+H]⁺ 474.2644, found 474.2644.

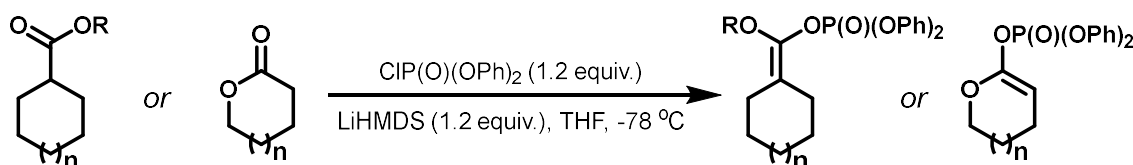
EXPERIMENTAL PROCEDURE FOR SILYL ENOL-ETHER, DIPHENYLPHOSPHATE-KETENE ACETALS AND DIPHENYLPHOSPHATE-KETENIMINYL ACETAL

GENERAL PROCEDURE A. PREPARATION OF TMS ENOL ETHERS



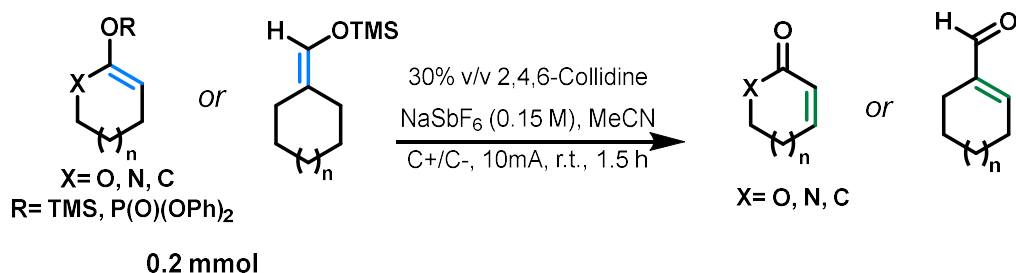
Sodium iodide (1.2 equiv.) was placed in a round bottom flask, flame dried under high vacuum, and allowed to cool to ambient temperature and was backfilled with Ar atmosphere. Dry MeCN (1 mL per 100 mg) was added to dissolve the NaI. To the prepared solution was added the desired ketone or aldehyde (1.0 equiv.), followed by Et₃N (1.5 equiv.). The flask was fitted with an addition funnel and TMSCl (1.3 equiv.) was added dropwise over 30 min. The resulting mixture was stirred at r.t. or 40 °C until complete consumption of starting material (as monitored by TLC or GC). Upon completion, the crude material was extracted with hexane [*Note: no aqueous solution was added at this point, namely, the MeCN layer was extracted with hexane*]. The combined hexane layer was washed with saturated aqueous NaHCO₃, brine, dried over anhydrous Na₂SO₄, and concentrated under reduced pressure. The corresponding TMS-enol ether was purified using silica gel column chromatography.

GENERAL PROCEDURE B. PREPARATION OF DIPHENYLPHOSPHATE-KETENE ACETALS AND DIPHENYLPHOSPHATE-KETENIMINYL ACETAL



Under an argon atmosphere, to a solution of lactone in THF (0.5 M) was added LiHMDS (1.0 M in THF, 1.2 equiv.) at -78 °C dropwise and stirred for 15 min. After adding diphenyl phosphoryl chloride (1.2 equiv.), the resulting mixture allowed to warm r.t., then stirred for an additional 30 min. The reaction was then quenched by adding saturated NaHCO₃, and the crude mixture was extracted with EtOAc. The organic layer was washed with brine, dried over anhydrous Na₂SO₄, and concentrated under reduced pressure. Column chromatography (basic Al₂O₃, hexane/EtOAc/Et₃N) gave the corresponding phosphate esters.

GENERAL PROCEDURE C. ELECTROCHEMICAL DESATURATION USING IKA ELECTRASYN 2.0



Unless otherwise specified, the reaction was carried out on 0.2 mmol scale. To a 5 mL undivided ElectraSyn vial equipped with a stirrer bar was added substrate (TMS enol ether or phosphate ester, 0.20 mmol), 2,4,6-collidine (0.90 mL), MeCN (2.1 mL) and then NaSbF₆ (116 mg, 0.15 M). The vial cap equipped with a pair of graphite electrodes was screwed on, and headspace of the vial was purged with argon and stirred for 5 min prior to electrolysis.

Reaction parameters of ElectraSyn device were set up as follows: constant current, 10 mA; no reference electrode; time, ranging from 1.5–4.0 h, 0.20 mmol substrate; no alternate polarity; stirring, 1,500 rpm.

The mixture was electrolyzed under Ar atmosphere until complete or reasonable consumption of the starting material as judged by TLC or GC. After electrolysis, the cap was removed, and the electrodes were taken out and rinsed with MeCN into the reaction mixture. The reaction mixture was poured into 1.0 M HCl and extracted with EtOAc. The combined organics were washed with brine, dried over anhydrous Na₂SO₄ and concentrated under reduced pressure [*Note: Crude ¹H NMR data may be collected at this point*]. The crude material was purified by silica gel column chromatography or preparative thin-layer chromatography to furnish the desired product. See Figure S1 for graphical guides.

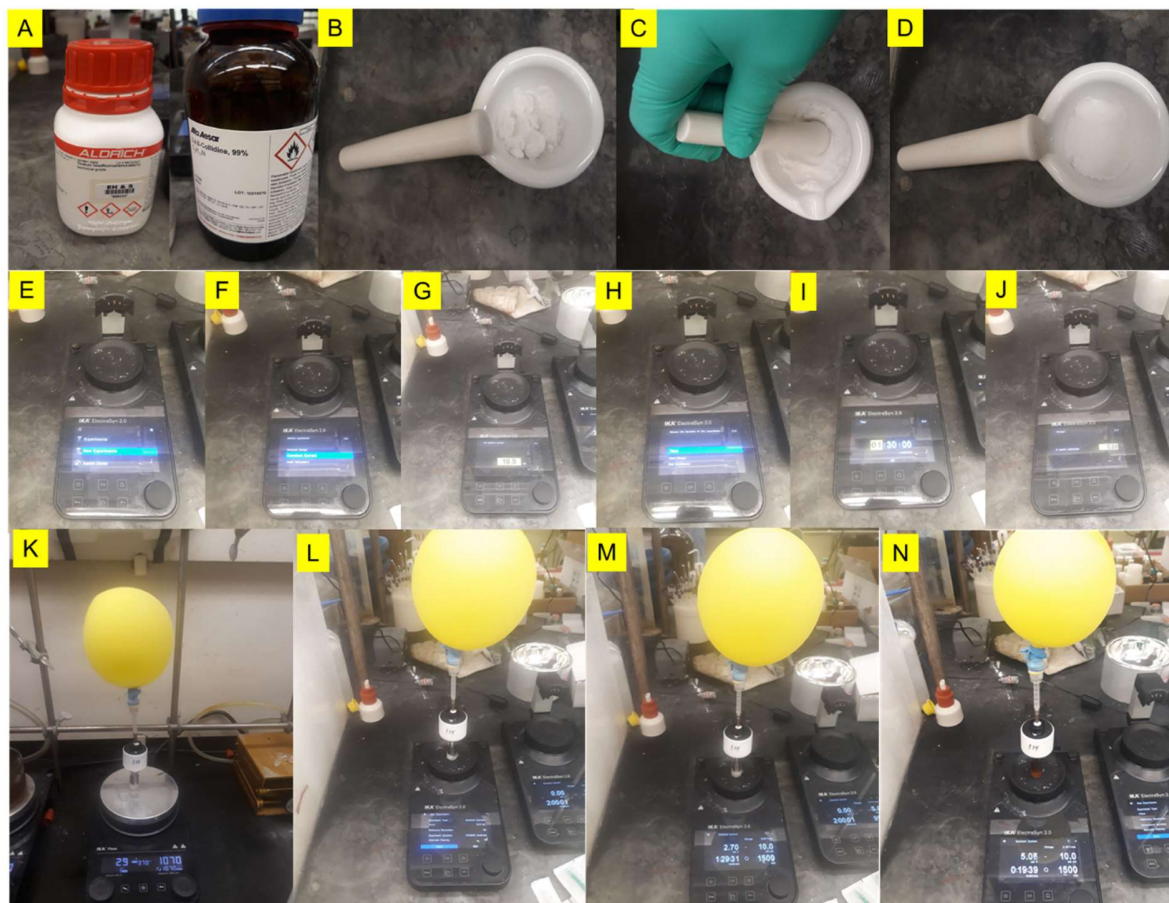
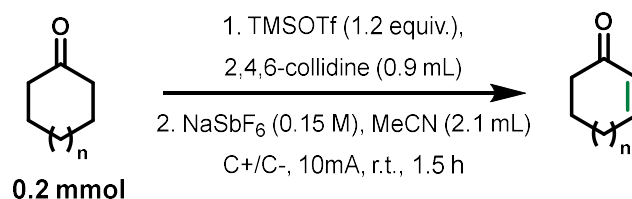


Figure S1: A) All reagents needed for this reaction. B-D) Grind the NaSbF_6 using “Mortar and Pestle”. E) Set new experiment without reference electrode. F) Choose constant current. G) Set the current on 10 mA H) Choose “Time” feature. I) Set the time on 1.5 h. J) Set the scale on 0.2 mmol or any desired scale. K) Pre-stir the reaction for 5 min prior electrolysis. L) Start electrolysis. M and N) Reaction mixture at 0 min and at the end.

GENERAL PROCEDURE D. ONE-POT SILYLATION-DESATURATION PROTOCOL OF KETONES



Under an argon atmosphere, to a flame-dried electrochemical cell without electrodes charged with ketone (44.9 mg, 0.20 mmol, 1 equiv.) and dry 2,4,6-collidine (dried over 3 Å molecular sieves, 0.9 mL) was added TMSOTf (43.4 μL, 0.24 mmol, 1.2 equiv.), and the resulting solution was stirred at r.t. After consumption of starting material as judged by TLC (typically < 5 min), MeCN (2.1 mL) and NaSbF₆ (116.4 mg, 0.45 mmol, 0.15 M) was added to the reaction mixture. The vial cap equipped with a pair of graphite electrodes was screwed on, and headspace of the vial was purged with argon. After pre-stirring for 5 min, the mixture was electrolyzed with a set of parameters as follows: constant current, 10 mA; no reference electrode; time, 1.5 h; 0.20 mmol substrate, 2.8 F/mol; no alternate polarity; stirring, 1,500 rpm.

The reaction mixture was quenched by 1.0 M HCl and extracted with EtOAc. The combined organic layers were washed with brine, dried over anhydrous Na₂SO₄, and concentrated under reduced pressure. Preparative thin-layer chromatography gave the corresponding enone. See Figure S2 for graphical guides.

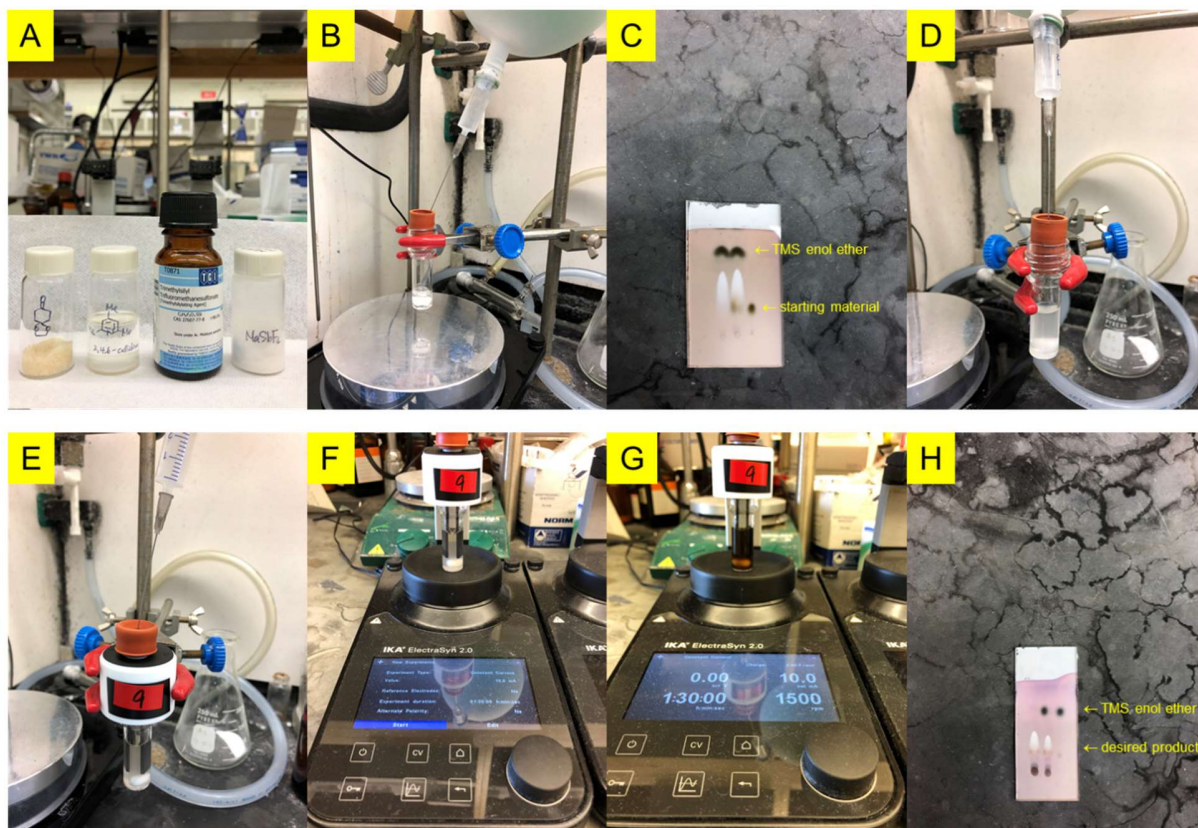
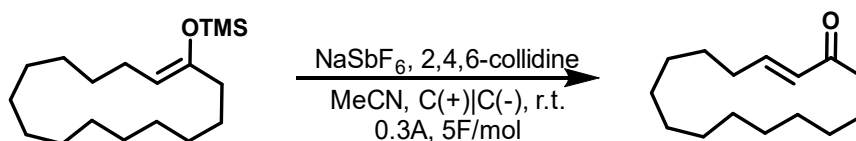


Figure S2: A) All reagents needed for this reaction. B) TMS-enolate preparation. C) TLC after completion. D) Addition of MeCN and electrolyte NaSbF₆. E) Pre-stirring for 5 min prior electrolysis. F) Start electrolysis. G) Reaction mixture after completion. H) TLC after completion after electrolysis.

GENERAL PROCEDURE E. GRAM-SCALE BATCH ELECTROCHEMICAL DESATURATION REACTION



Experimental procedure: To a clean 250 mL beaker was added NaSbF_6 (7.8 g, 30 mmol, 0.15 M) and 140 mL MeCN. Stirring continued until a clear solution was obtained. Then TMS-enol **S36** (4.0 g, 13.5 mmol, 1.0 equiv.) and 60 mL 2,4,6-collidine were added into the beaker and the reaction mixture was allowed to stir at r.t. until homogeneous. The solution was allowed to undergo electrolysis with one graphite electrode as anode and two graphite electrodes as cathodes. The area of each electrode immersed in the reaction mixture was 30cm^2 . The reaction progress was monitored with TLC as well as GC.

Upon completion, the reaction mixture was transferred to a 1 L conical flask and 300 mL 3 M HCL was added dropwise. The mixture was extracted with MTBE (3 x 300 mL) and the combined organic layers were dried and concentrated to give the crude mixture. The crude product was further purified via column chromatography to give the desired product as an oil (1.6 g, 8.91 mmol, 66% yield)

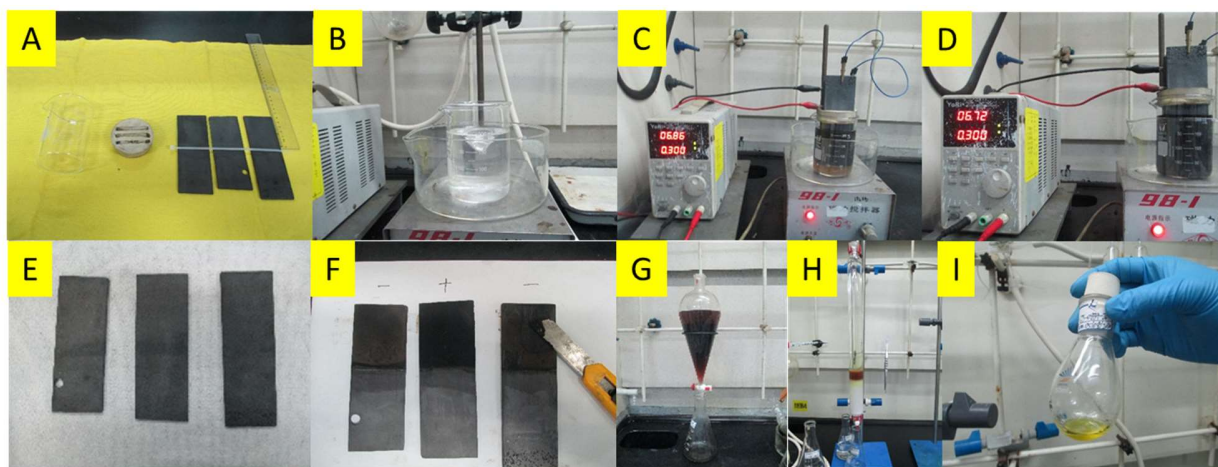
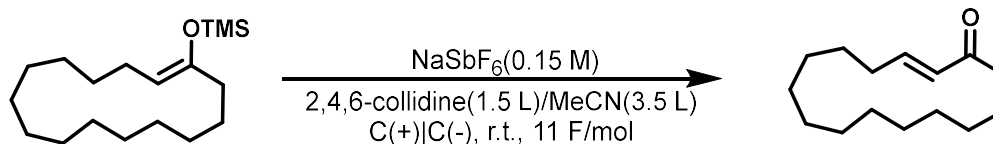


Figure S3: A) Equipment for batch reaction. B) Reaction mixture before electrolysis C) Half time of the reaction D) End of the reaction. E) Electrodes before reaction. F) Electrodes after reaction. G) Extraction of the crude mixture. H) Purification of the crude mixture using silica gel column. I) Pure isolated product.

GENERAL PROCEDURE F. 100 GRAM-SCALE ELECTROCHEMICAL DESATURATION REACTION IN FLOW



Frame Cell Setup (Two sets of 3-in-one frame cells combined): Six Teflon frame blocks (length: 30.0 cm, width: 20.0 cm, thickness: 2.0 cm) were packed in a row. Eight graphite plates (length: 34.0 cm, width: 20.0 cm, thickness: 2.0 mm) as cathodes and anodes which have two silica pads (length: 30.0 cm, width: 20.0 cm, thickness: 2.0 mm) attached on their both sides were inserted between each frame. The two ends of frame cell were attached by two Teflon plates (length: 30.0 cm, width: 20.0 cm, thickness: 2.0 cm) and all components were then threaded through 14 stainless steel screws (length: 34.0 cm, diameter: 7.0 mm) and locked by nuts above stainless steel gasket. The side of each frame was screwed a Teflon joint with which connected rubber tube (6 mm in diameter). The immersion surface area of each electrode in frame cell was 12.0 cm $\times$ 16.0 cm.

Experimental procedure: A clean and dry 5.0 L 4-necked round bottom flask with mechanical stirrer as external container was charged with NaSbF_6 (194 g, 750 mmol, 0.15 M), 1.5 L 2,4,6-collidine, 3.5 L acetonitrile and enol ether **S36** (100 g, 338 mmol, 1 equiv.). The mixture was stirred vigorously until a clear, colorless solution was obtained. A peristaltic pump was connected with frame cell, external round bottom flask by rubber tubes (diameter: 8.0 mm) and Teflon tubes (diameter: 6.0 mm) respectively to form a circulatory system. The mixture was then pumped into frame cell with a speed of 500 rpm in the loop by peristaltic pump. The frame cell with a distance of 2.0 cm between each electrode then underwent electrolysis (Figure S5) with a constant current of 3.64 A from DC power for 25 h and the reaction progress was monitored by GC as well as TLC. Upon completion of the reaction, all mixture was driven into a 30.0 L pail from frame cell and external round bottom flask by peristaltic pump. 6.0 L MeCN was added and circulated for 60 min to wash the frame cell and connecting tubes two times (2 X 4 L).

Under ice-water bath, 3 M HCl (7.2 L) was added into the reaction mixture and stirred vigorously. The mixture was then extracted with MTBE (3 x 5 L). The combined organic phases were dried over sodium sulfate and concentrated on a rotary evaporator (>120 mbar, 35 °C water bath). The crude material obtained as brown oil and was purified by column chromatography (hexanes/EtOAc, 1:50) on silica gel to afford desired product in 61% isolated yield with 27% recovered starting material.

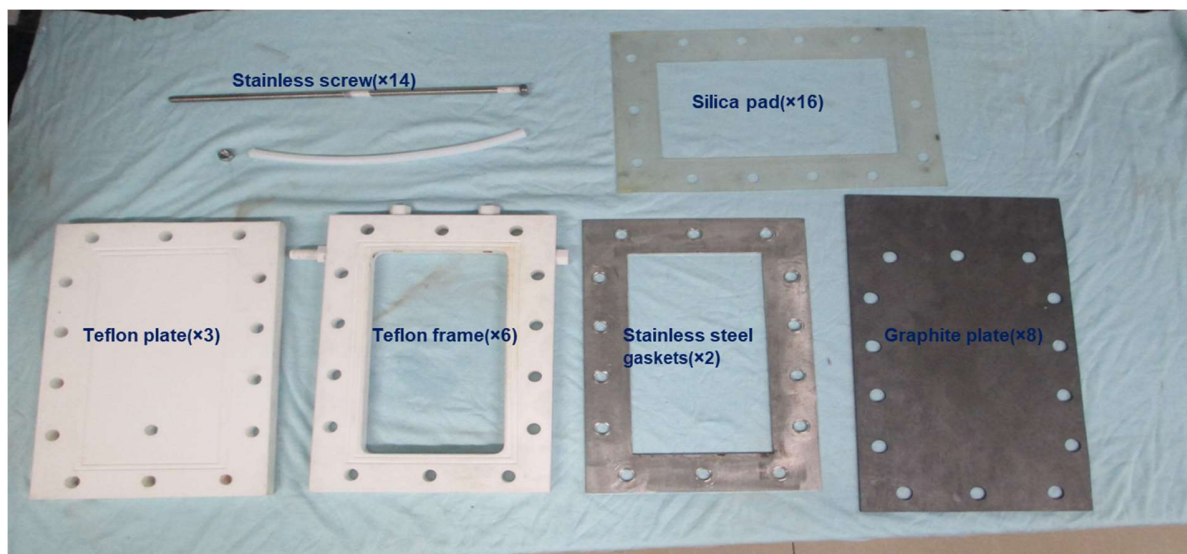


Figure S4: Components of frame cell.

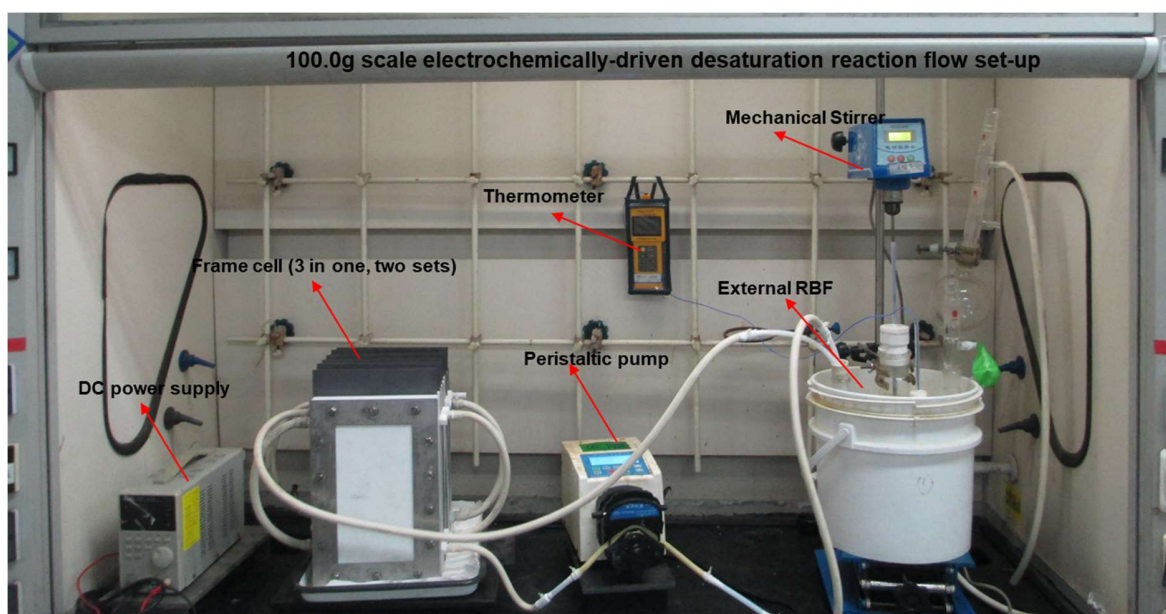


Figure S5: Flow system set up on 100 gram scale.

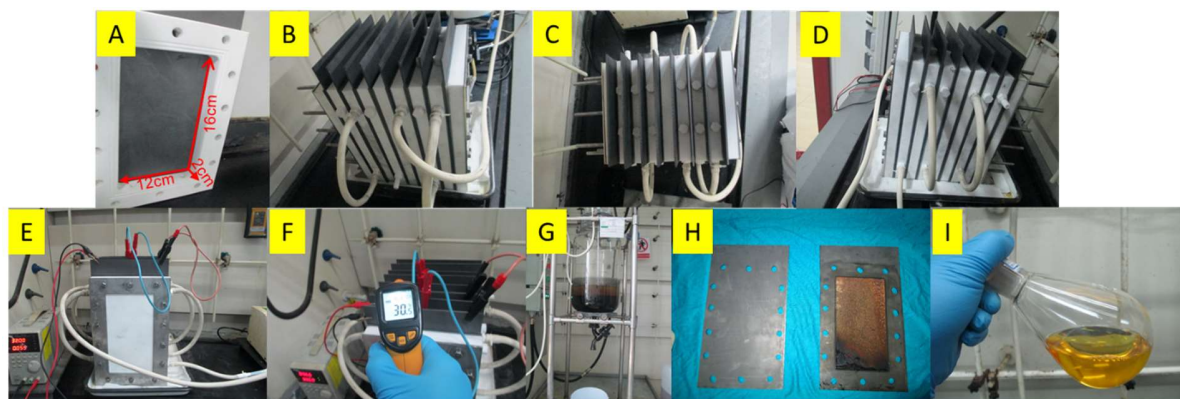
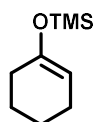


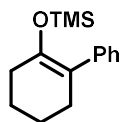
Figure S6: A) One single reaction cell. B) Left view. C) Top view. D) Right view. E) Frame cell and DC power during electrolysis. F) Temperature monitor of frame cell. G) Extraction of the crude mixture. H) Graphite electrode: before and after electrolysis. I) Pure isolated product.

SILYL AND PHOSPHATE ENOL ETHER SUBSTRATES SYNTHESIS: EXPERIMENTAL PROCEDURES AND CHARACTERIZATION DATA



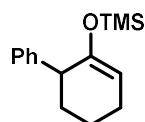
53

Org. Let., 2019, 21, 8805-8809



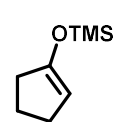
S21

JACS, 2011, 133, 13248-13251



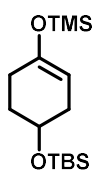
52

ACIE, 2011, 50, 4189-4192



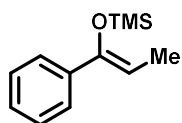
S22

ACIE, 2011, 50, 2756-2760



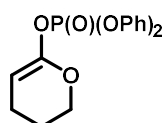
S23

Synlett, 2008, 9, 1386-1390



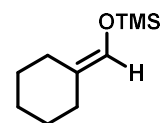
S24

JACS, 2005, 127, 14375-14382



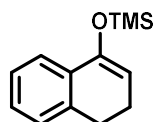
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Tet. Let., 2008, 49, 4142-4144



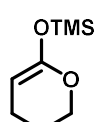
S26

ACIE, 2019, 58, 15813-15818



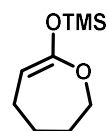
45

Eur. J. Med. Chem., 2011, 46, 1545-1554



56

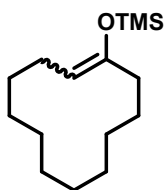
Org. Let., 2015, 17, 5898-5901



61

Org. Let., 2015, 17, 5898-5901

Compound 1

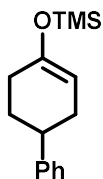


Following the general procedure A on 920 mg (5.05 mmol) scale of the corresponding ketone at r.t. Compound **1** was purified by column chromatography on silica gel (Hex/EtOAc, 99:1) to afford 73% yield (937 mg, 3.67 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹

R_f = 0.3 (Hexane)

¹H NMR (600 MHz, CDCl₃): δ 4.55 (t, *J* = 7.3 Hz, 1H), 2.07 - 2.01 (m, 4H), 1.58 - 1.42 (m, 4H), 1.37 - 1.29 (m, 12H), 0.19-0.21 (s, 9H).

Compound 60

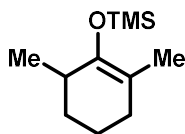


Following the general procedure A on 1 g (5.74 mmol) scale of the corresponding ketone at r.t. Compound **S31** was purified by column chromatography on silica gel (Hex/EtOAc, 94:1) to afford 83% yield (1.19 g, 4.77 mmol) as a colorless oil. The NMR data were consistent with those previously reported.²

R_f = 0.5 (hexanes/EtOAc, 94:1)

¹H NMR (600 MHz, CDCl₃): δ 7.34 (dd, *J* = 8.0, 7.1 Hz, 2H), 7.29 - 7.28 (m, 1H), 7.27 - 7.24 (m, 1H), 4.99 (dt, *J* = 4.7, 1.9 Hz, 1H), 2.80 (dddd, *J* = 14.9, 10.0, 5.1, 2.9 Hz, 1H), 2.34 - 2.12 (m, 3H), 2.01 - 1.92 (m, 1H), 1.90 (dddd, *J* = 12.8, 11.7, 10.8, 5.7 Hz, 1H), 0.26 (s, 9H).

Compound S27

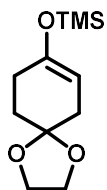


Following the general procedure A on 1 g (7.93 mmol) scale of the corresponding ketone at 40 °C. Compound **S27** was purified by column chromatography on silica gel (Hex) to afford 78% yield (1.22 g, 6.19 mmol) as a colorless oil. The NMR data were consistent with those previously reported.³

R_f = 0.4 (hexanes)

¹H NMR (600 MHz, CDCl₃): δ 2.15 (ttdd, *J* = 8.7, 6.8, 4.6, 2.9 Hz, 1H), 1.96 (tdd, *J* = 6.3, 2.8, 1.5 Hz, 2H), 1.80 (dddd, *J* = 12.7, 8.8, 5.8, 2.9 Hz, 1H), 1.65 – 1.57 (m, 1H), 1.49 – 1.46 (m, 1H), 1.38 (dddd, *J* = 12.8, 9.0, 6.2, 2.9 Hz, 1H), 1.07 (d, *J* = 6.9 Hz, 3H), 0.19 (s, 9H).

Compound S28

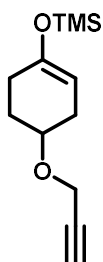


Following the general procedure A on 1.1 g (7.05 mmol) scale of the corresponding ketone at 40 °C. Compound **S28** was purified by column chromatography on silica gel (Hex/EtOAc, 95:5) to afford 84% yield (1.37 g, 5.82 mmol) as a colorless oil. The NMR data were consistent with those previously reported.⁴

R_f = 0.5 (hexanes/EtOAc, 95:5)

¹H NMR (400 MHz, CDCl₃): δ 4.72 (t, *J* = 3.8 Hz, 1H), 3.98 – 3.95 (m, 5H), 2.27 – 2.19 (m, 2H), 1.80 (t, *J* = 6.6 Hz, 2H), 0.18 (s, 9H).

Compound S29



Following the general procedure A on 304 mg (2.0 mmol) scale of the corresponding ketone at r.t. Compound **S29** was purified by column chromatography on silica gel (Hex/EtOAc, 97:3) to afford 87% yield (390 mg, 1.74 mmol) as a colorless oil.

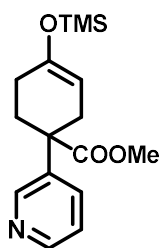
R_f = 0.7 (hexanes/EtOAc, 97:3)

¹H NMR (500 MHz, CDCl₃): δ 4.73 (td, *J* = 3.2, 1.5 Hz, 1H), 4.21 (d, *J* = 2.4 Hz, 2H), 3.76 (dddd, *J* = 10.2, 9.3, 5.2, 2.7 Hz, 1H), 2.42 (t, *J* = 2.4 Hz, 1H), 2.38 – 2.34 (m, 1H), 2.14 – 2.07 (m, 3H), 1.98 – 1.94 (m, 1H), 1.76 – 1.72 (m, 1H), 0.20 (s, 9H).

¹³C NMR (126 MHz, CDCl₃): δ 150.0, 100.5, 80.4, 73.8, 73.2, 55.4, 29.5, 28.0, 27.8, 0.3.

GCMS: calc. for C₁₂H₂₀O₂Si [M]⁺ 224.1, found 224.1.

Compound S30



Following the general procedure A on 370 mg (1.58 mmol) scale of the corresponding ketone at r.t. Compound **S30** was purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford 75% yield (361 mg, 1.18 mmol) as a yellowish oil.

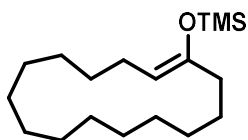
R_f = 0.3 (hexanes/EtOAc, 7:3)

¹H NMR (500 MHz, CDCl₃): δ 8.61 (d, *J* = 2.5 Hz, 1H), 8.46 (dd, *J* = 4.8, 1.6 Hz, 1H), 7.66 (ddd, *J* = 8.1, 2.5, 1.6 Hz, 1H), 7.23 – 7.20 (m, 1H), 4.92 (td, *J* = 4.0, 2.0 Hz, 1H), 3.61 (s, 3H), 2.80 (ddq, *J* = 16.7, 3.9, 1.9 Hz, 1H), 2.57 (ddq, *J* = 16.5, 3.2, 1.8 Hz, 1H), 2.41 – 2.37 (m, 1H), 2.20 – 2.08 (m, 2H), 1.81 – 1.77 (m, 1H), 0.09 (s, 9H).

^{13}C NMR (126 MHz, CDCl_3): δ 174.8, 150.2, 148.2, 148.1, 137.1, 134.0, 123.2, 101.7, 52.4, 47.5, 31.4, 30.7, 27.2, 0.2.

GCMS: calc. for $\text{C}_{16}\text{H}_{23}\text{NO}_4\text{Si}$ $[\text{M}]^+$ 305.1, found 305.1.

Compound S31



Following the general procedure A on 1 g (4.50 mmol) scale of the corresponding ketone at 40 °C. Compound **S31** was purified by column chromatography on silica gel (Hex) to afford 98% yield (1.36 g, 4.41 mmol) as a colorless oil.

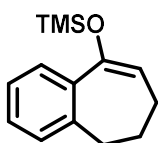
R_f = 0.7 (hexanes)

^1H NMR (500 MHz, CDCl_3): δ 4.63 (t, J = 7.6 Hz, 1H), 2.09 – 2.05 (m, 2H), 1.96 (q, J = 7.3 Hz, 2H), 1.38 – 1.34 (m, 22H), 0.20 (s, 9H).

^{13}C NMR (126 MHz, CDCl_3): δ 151.6, 108.2, 30.7, 29.3, 27.6, 27.4, 27.3, 27.3, 27.0, 26.9, 26.9, 26.8, 26.7, 26.5, 26.4, 26.3, 26.2, 25.9, 0.4.

GCMS: calc. for $\text{C}_{18}\text{H}_{36}\text{OSi}$ $[\text{M}]^+$ 296.1, found 296.1.

Compound S32



Following the general procedure A on 820 mg (5.12 mmol) scale of the corresponding ketone at 40 °C. Compound **S32** was purified by column chromatography on silica gel (Hex/EtOAc, 99:1) to afford 76% yield (903 g, 3.89 mmol) as a colorless oil.

R_f = 0.5 (hexanes)

^1H NMR (500 MHz, CDCl_3): δ 7.51 (dd, J = 7.5, 1.5 Hz, 1H), 7.28 – 7.17 (m, 3H), 5.45 (t, J = 6.7 Hz, 1H), 2.68 (t, J = 6.6 Hz, 2H), 2.05 (td, J = 7.1, 5.9 Hz, 2H), 1.97 – 1.92 (m, 2H), 0.21 (s, 9H).

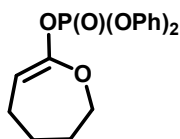
^{13}C NMR (126 MHz, CDCl_3): δ 149.5, 141.0, 138.2, 129.7, 127.5, 126.9, 125.8, 109.5, 33.3, 33.0, 23.9, 0.3.

(m, 6H), 1.55–1.24 (m, 6H), 1.22–1.07 (m, 4H), 1.13 (s, 3H), 1.01 (s, 3H), 0.94 (d, $J = 0.9$ Hz, 3H), 0.93 (s, 3H), 0.90 (s, 6H), 0.76 (s, 3H), 0.18 (s, 9H)..

^{13}C NMR (101 MHz, CDCl_3): δ 178.5, 156.0, 143.8, 122.7, 99.4, 53.0, 51.7, 47.0, 46.3, 46.0, 41.9, 41.6, 39.9, 39.3, 37.9, 36.2, 34.0, 33.3, 32.5, 32.3, 30.8, 28.5, 27.9, 25.9, 23.8, 23.4, 23.3, 19.9, 19.8, 16.7, 15.5, 0.6.

HRMS (APCI): calcd for $\text{C}_{31}\text{H}_{49}\text{O}_3$ $[\text{M}+2\text{H}-\text{TMS}]^+$ 469.3682, found 469.3683.

Compound 55



Following general procedure B on 350 mg (3.07 mmol) scale of the corresponding lactone. Compound **55** was purified by column chromatography on basic alumina (Hex/EtOAc, 7:3 with 1% Et_3N) to afford 52% yield (552 mg, 1.59 mmol) as a colorless oil.

$R_f = 0.3$ (hexanes/EtOAc, 7:3)

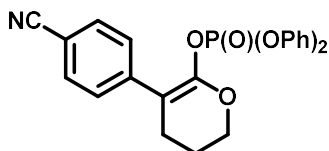
^1H NMR (500 MHz, CDCl_3): δ 7.39 – 7.35 (m, 4H), 7.26 (m, 4H), 7.22 (td, $J = 7.4, 1.1$ Hz, 2H), 4.75 (td, $J = 6.2, 2.2$ Hz, 1H), 4.07 – 4.05 (m, 2H), 2.08 (ddt, $J = 8.8, 6.1, 2.7$ Hz, 2H), 1.85 (dtd, $J = 6.4, 5.4, 3.7$ Hz, 2H), 1.68 – 1.59 (m, 2H).

^{13}C NMR (151 MHz, CDCl_3): δ 155.1, 155.1, 150.1, 150.1, 129.4, 129.3, 129.3, 129.2, 125.0, 124.7, 119.8, 119.7, 119.7, 119.7, 119.6, 91.6, 91.5, 73.0, 68.9, 30.7, 25.0, 22.8.

^{31}P NMR (162 MHz, CDCl_3) δ –18.9.

GCMS: calc. for $\text{C}_{18}\text{H}_{19}\text{O}_5\text{P}$ $[\text{M}]^+$ 346.1, found 346.0.

Compound S34



Following general procedure B on 70 mg (0.35 mmol) scale of the corresponding lactone. Compound **S34** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 3:2 with 1% Et_3N) to afford 76% yield (116 mg, 0.267 mmol) as a yellow oil.

R_f = 0.3 (hexanes/EtOAc, 3:2)

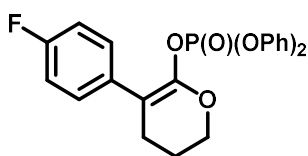
¹H NMR (400 MHz, CDCl₃): δ 7.35–7.27 (m, 8H), 7.23–7.18 (m, 2H), 7.15–7.12 (m, 4H), 4.28–4.25 (m, 2H), 2.46–2.42 (m, 2H), 2.04–2.00 (m, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 150.4 (d, *J* = 7.4 Hz), 148.7 (d, *J* = 9.4 Hz), 142.3, 131.8, 129.9, 128.4, 125.7, 120.2 (d, *J* = 4.9 Hz), 119.3, 109.2, 93.0 (d, *J* = 7.6 Hz), 68.8, 24.7, 22.3.

³¹P NMR (162 MHz, CDCl₃): δ –18.4.

HRMS (ESI): calcd for C₂₄H₂₁NO₅P [M+H]⁺ 434.1157, found 434.1150.

Compound S35



Following general procedure B on 194 mg (1.0 mmol) scale of the corresponding lactone. Compound **S35** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 3:2 with 1% Et₃N) to afford 98% yield (417 mg, 0.979 mmol) as a yellow oil.

R_f = 0.2 (hexanes/EtOAc, 2:1)

¹H NMR (400 MHz, CDCl₃): δ 7.30–7.25 (m, 4H), 7.21–7.14 (m, 4H), 7.12–7.08 (m, 4H), 6.85–6.78 (m, 2H), 4.25–4.21 (m, 2H), 2.43–2.35 (m, 2H), 2.04–1.95 (m, 2H).

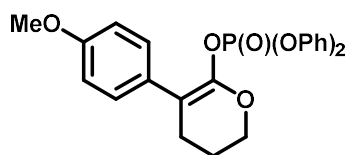
¹³C NMR (151 MHz, CDCl₃): δ 161.3 (d, *J* = 245.0 Hz), 150.5 (d, *J* = 7.6 Hz), 147.5 (d, *J* = 9.5 Hz), 133.3 (d, *J* = 3.5 Hz), 129.8, 129.8, 125.5, 120.2 (d, *J* = 5.0 Hz), 114.9 (d, *J* = 21.4 Hz), 93.6 (d, *J* = 7.8 Hz), 68.6, 25.6, 22.6.

¹⁹F NMR (376 MHz, CDCl₃): δ –116.9.

³¹P NMR (162 MHz, CDCl₃): δ –18.9.

HRMS (ESI): calcd for C₂₃H₂₁FO₅P [M+H]⁺ 427.1111, found 427.1109.

Compound S36



Following general procedure B on 206 mg (1.0 mmol) scale of the corresponding lactone. Compound **S36** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 3:2 with 1% Et₃N) to afford 96% yield (420 mg, 0.958 mmol) as a yellow oil.

R_f = 0.3 (hexanes/EtOAc, 3:2)

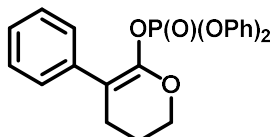
¹H NMR (400 MHz, CDCl₃): δ 7.30–7.23 (m, 4H), 7.20–7.13 (m, 4H), 7.10 (dt, *J* = 7.4, 1.2 Hz, 4H), 6.73–6.67 (m, 2H), 4.24–4.19 (m, 2H), 3.77 (s, 3H), 2.40 (td, *J* = 6.4, 3.7 Hz, 2H), 2.03–1.93 (m, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 157.9, 150.6 (d, *J* = 7.7 Hz), 147.1 (d, *J* = 9.6 Hz), 129.8, 129.7, 129.3, 125.4, 120.3 (d, *J* = 5.0 Hz), 113.5, 94.0 (d, *J* = 7.9 Hz), 68.5, 55.3, 25.6, 22.7.

³¹P NMR (162 MHz, CDCl₃): δ –18.8.

HRMS (ESI): calcd for C₂₄H₂₄O₆P [M+H]⁺ 439.1310, found 439.1315.

Compound S37



Following general procedure B on 352 mg (2.0 mmol) scale of the corresponding lactone. Compound **S37** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 3:2 with 1% Et₃N) to afford 88% yield (718 mg, 1.76 mmol) as a white solid.

R_f = 0.6 (hexanes/EtOAc, 3:2)

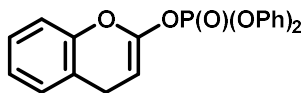
¹H NMR (400 MHz, CDCl₃): δ 7.30–7.05 (m, 15H), 4.27–4.19 (m, 1H), 2.44 (td, *J* = 6.4, 3.6 Hz, 2H), 2.05–1.95 (m, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 150.5 (d, *J* = 7.6 Hz), 147.4 (d, *J* = 9.3 Hz), 137.4, 129.7, 128.2, 128.1, 126.2, 125.4, 120.3 (d, *J* = 4.9 Hz), 94.3 (d, *J* = 7.7 Hz), 68.5, 25.4, 22.6.

³¹P NMR (162 MHz, CDCl₃): δ –18.0.

HRMS (APCI): calcd for C₂₃H₂₂O₅P [M+H]⁺ 409.1205, found 409.1195.

Compound S38



Following general procedure B on 0.5 g (3.37 mmol) scale of the corresponding lactone. Compound **S38** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 7:3 with 1% Et₃N) to afford 87% yield (1.1 g, 2.93 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 75:25)

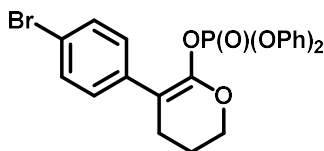
¹H NMR (400 MHz, CDCl₃): δ 7.40 (dd, *J* = 8.5, 7.3 Hz, 4H), 7.32 (dt, *J* = 8.8, 1.2 Hz, 4H), 7.25 (td, *J* = 7.4, 1.2 Hz, 2H), 7.15 (ddd, *J* = 8.1, 6.6, 2.4 Hz, 1H), 7.13 – 7.04 (m, 2H), 6.82 (dd, *J* = 8.2, 1.2 Hz, 1H), 4.71 (td, *J* = 3.6, 2.6 Hz, 1H), 3.54 (t, *J* = 3.6 Hz, 2H).

¹³C NMR (101 MHz, CDCl₃): δ 151.0, 150.4, 150.3, 147.6, 147.5, 129.9, 128.9, 127.6, 125.7, 125.7, 124.3, 120.2, 119.2, 116.6, 81.3, 24.5.

³¹P NMR (162 MHz, CDCl₃): δ –17.4.

HRMS (ESI): calc. for C₂₁H₁₈O₅P [M+H]⁺ 380.0813, found 380.0811.

Compound S39



Following general procedure B on 255 mg (1.0 mmol) scale of the corresponding lactone. Compound **S39** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 3:2 with 1% Et₃N) to afford 94% yield (459 mg, 0.943 mmol) as a yellow solid.

R_f = 0.3 (hexanes/EtOAc, 3:2)

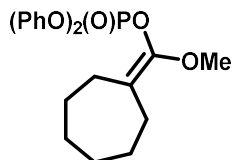
¹H NMR (400 MHz, CDCl₃): δ 7.31–7.25 (m, 4H), 7.24–7.15 (m, 4H), 7.13–7.06 (m, 6H), 4.25–4.21 (m, 2H), 2.39 (td, *J* = 6.4, 3.7 Hz, 2H), 2.03–1.96 (m, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 150.5 (d, *J* = 7.7 Hz), 147.6 (d, *J* = 9.4 Hz), 136.4, 131.2, 129.8, 129.8, 125.6, 120.2 (d, *J* = 5.0 Hz), 120.0, 93.5 (d, *J* = 7.7 Hz), 68.6, 25.3, 22.5.

³¹P NMR (162 MHz, CDCl₃): δ −19.0.

HRMS (ESI): calcd for C₂₃H₂₁BrO₅P [M+H]⁺ 487.0310, found 487.0303.

Compound S40



Following general procedure B on 1.0 g (6.41 mmol) scale of the corresponding ester. Compound **S40** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 4:1 with 1% Et₃N) to afford 84% yield (2.1 g, 5.38 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 4:1)

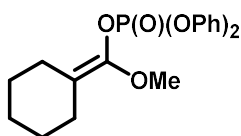
¹H NMR (500 MHz, CDCl₃): δ 7.37 (t, *J* = 7.9 Hz, 4H), 7.30 (d, *J* = 8.2 Hz, 4H), 7.21 (t, *J* = 7.4 Hz, 2H), 3.65 (s, 3H), 2.25 (dq, *J* = 6.4, 2.9 Hz, 2H), 2.13 (dd, *J* = 6.0, 3.4 Hz, 2H), 1.60 (dq, *J* = 12.0, 6.5, 5.0 Hz, 2H), 1.50 (dd, *J* = 8.0, 3.6 Hz, 6H).

¹³C NMR (126 MHz, CDCl₃): δ 150.7, 150.6, 146.9, 146.8, 129.9, 129.9, 129.8, 125.6, 125.4, 120.3, 120.3, 120.2, 120.1, 120.1, 109.5, 109.4, 59.3, 59.3, 29.5, 29.4, 28.1, 28.1, 28.0, 27.9, 27.3.

³¹P NMR (162 MHz, CDCl₃): δ −16.8.

GCMS: calc. for C₂₁H₂₅O₅P [M]⁺ 388.1, found 388.1.

Compound S41



Following general procedure B on 1.0 g (7.01 mmol) scale of the corresponding ester. Compound **S41** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 85:15 with 1% Et₃N) to afford 81% yield (1.9 g, 5.37 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 75:25)

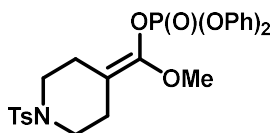
¹H NMR (400 MHz, CDCl₃): δ 7.38 – 7.34 (m, 4H), 7.29 (dt, *J* = 7.6, 1.3 Hz, 4H), 7.22 (ddt, *J* = 7.4, 5.6, 1.1 Hz, 2H), 3.64 (s, 3H), 2.17 – 2.14 (m, 2H), 2.05 (dt, *J* = 7.1, 2.4 Hz, 2H), 1.52 – 1.45 (m, 6H).

^{13}C NMR (151 MHz, CDCl_3): δ 150.7, 144.7, 129.7, 125.4, 120.2, 120.2, 107.9, 59.7, 27.2, 26.8, 26.7, 26.3.

^{31}P NMR (162 MHz, CDCl_3): δ -16.7.

GCMS: calc. for $\text{C}_{20}\text{H}_{23}\text{O}_5\text{P}$ $[\text{M}]^+$ 374.1, found 374.1.

Compound S42



Following general procedure B on 0.5 g (1.68 mmol) scale of the corresponding ester. Compound **S42** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 65:35 with 1% Et_3N) to afford 73% yield (650 mg, 1.22 mmol) as a white solid.

R_f = 0.5 (hexanes/EtOAc, 65:35)

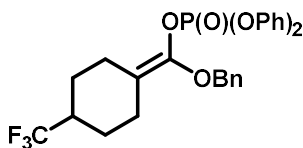
^1H NMR (400 MHz, CDCl_3): δ 7.62 – 7.60 (m, 1H), 7.33 (dt, J = 7.3, 4.5, 0.7 Hz, 3H), 7.23 – 7.20 (m, 3H), 3.88 (q, J = 7.1 Hz, 1H), 3.00 (t, J = 5.8 Hz, 1H), 2.91 – 2.88 (m, 1H), 2.45 (s, 2H), 2.35 (ddd, J = 6.4, 5.2, 2.4 Hz, 1H), 2.21 – 2.19 (m, 1H), 1.18 (t, J = 7.1 Hz, 2H).

^{13}C NMR (151 MHz, CDCl_3): δ 150.4, 144.4, 144.4, 143.5, 133.3, 129.8, 129.7, 129.6, 127.6, 125.6, 120.1, 120.0, 115.3, 102.4, 67.8, 46.7, 46.5, 26.0, 25.9, 21.5, 14.5.

^{31}P NMR (162 MHz, CDCl_3): δ -18.1.

HRMS (ESI, ACPI): Not found.

Compound S43



Following general procedure B on 0.5 g (1.75 mmol) scale of the corresponding ester. Compound **S43** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 75:25 with 1% Et_3N) to afford 54% yield (489 mg, 0.94 mmol) as a yellowish oil.

R_f = 0.2 (hexanes/EtOAc, 75:25)

¹H NMR (400 MHz, CDCl₃): δ 7.41-7.32 (m, 14H), 7.26 – 7.22 (m, 3H), 4.92 – 4.85 (m, 2H), 2.61 – 2.49 (m, 2H), 2.01 – 1.55 (m, 5H), 1.17 (m, 1H), 0.83 (m, 1H).

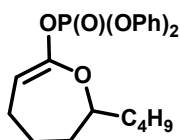
¹³C NMR (126 MHz, CDCl₃): δ 150.7, 150.6, 150.6, 150.6, 142.8, 142.7, 135.2, 129.9, 129.7, 129.4, 128.7, 128.5, 125.6, 125.6, 120.2, 120.2, 120.2, 120.2, 106.8, 106.7, 73.2, 73.2, 41.6, 41.4, 25.0.

¹⁹F NMR (376 MHz, CDCl₃): δ –73.7.

³¹P NMR (162 MHz, CDCl₃): δ –16.7.

HRMS (ESI): calcd for C₂₇H₂₇F₃O₅P [M+H]⁺ 519.1548, found 519.1551.

Compound S44



Following general procedure B on 841 mg (3.07 mmol) scale of the corresponding lactone. Compound **S44** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 4:1 with 1% Et₃N) to afford 68% yield (522 mg, 2.09 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 4:1)

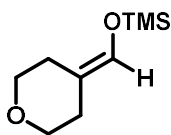
¹H NMR (500 MHz, CDCl₃): δ 7.38 – 7.34 (m, 4H), 7.30 – 7.26 (m, 4H), 7.21 (dddd, *J* = 7.5, 6.7, 2.6, 1.1 Hz, 2H), 4.73 (ddd, *J* = 6.7, 5.2, 2.4 Hz, 1H), 3.99 (dddd, *J* = 10.6, 7.3, 5.0, 2.0 Hz, 1H), 2.07 (tdd, *J* = 6.0, 3.2, 2.1 Hz, 1H), 1.86 – 1.81 (m, 2H), 1.73 – 1.59 (m, 2H), 1.56 – 1.22 (m, 4H), 1.10 (t, *J* = 7.2 Hz, 1H), 0.85 (t, *J* = 7.2 Hz, 3H).

¹³C NMR (126 MHz, CDCl₃): δ 154.5, 154.4, 150.6, 150.5, 129.7, 129.7, 125.4, 120.3, 120.2, 120.2, 120.2, 92.2, 92.2, 84.8, 46.2, 36.1, 35.9, 27.6, 24.9, 23.1, 22.6, 14.0.

³¹P NMR (162 MHz, CDCl₃): δ –17.1.

HRMS (ESI): calcd for C₂₂H₂₈O₅P [M+H]⁺ 403.1596, found 403.1673.

Compound S45



Following the general procedure A on 1.14 g (10 mmol) scale of the corresponding ketone at 40 °C. Compound **S45** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 64% yield (1.18 g, 6.35 mmol) as a colorless oil.

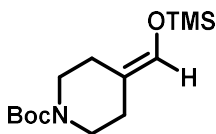
R_f = 0.9 (hexanes/EtOAc, 9:1)

¹H NMR (400 MHz, CDCl₃): δ 6.16–6.07 (m, 1H), 3.66–3.61 (m, 4H), 2.32 (ddd, *J* = 6.3, 5.1, 1.3 Hz, 2H), 2.08 (ddd, *J* = 6.3, 5.1, 1.3 Hz, 2H), 0.17 (s, 9H).

¹³C NMR (151 MHz, CDCl₃): δ 131.9, 117.1, 69.7, 68.6, 30.7, 26.5, –0.4.

HRMS (ESI, APCI): not found.

Compound S46



Following the general procedure A on 2.13 g (10 mmol) scale of the corresponding ketone at 40 °C. Compound **S46** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 14% yield (390 mg, 0.14 mmol) as a white solid.

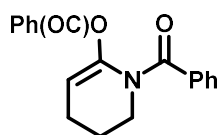
R_f = 0.7 (hexanes/EtOAc, 9:1)

¹H NMR (400 MHz, CDCl₃): δ 6.10 (t, *J* = 1.3 Hz, 1H), 3.39–3.33 (m, 4H), 2.25 (t, *J* = 5.8 Hz, 2H), 2.01 (t, *J* = 5.8 Hz, 2H), 1.46 (s, 9H), 0.17 (s, 9H).

¹³C NMR (151 MHz, CDCl₃): δ 155.0, 132.3, 117.9, 79.5, 45.1 (2 carbons, br), 29.8 (br), 28.6, 25.3 (br), –0.4. The broadened signals are likely to be attributed to a pair of rotamers.

HRMS (ESI): calc' for C₉H₂₀NOSi [M–isobutylene]⁺ 186.1314, found 186.1316.

Compound S47



To a solution of **S11** (406 mg, 2.00 mmol, 1 equiv.) in toluene (5 mL) was added Et₃N (0.52 mL, 4 mmol, 2 equiv.) and benzoylchloride (0.3 mL, 2.6 mmol, 1.3 equiv.). The reaction mixture heated to 50 °C for 2 hours. After completion, the solution diluted in EtOAc (50 mL) and washed with saturated NaHCO₃ (50 mL). The organic layer dried over Na₂SO₄ and evaporated under reduced pressure. The crude residue purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford compound **S47** as a white solid (558 mg, 0.84 mmol, 42%).

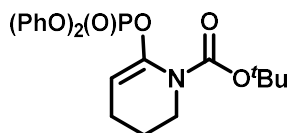
R_f = 0.4 (hexanes/EtOAc, 7:3)

¹H NMR (500 MHz, CDCl₃): δ 7.70 – 7.52 (m, 2H), 7.53 – 7.44 (m, 3H), 7.41 – 7.34 (m, 1H), 7.33 – 7.05 (m, 4H), 5.08 (t, *J* = 3.8 Hz, 1H), 3.98 (t, *J* = 5.5 Hz, 2H), 2.42 (td, *J* = 6.7, 3.8 Hz, 2H), 2.01 (p, *J* = 6.5 Hz, 2H).

¹³C NMR (126 MHz, CDCl₃): δ 168.3, 163.7, 140.3, 136.7, 133.5, 133.5, 130.5, 130.1, 129.9, 128.4, 128.3, 128.2, 128.1, 127.8, 102.5, 44.9, 23.3, 22.0.

GCMS: calc. for C₁₉H₁₇NO₃ [M]⁺ 307.1, found 307.1.

Compound 58



Following general procedure B on 400 mg (1.96 mmol) scale of the corresponding lactame **S7**. Compound **58** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 7:3 with 1% Et₃N) to afford 78% yield (665 mg, 1.52 mmol) as a colorless oil.

Note: The title compound is only stable for couple hours and should be used immediately.

R_f = 0.25 (hexanes/EtOAc, 7:3)

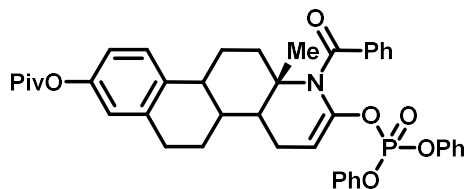
¹H NMR (600 MHz, CDCl₃): δ 7.41 – 7.33 (m, 4H), 7.31 – 7.24 (m, 4H), 7.23 – 7.16 (m, 2H), 5.12 (td, *J* = 3.8, 2.9 Hz, 1H), 3.82 – 3.51 (m, 2H), 2.19 (tt, *J* = 6.8, 4.1 Hz, 2H), 1.88 – 1.64 (m, 4H), 1.45 (m, 9H).

¹³C NMR (151 MHz, CDCl₃): δ 153.3, 150.6, 150.5, 140.6, 140.6, 129.8, 129.7, 129.6, 125.5, 120.1, 120.1, 100.0, 99.9, 81.7, 45.5, 28.1, 22.7, 21.8.

³¹P NMR (162 MHz, CDCl₃): δ -17.6.

HRMS (ESI): Not found.

Compound S48



Following general procedure B on 473 mg (1.0 mmol) scale of the corresponding lactame **S20**. Compound **S48** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 4:1 with 1% Et₃N) to afford 68% yield (480 mg, 0.68 mmol) as a yellowish solid.

R_f = 0.6 (hexanes/EtOAc, 4:1)

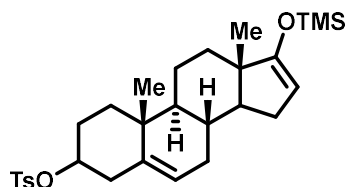
¹H NMR (600 MHz, CDCl₃): δ 7.76 – 7.65 (m, 2H), 7.47 (td, *J* = 7.3, 1.4 Hz, 1H), 7.37 (td, *J* = 7.7, 1.6 Hz, 2H), 7.33 – 7.29 (m, 2H), 7.28 – 7.22 (m, 3H), 7.22 – 7.13 (m, 3H), 7.09 (dq, *J* = 7.8, 1.1 Hz, 2H), 6.88 – 6.81 (m, 4H), 6.80 (d, *J* = 2.4 Hz, 1H), 5.12 – 5.09 (m, 1H), 3.10 – 3.03 (m, 1H), 2.92 – 2.84 (m, 2H), 2.76 – 2.60 (m, 2H), 2.52 – 2.38 (m, 2H), 2.12 (ddt, *J* = 11.1, 5.7, 2.7 Hz, 1H), 1.92 – 1.82 (m, 2H), 1.58 – 1.49 (m, 2H), 1.39 (d, *J* = 1.7 Hz, 3H), 1.36 (d, *J* = 1.7 Hz, 9H), 1.27 (tdd, *J* = 12.0, 6.7, 2.7 Hz, 1H), 1.14 (d, *J* = 8.0 Hz, 1H).

¹³C NMR (151 MHz, CDCl₃): δ 177.4, 170.0, 150.3, 150.3, 150.1, 150.1, 149.1, 140.0, 140.0, 138.7, 137.6, 136.8, 131.6, 129.8, 129.7, 129.6, 128.6, 128.3, 126.4, 125.5, 125.4, 121.2, 119.9, 119.8, 119.8, 119.8, 118.8, 115.4, 92.3, 92.3, 61.6, 46.1, 45.8, 42.2, 41.4, 39.0, 36.9, 29.8, 27.4, 27.2, 26.1, 24.2, 16.0.

³¹P NMR (162 MHz, CDCl₃): δ -18.6.

HRMS (ESI): calc' for C₄₂H₄₅NO₇P [M+H]⁺ 706.29, found 706.28.

Compound 54



Following general procedure A on 441 mg (1.0 mmol) scale of the corresponding ketone **S15**. Compound **54** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 99% yield (510 mg, 0.99 mmol) as a white solid.

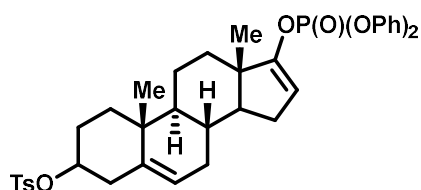
R_f = 0.5 (hexanes/EtOAc, 9:1)

¹H NMR (500 MHz, CDCl₃): δ 7.83 – 7.77 (m, 2H), 7.37 – 7.31 (m, 2H), 5.32 (dt, *J* = 5.2, 1.8 Hz, 1H), 4.48 (dd, *J* = 3.2, 1.5 Hz, 1H), 4.32 (tt, *J* = 11.5, 4.7 Hz, 1H), 2.44 (m, 4H), 2.29 (ddd, *J* = 13.3, 5.2, 2.1 Hz, 1H), 1.99 (dddd, *J* = 15.6, 9.3, 5.7, 2.8 Hz, 2H), 1.87 – 1.76 (m, 3H), 1.73 – 1.64 (m, 2H), 1.62 – 1.49 (m, 3H), 1.28 (dtd, *J* = 44.4, 12.5, 11.7, 5.6 Hz, 2H), 1.07 – 0.94 (m, 5H), 0.84 (s, 3H), 0.19 (s, 9H).

¹³C NMR (126 MHz, CDCl₃): δ 164.8, 144.4, 139.2, 134.7, 129.8, 129.8, 127.6, 123.3, 99.3, 82.3, 54.7, 50.6, 44.2, 38.9, 36.8, 36.6, 33.3, 30.9, 30.2, 28.6, 28.3, 21.6, 20.4, 19.1, 15.0, 0.1.

HRMS (ESI): not found

Compound **51**



Following general procedure B on 441 mg (1.0 mmol) scale of the corresponding ketone **S15**. Compound **51** was purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford 81% yield (546 mg, 0.81 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 7:3)

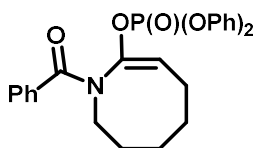
¹H NMR (500 MHz, CDCl₃): δ 7.82 (d, *J* = 8.4 Hz, 2H), 7.51 – 7.14 (m, 12H), 5.38 (dt, *J* = 3.1, 1.5 Hz, 1H), 5.36 – 5.12 (m, 1H), 4.34 (tt, *J* = 11.5, 4.8 Hz, 1H), 2.47 (s, 4H), 2.31 (ddd, *J* = 13.5, 5.2, 2.3 Hz, 1H), 2.15 (dddd, *J* = 14.4, 6.4, 3.4, 1.2 Hz, 1H), 2.01 – 1.92 (m, 2H), 1.88 – 1.67 (m, 4H), 1.65 – 1.42 (m, 6H), 1.36 (td, *J* = 12.4, 4.6 Hz, 1H), 1.11 – 0.98 (m, 5H), 0.91 (s, 3H).

¹³C NMR (151 MHz, CDCl₃): δ 159.3, 159.3, 150.5, 150.5, 144.5, 139.3, 134.6, 129.8, 129.8, 127.7, 125.5, 123.0, 120.1, 120.1, 108.1, 108.08, 8.1, 54.4, 50.4, 44.3, 44.3, 38.9, 36.8, 36.6, 32.8, 30.7, 29.9, 28.6, 28.5, 21.7, 20.2, 19.1, 15.0.

³¹P NMR (162 MHz, CDCl₃): δ –16.9.

HRMS (ESI): calc' for C₃₈H₄₄O₇PS [M+H]⁺ 675.2545, found 675.2545.

Compound 57



Following general procedure B on 231 mg (1.0 mmol) scale of the corresponding lactam **S13**. Compound **57** was purified by column chromatography on silica gel (Hex/EtOAc, 75:25) to afford 72% yield (333 mg, 0.72 mmol) as a white solid.

R_f = 0.4 (hexanes/EtOAc, 75:25)

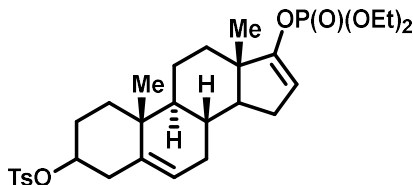
¹H NMR (500 MHz, CDCl₃): δ 7.36 (t, *J* = 7.9 Hz, 4H), 7.31 – 7.23 (m, 6H), 5.57 (td, *J* = 7.3, 2.4 Hz, 1H), 2.28 – 2.04 (m, 2H), 1.84 – 1.57 (m, 6H), 1.49 (m, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 153.9, 150.6, 150.5, 140.2, 140.2, 129.9, 129.8, 129.8, 125.5, 120.4, 120.4, 120.2, 120.1, 120.0, 113.6, 113.6, 80.9, 48.1, 28.2, 27.3, 26.8, 25.5, 25.4.

³¹P NMR (162 MHz, CDCl₃): δ –17.3.

HRMS (ESI): calc⁺ for C₂₆H₂₇NO₅P [M+H]⁺ 460.1889, found 460.1882.

Compound 48



Following general procedure B on 441 mg (1.0 mmol) scale of the corresponding ketone **S15**. Compound **48** was purified by column chromatography on silica gel (Hex/EtOAc, 65:35) to afford 78% yield (451 mg, 0.78 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 65:35)

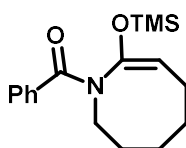
¹H NMR (600 MHz, CDCl₃): δ 7.81 (d, *J* = 8.3 Hz, 2H), 7.35 (d, *J* = 8.1 Hz, 2H), 5.44 – 5.31 (m, 1H), 5.28 – 5.04 (m, 1H), 4.33 (ddd, *J* = 11.5, 6.7, 4.7 Hz, 1H), 4.23 – 4.15 (m, 4H), 2.46 (m, 4H), 2.31 (ddd, *J* = 13.2, 5.2, 2.2 Hz, 1H), 2.16 – 2.09 (m, 1H), 1.99 (ddt, *J* = 14.4, 4.9, 2.0 Hz, 1H), 1.92 (ddt, *J* = 14.4, 11.1, 1.8 Hz, 1H), 1.85 – 1.58 (m, 8H), 1.53 – 1.39 (m, 3H), 1.37 (td, *J* = 7.1, 1.0 Hz, 6H), 1.08 – 0.98 (m, 5H), 0.94 (s, 3H).

¹³C NMR (151 MHz, CDCl₃): δ 159.6, 159.5, 144.5, 139.3, 134.6, 129.8, 127.7, 123.1, 106.5, 106.5, 82.2, 64.4, 64.3, 60.4, 54.5, 50.5, 44.3, 44.2, 38.9, 36.8, 36.6, 33.0, 30.7, 29.9, 28.6, 28.4, 21.7, 21.1, 20.3, 19.1, 16.1, 16.1, 15.1, 14.2.

³¹P NMR (162 MHz, CDCl₃): δ -5.4.

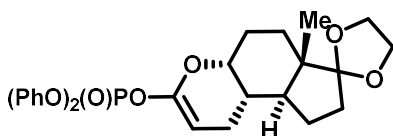
HRMS (ESI): calc' for C₃₀H₄₄O₇PS [M+H]⁺ 579.2545, found 579.2543.

Compound 59



Following general procedure B on 231 mg (1.0 mmol) scale of the corresponding lactam **S13** using TMSCl (1.1 mmol). Compound **59** is not stable for purification under silica-gel or basic alumina chromatography, and it was used as a crude mixture after extraction.

Compound S49



Following general procedure B on 346 mg (1.3 mmol) scale of the corresponding lactone **S-19**. Compound **S49** was purified by column chromatography on basic alumina basic alumina (Hex/EtOAc, 7:3 with 1% Et₃N) to afford 82% yield (531 mg, 1.07 mmol) as a colorless oil.

R_f = 0.4 (hexanes/EtOAc, 7:3)

¹H NMR (600 MHz, CDCl₃): δ 7.53 – 7.31 (m, 7H), 7.22 (tdd, *J* = 7.3, 2.0, 1.0 Hz, 2H), 5.32 (s, 1H), 4.43 – 4.30 (m, 1H), 4.22 (d, *J* = 2.6 Hz, 1H), 3.97 – 3.72 (m, 4H), 2.29 (dddd, *J* = 17.0, 7.1, 5.0, 2.3 Hz, 1H), 2.09 – 2.02 (m, 1H), 1.98 (ddd, *J* = 14.6, 11.7, 3.1 Hz, 1H), 1.93 – 1.86 (m, 2H), 1.81 (dtt, *J* = 14.3, 9.7, 4.5 Hz, 2H), 1.74 – 1.66 (m, 2H), 1.31 – 1.23 (m, 1H), 1.22 – 1.16 (m, 1H), 0.91 (s, 3H).

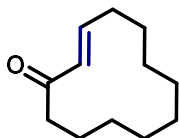
¹³C NMR (151 MHz, CDCl₃): δ 150.58, 150.53, 149.24, 149.19, 129.72, 129.66, 125.41, 125.38, 120.38, 120.35, 120.26, 120.23, 119.15, 78.83, 78.80, 65.22, 64.56, 46.00, 39.49, 33.63, 33.04, 26.73, 25.70, 22.37, 22.09, 13.31.

³¹P NMR (162 MHz, CDCl₃): δ -18.0.

HRMS (ESI): calc' for C₂₇H₃₂O₇P [M+H]⁺ 499.1886, found 499.1882.

CHARACTERIZATION DATA OF KETONES, ESTERS, ALDEHYDES AND LACTAMS

Compound 2

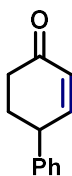


Following the general procedure C on 0.2 mmol scale of **1** with a time of 1.5 h (2.8 F/mol). Compound **2** was purified by column chromatography on silica gel (Hex/EtOAc, 95:5) to afford 62% yield (22.3 mg, 0.124 mmol) as a colorless amorphous oil. The NMR data were consistent with those previously reported.⁵

R_f = 0.5 (hexanes/EtOAc, 97:3)

¹H NMR (500 MHz, CDCl₃): δ 6.79 (dt, *J* = 15.5, 7.6 Hz, 1H), 6.31 (dt, *J* = 15.7, 1.3 Hz, 1H), 2.52 – 2.46 (m, 2H), 2.26 (tdd, *J* = 7.5, 3.9, 1.2 Hz, 2H), 1.72 (p, *J* = 6.6 Hz, 2H), 1.65 – 1.55 (m, 2H), 1.39 (dddd, *J* = 11.5, 7.6, 5.4, 3.0 Hz, 2H), 1.35 – 1.19 (m, 9H).

Compound 3

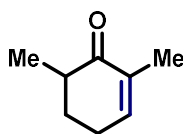


Following the general procedure C on 0.2 mmol scale of **60** with a time of 1.5 h (2.8 F/mol). Compound **3** was purified by column chromatography on silica gel (Hex/EtOAc, 5:2) to afford 62% yield (21.3 mg, 0.124 mmol) as a white solid. The NMR data were consistent with those previously reported.⁶

R_f = 0.3 (hexanes/EtOAc, 5:2)

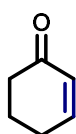
¹H NMR (500 MHz, CDCl₃): δ 7.39 (dd, *J* = 8.2, 6.8 Hz, 2H), 7.35 – 7.30 (m, 1H), 7.25 (dd, *J* = 8.2, 1.3 Hz, 2H), 7.02 (ddd, *J* = 10.1, 2.9, 1.3 Hz, 1H), 6.19 (dd, *J* = 10.2, 2.5 Hz, 1H), 3.75 (ddt, *J* = 9.8, 5.1, 2.7 Hz, 1H), 2.71 – 2.45 (m, 2H), 2.39 (dq, *J* = 13.6, 5.0, 1.4 Hz, 1H), 2.08 (dddd, *J* = 13.7, 11.7, 9.4, 4.6 Hz, 1H).

Compound 4



Following the general procedure C on 0.2 mmol scale of **S27** with a time of 1.5 h (2.8 F/mol). Compound **4** was obtained in 81% GC-conversion.

Compound 5

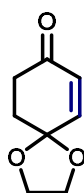


Following the general procedure C on 1 mmol scale of **53** with a time of 9 h (2.8 F/mol). Compound **5** was purified by column chromatography on silica gel (Hex/Et₂O, 75:25) to afford 67% yield (64.3 mg, 0.67 mmol) as a yellowish oil. The NMR data were consistent with those previously reported.⁷

R_f = 0.4 (hexanes/Et₂O, 75:25)

¹H NMR (500 MHz, CDCl₃): δ 7.00 (dt, *J* = 10.3, 4.1 Hz, 1H), 6.02 (dt, *J* = 10.1, 2.0 Hz, 1H), 2.47 – 2.40 (m, 2H), 2.36 (tdd, *J* = 6.1, 4.1, 2.1 Hz, 2H), 2.07 – 1.98 (m, 2H).

Compound 6



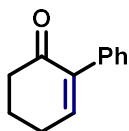
Following the general procedure C on 0.2 mmol scale of **S28** with a time of 1.5 h (2.8 F/mol). Compound **6** was purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford 64% yield (19.7 mg, 0.128 mmol) as a colorless amorphous oil. The NMR data were consistent with those previously reported.⁸

Alternatively, following the general procedure D on 0.2 mmol scale of the corresponding ketone with a time of 1.5 h (2.8 F/mol), the title compound was obtained in 35% yield (11.5 mg, 0.07 mmol).

R_f = 0.3 (hexanes/EtOAc = 65:35)

¹H NMR (400 MHz, CDCl₃): δ 6.60 (dt, *J* = 10.2, 1.0 Hz, 1H), 6.00 (d, *J* = 10.2 Hz, 1H), 4.10 – 3.98 (m, 4H), 2.62 (dd, *J* = 7.1, 6.1 Hz, 2H), 2.19 (ddd, *J* = 7.3, 6.0, 1.0 Hz, 2H).

Compound 7

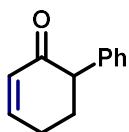


Following the general procedure C on 0.2 mmol scale of **S21** with a time of 1.5 h (2.8 F/mol). Compound **7** was purified by column chromatography on silica gel (Hex/EtOAc, 25:75) to afford 78% yield (26.8 mg, 0.156 mmol) as a white amorphous solid. The NMR data were consistent with those previously reported.⁹

R_f = 0.6 (hexanes/EtOAc, 7:3)

¹H NMR (400 MHz, CDCl₃): δ 7.42 – 7.27 (m, 5H), 7.06 (t, *J* = 4.3 Hz, 1H), 2.66 – 2.51 (m, 4H), 2.14 (dq, *J* = 8.2, 6.1 Hz, 2H).

Compound 8

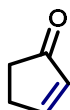


Following the general procedure C on 0.2 mmol scale of **52** with a time of 1.5 h (2.8 F/mol). Compound **8** was purified by column chromatography on silica gel (Hex/EtOAc, 75:25) to afford 72% yield (24.7 mg, 0.144 mmol) as a white amorphous solid. The NMR data were consistent with those previously reported.¹⁰

R_f = 0.65 (hexanes/EtOAc, 7:3)

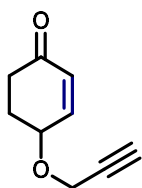
¹H NMR (400 MHz, CDCl₃): δ 7.50 – 7.29 (m, 3H), 7.22 – 7.15 (m, 2H), 7.07 (ddd, *J* = 10.1, 4.6, 3.6 Hz, 1H), 6.19 (ddd, *J* = 10.1, 2.3, 1.7 Hz, 1H), 3.70 – 3.58 (m, 1H), 2.61 – 2.41 (m, 2H), 2.39 – 2.27 (m, 2H).

Compound 9



Following the general procedure C on 0.2 mmol scale of **S22** with a time of 1.5 h (2.8 F/mol). Compound **9** was obtained in 33% GC-yield.

Compound 10



Following the general procedure C on 0.2 mmol scale of **S29** with a time of 1.5 h (2.8 F/mol). Compound **10** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 50% yield (15.0 mg, 0.1 mmol) as a colorless oil.

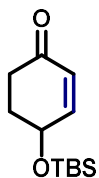
R_f = 0.5 (hexanes/EtOAc, 9:1)

¹H NMR (500 MHz, CDCl₃): δ 6.98 (dq, J = 10.3, 1.8 Hz, 1H), 6.01 (dd, J = 10.2, 2.0 Hz, 1H), 4.45 (ddt, J = 9.1, 4.3, 2.1 Hz, 1H), 4.36 – 4.22 (m, 2H), 2.62 (dt, J = 18.1, 4.9 Hz, 1H), 2.38 (ttd, J = 13.6, 4.7, 1.6 Hz, 2H), 2.05 – 1.96 (m, 1H).

¹³C NMR (126 MHz, CDCl₃): δ 198.6, 149.8, 130.0, 79.3, 75.1, 72.1, 35.1, 28.9.

GCMS: calc. for C₉H₁₀O₂ [M]⁺ 150.0, found 150.1.

Compound 11

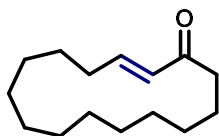


Following the general procedure C on 0.2 mmol scale of **S23** with a time of 1.5 h (2.8 F/mol). Compound **11** was purified by column chromatography on silica gel (Hex/EtOAc, 95:5) to afford 67% yield (30.2 mg, 0.134 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹¹

R_f = 0.3 (hexanes/EtOAc, 95:5)

¹H NMR (400 MHz, CDCl₃): δ 6.85 (ddd, J = 10.2, 2.4, 1.7 Hz, 1H), 5.94 (ddd, J = 10.2, 2.0, 1.1 Hz, 1H), 4.55 (ddt, J = 9.1, 4.6, 2.2 Hz, 1H), 2.59 (dtd, J = 16.8, 4.6, 1.1 Hz, 1H), 2.47 – 2.33 (m, 1H), 2.23 (dq, J = 12.8, 4.8, 1.7 Hz, 1H), 2.02 (tdd, J = 12.9, 9.1, 4.4 Hz, 1H), 0.94 (s, 9H), 0.15 (s, 3H), 0.14 (s, 3H).

Compound 12



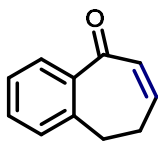
Following the general procedure C on 0.2 mmol scale of **S31** with a time of 1.5 h (2.8 F/mol). Compound **12** was purified by column chromatography on silica gel (Hex/EtOAc, 97:3) to afford 44% yield (19.5 mg, 0.088 mmol) as a yellow oil. The NMR data were consistent with those previously reported.¹³

R_f = 0.6 (hexanes/EtOAc, 95:5)

Alternatively, following the general procedure D on 0.2 mmol scale of the corresponding ketone with a time of 1.5 h (2.8 F/mol). Compound **12** was obtained in 54% yield (23.9 mg, 0.108 mmol).

¹H NMR (500 MHz, CDCl₃): δ 6.84 (dt, *J* = 15.3, 7.4 Hz, 1H), 6.21 (dt, *J* = 15.7, 1.4 Hz, 1H), 2.55 – 2.49 (m, 2H), 2.33 – 2.25 (m, 2H), 1.75 – 1.66 (m, 2H), 1.58 – 1.52 (m, 2H), 1.37 – 1.21 (m, 16H).

Compound 13

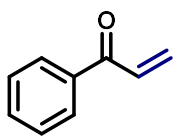


Following the general procedure C on 0.2 mmol scale of **S32** with a time of 1.5 h (2.8 F/mol). Compound **13** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 88% yield (27.8 mg, 0.176 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹⁴

R_f = 0.4 (hexanes/EtOAc, 9:1)

¹H NMR (500 MHz, CDCl₃): δ 7.78 (d, *J* = 7.8 Hz, 1H), 7.44 (d, *J* = 7.4 Hz, 1H), 7.33 (t, *J* = 7.4 Hz, 1H), 7.26 – 7.19 (m, 2H), 6.78 (dt, *J* = 11.7, 5.0 Hz, 1H), 6.30 (d, *J* = 12.1 Hz, 1H).

Compound 14

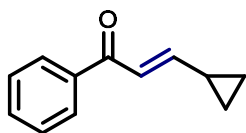


Following the general procedure C on 0.2 mmol scale of **S24** with a time of 1.5 h (2.8 F/mol). Compound **14** was purified by column chromatography on silica gel (Hex/EtOAc, 95:5) to afford 46% yield (12.2 mg, 0.092 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹²

R_f = 0.5 (hexanes/EtOAc, 95:5)

¹H NMR (400 MHz, CDCl₃): δ 8.01 – 7.93 (m, 2H), 7.65 – 7.56 (m, 1H), 7.55 – 7.46 (m, 2H), 7.18 (dd, *J* = 17.1, 10.6 Hz, 1H), 6.46 (dd, *J* = 17.1, 1.7 Hz, 1H), 5.96 (dd, *J* = 10.6, 1.7 Hz, 1H).

Compound 15

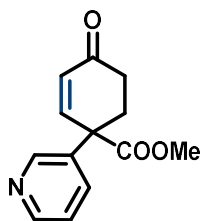


Following the general procedure C on 0.2 mmol scale of **S33** with a time of 1.5 h (2.8 F/mol). Compound **15** was purified by column chromatography on silica gel (Hex/EtOAc, 95:5) to afford 38% yield (13.1 mg, 0.076 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹⁵

R_f = 0.7 (hexanes/EtOAc, 9:1)

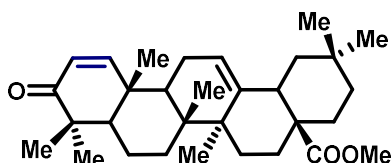
¹H NMR (600 MHz, CDCl₃): δ 7.96 (dd, *J* = 8.3, 1.4 Hz, 2H), 7.62 – 7.55 (m, 1H), 7.54 – 7.45 (m, 2H), 7.04 (d, *J* = 15.1 Hz, 1H), 6.58 (dd, *J* = 15.1, 10.2 Hz, 1H), 1.78 – 1.69 (m, 1H), 1.09 – 1.01 (m, 2H), 0.76 (dd, *J* = 4.5, 2.3 Hz, 2H).

Compound 16



Following the general procedure C on 0.2 mmol scale of **S30** with a time of 1.5 h (2.8 F/mol). Compound **16** was obtained in 50% NMR-yield.

Compound 17



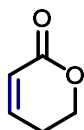
Following the general procedure C on 0.1 mmol scale of **62** with a time of 0.75 h (2.8 F/mol). Compound **17** was p-TLC (Hex/EtOAc, 9:1) to afford 27% yield (12.8 mg, 0.274 mmol) as a colorless amorphous solid. The NMR data were consistent with those previously reported.¹⁶

Alternatively, following the general procedure D on 0.1 mmol scale of **S1** with a time of 0.75 h (2.8 F/mol). Compound **17** was obtained in 24% yield (11.4 mg, 0.244 mmol).

R_f = 0.5 (hexanes/EtOAc, 85:15)

¹H NMR (400 MHz, CDCl₃): δ 7.05 (d, *J* = 10.2 Hz, 1H), 5.82 (d, *J* = 10.1 Hz, 1H), 5.37 (t, *J* = 3.7 Hz, 1H), 3.66 (s, 3H), 2.92 (dd, *J* = 13.9, 4.6 Hz, 1H), 2.18 – 2.08 (m, 2H), 2.00 (td, *J* = 14.2, 13.7, 4.1 Hz, 1H), 1.86 (dd, *J* = 10.3, 7.2 Hz, 1H), 1.79 – 1.51 (m, 9H), 1.45 – 1.31 (m, 2H), 1.27 – 1.04 (m, 15H), 0.96 (s, 3H), 0.93 (s, 3H), 0.84 (s, 3H).

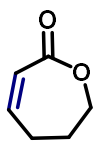
Compound 18



Following the general procedure C on 0.2 mmol scale of **S25** using LiClO₄ (0.1 M) as an electrolyte with a time of 1.5 h (2.8 F/mol). Compound **18** was obtained with 41% NMR yield.

R_f = 0.5 (hexanes:EtOAc = 3:2)

Compound 19

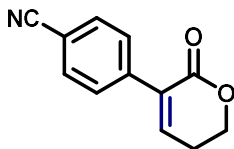


Following the general procedure C on 0.2 mmol scale of **S55** using LiClO₄ (0.1M) as an electrolyte with a time of 1.5 h (2.8 F/mol). Compound **19** was purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford 55% yield (12.3 mg, 0.11 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹⁷

R_f = 0.5 (hexanes/EtOAc, 7:3)

¹H NMR (400 MHz, CDCl₃): δ 6.41 (td, *J* = 4.4, 12.1, 1 H), 5.98 (d, *J* = 12.4), 4.28 (m, 2H), 2.50 (dd, *J* = 5.4, 10.2, 2 H), 2.12 (td, *J* = 6.6, 12.9, 2 H).

Compound 20



Following the general procedure C on 0.2 mmol scale of **S34** with a time of 2.0 h (3.7 F/mol). Compound **20** was p-TLC (Hex/EtOAc, 2:3) to afford 53% yield (21.0 mg, 0.105 mmol) as a colorless amorphous solid.

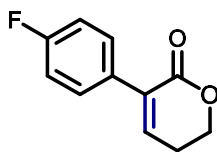
R_f = 0.5 (Hex/EtOAc, 2:3)

¹H NMR (400 MHz, CDCl₃): δ 7.69–7.64 (m, 2H), 7.62–7.58 (m, 2H), 7.11 (t, *J* = 4.5 Hz, 1H), 4.52 (dd, *J* = 6.2, 0.7 Hz, 2H), 2.69 (td, *J* = 6.2, 4.5 Hz, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 163.1, 143.6, 140.0, 132.3, 132.1, 129.2, 118.7, 112.1, 66.5, 25.0.

HRMS (ESI): calcd for C₁₂H₁₀NO₂ [M+H]⁺ 200.0712, found 200.0714.

Compound 21



Following the general procedure C on 0.2 mmol scale of **S35** with a time of 2.0 h (3.7 F/mol). Compound **21** was p-TLC (Hex/EtOAc, 3:2) to afford 54% yield (20.7 mg, 0.108 mmol) as a colorless amorphous solid.

R_f = 0.6 (DCM/EtOAc, 97:3)

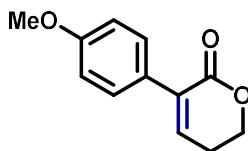
¹H NMR (400 MHz, CDCl₃): δ 7.47–7.41 (m, 2H), 7.08–7.02 (m, 2H), 6.97 (t, *J* = 4.5 Hz, 1H), 4.48 (td, *J* = 6.2, 0.7 Hz, 2H), 2.62 (td, *J* = 6.2, 4.5 Hz, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 163.9, 162.9 (d, *J* = 247.7 Hz), 141.4, 132.6, 131.7 (d, *J* = 3.4 Hz), 130.2 (d, *J* = 8.1 Hz), 115.3 (d, *J* = 21.6 Hz), 66.6, 24.9.

¹⁹F NMR (376 MHz, CDCl₃): δ –113.9.

HRMS (ESI): calcd for C₁₁H₁₀FO₂ [M+H]⁺ 193.0665, found 193.0667.

Compound 22



Following the general procedure C on 0.2 mmol scale of **S36** with a time of 2.0 h (3.7 F/mol). Compound **22** was p-TLC (Hex/EtOAc, 3:2) to afford 36% yield (14.7 mg, 0.0720 mmol) as a colorless amorphous solid.

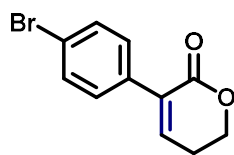
R_f = 0.6 (DCM/EtOAc, 97:3)

¹H NMR (400 MHz, CDCl₃): δ 7.44–7.39 (m, 2H), 6.93 (t, *J* = 4.6 Hz, 1H), 6.92–6.87 (m, 2H), 4.47 (td, *J* = 6.2, 0.7 Hz, 2H), 3.81 (s, 3H), 2.60 (td, *J* = 6.2, 4.6 Hz, 2H).

¹³C NMR (151 MHz, CDCl₃): δ 164.2, 159.8, 139.9, 132.9, 129.6, 128.1, 113.8, 66.6, 55.4, 24.9.

HRMS (ESI): calcd for C₁₂H₁₃O₃ [M+H]⁺ 205.0865, found 205.0869.

Compound 23



Following the general procedure C on 0.2 mmol scale of **S39** with a time of 2.0 h (3.7 F/mol). Compound **23** was p-TLC (Hex/EtOAc, 3:2) to afford 41% yield (20.9 mg, 0.0826 mmol) as a colorless amorphous solid.

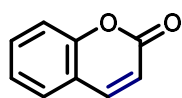
R_f = 0.6 (DCM/EtOAc, 97:3)

^1H NMR (400 MHz, CDCl_3): δ 7.51–7.46 (m, 2H), 7.36–7.32 (m, 2H), 7.00 (t, J = 4.5 Hz, 1H), 4.48 (td, J = 6.3, 0.7 Hz, 2H), 2.62 (td, J = 6.3, 4.5 Hz, 2H).

^{13}C NMR (151 MHz, CDCl_3): δ 163.6, 141.8, 134.5, 132.6, 131.5, 130.1, 122.7, 66.5, 25.0.

HRMS (ESI): calcd for $\text{C}_{11}\text{H}_{10}\text{BrO}_2$ $[\text{M}+\text{H}]^+$ 252.9864, found 252.9867.

Compound 24

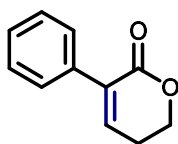


Following the general procedure C on 0.2 mmol scale of **S38** with a time of 1.5 h (2.8 F/mol). Compound **24** was purified by column chromatography on silica gel (Hex/EtOAc, 4:1) to afford 58% yield (16.9 mg, 0.116 mmol) as a colorless oil. The NMR data were consistent with those previously reported.¹⁸

R_f = 0.5 (hexanes/EtOAc, 4:1)

^1H NMR (400 MHz, CDCl_3): δ 7.74 (dd, J = 9.6, 0.7 Hz, 1H), 7.56 (ddd, J = 8.6, 7.3, 1.6 Hz, 1H), 7.51 (dd, J = 7.7, 1.6 Hz, 1H), 7.42 – 7.35 (m, 1H), 7.34 – 7.29 (m, 1H), 6.45 (d, J = 9.6 Hz, 1H).

Compound 25

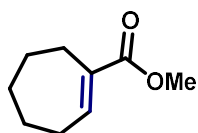


Following the general procedure C on 0.2 mmol scale of **S37** with a time of 2.0 h (3.7 F/mol). Compound **25** was p-TLC (Hex/EtOAc, 3:2) to afford 64% yield (22.4 mg, 0.129 mmol) as a colorless amorphous solid. The NMR data were consistent with those previously reported.¹⁹

R_f = 0.5 (DCM/EtOAc, 97:3)

¹H NMR (500 MHz, CDCl₃): δ 7.51 – 7.45 (m, 2H), 7.43 – 7.32 (m, 3H), 7.02 (t, *J* = 4.5 Hz, 1H), 4.50 (t, *J* = 6.3 Hz, 2H), 2.64 (td, *J* = 6.2, 4.5 Hz, 2H).

Compound 26

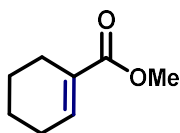


Following the general procedure C on 0.2 mmol scale of **S40** with a time of 1.5 h (2.8 F/mol). Compound **26** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 54% yield (16.6 mg, 0.108 mmol) as a colorless oil. The NMR data were consistent with those previously reported.²⁰

R_f = 0.5 (Hex/EtOAc, 9:1)

¹H NMR (500 MHz, CDCl₃): δ 7.23 – 7.17 (m, 1H), 3.74 (s, 3H), 2.58 – 2.51 (m, 2H), 2.35 – 2.28 (m, 2H), 1.84 – 1.74 (m, 2H), 1.60 – 1.50 (m, 4H).

Compound 27

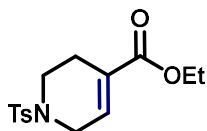


Following the general procedure C on 0.2 mmol scale of **S41** with a time of 1.5 h (2.8 F/mol). Compound **27** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 71% yield (20.0 mg, 0.142 mmol) as a colorless oil. The NMR data were consistent with those previously reported.²¹

R_f = 0.4 (hexanes/EtOAc, 9:1)

¹H NMR (600 MHz, CDCl₃): δ 6.97 (tt, *J* = 3.9, 1.8 Hz, 1H), 3.71 (d, *J* = 1.1 Hz, 3H), 2.24 (ddq, *J* = 8.5, 6.2, 2.3 Hz, 2H), 2.17 (dddd, *J* = 8.9, 6.1, 4.0, 2.7 Hz, 2H), 1.74 – 1.61 (m, 2H), 1.58 (qd, *J* = 6.0, 2.4 Hz, 2H).

Compound 28

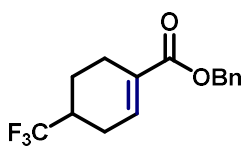


Following the general procedure C on 0.2 mmol scale of **S42** with a time of 4 h (7.4 F/mol). Compound **28** was purified by column chromatography on silica gel (Hex/EtOAc, 75:25) to afford 81% yield (50.1 mg, 0.162 mmol) as white solid. The NMR data were consistent with those previously reported.²¹

R_f = 0.3 (hexanes/EtOAc, 75:25)

¹H NMR (400 MHz, CDCl₃): δ 7.70 (d, *J* = 8.3 Hz, 2H), 7.35 (d, *J* = 8.0 Hz, 2H), 6.83 (tt, *J* = 3.5, 1.7 Hz, 1H), 4.20 (q, *J* = 7.1 Hz, 2H), 3.77 (q, *J* = 3.0 Hz, 2H), 3.22 (t, *J* = 5.7 Hz, 2H), 2.86 – 2.16 (m, 4H), 1.29 (t, *J* = 7.1 Hz, 3H).

Compound 29



Following the general procedure C on 0.2 mmol scale of **S43** with a time of 1.5 h (2.8 F/mol). Compound **29** was purified by column chromatography on silica gel (Hex/EtOAc, 9:1) to afford 54% yield (30.6 mg, 0.108 mmol) as a colorless oil.

R_f = 0.6 (hexanes/EtOAc, 9:1)

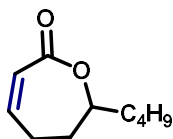
¹H NMR (400 MHz, CDCl₃): δ 7.41 – 7.31 (m, 5H), 7.07 – 6.97 (m, 1H), 5.22 (s, 2H), 2.69 – 2.58 (m, 1H), 2.55 – 2.41 (m, 1H), 2.40 – 2.21 (m, 3H), 2.18 – 2.01 (m, 1H), 1.64 – 1.46 (m, 1H).

¹³C NMR (151 MHz, CDCl₃): δ 166.4, 136.4, 136.1, 130.3, 128.6, 128.6, 128.2, 128.1, 126.7, 66.4, 66.3, 66.3, 37.9, 37.7, 24.8, 24.8, 23.3, 21.1, 21.1.

¹⁹F NMR (376 MHz, CDCl₃): δ -73.9.

GCMS: calc. for C₁₅H₁₅F₃O₂ [M]⁺ 284.1, found 284.1.

Compound 30



Following the general procedure C on 0.2 mmol scale of **S44** using LiClO₄ (0.1M) as an electrolyte with a time of 1.5 h (2.8 F/mol). Compound **30** was purified by column chromatography on silica gel (Hex/EtOAc, 75:25) to afford 52% yield (18.1 mg, 0.104 mmol) as a colorless oil.

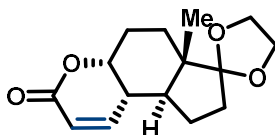
R_f = 0.3 (hexanes/EtOAc, 4:1)

¹H NMR (600 MHz, CDCl₃): δ 6.42 (dt, *J* = 12.2, 4.6 Hz, 1H), 6.01 (dt, *J* = 12.2, 2.0 Hz, 1H), 4.32 (dq, *J* = 7.4, 4.9 Hz, 1H), 2.58 – 2.39 (m, 2H), 2.04 (dt, *J* = 7.3, 4.6 Hz, 2H), 1.85 – 1.76 (m, 1H), 1.61 (ddd, *J* = 13.6, 10.3, 5.1 Hz, 1H), 1.55 – 1.44 (m, 1H), 1.38 – 1.34 (m, 1H), 0.93 (t, *J* = 7.1 Hz, 3H).

¹³C NMR (151 MHz, CDCl₃): δ 168.6, 143.6, 122.4, 78.6, 35.1, 32.2, 29.1, 27.5, 22.5, 14.0.

GCMS: calc. for C₁₀H₁₆O₂ [M]⁺ 168.1, found 168.1.

Compound 31



Following the general procedure C on 0.2 mmol scale of **S49** using LiClO₄ (0.1M) as an electrolyte with a time of 1.5 h (2.8 F/mol). Compound **31** was purified by column chromatography on silica gel (Hex/EtOAc, 55:45) to afford 34% yield (17.8 mg, 0.068 mmol) as a colorless oil.

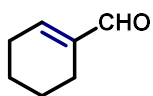
R_f = 0.3 (hexanes/EtOAc, 55:45)

¹H NMR (400 MHz, CDCl₃): δ 6.97 (dd, *J* = 9.7, 6.3 Hz, 1H), 6.02 (dd, *J* = 9.7, 0.7 Hz, 1H), 4.55 (q, *J* = 3.0 Hz, 1H), 3.99 – 3.80 (m, 5H), 2.26 (ddd, *J* = 12.2, 6.3, 3.1 Hz, 1H), 2.14 – 1.90 (m, 5H), 1.88 – 1.78 (m, 2H), 1.70 (tdd, *J* = 10.0, 7.0, 3.6 Hz, 1H), 1.41 (qd, *J* = 12.1, 6.2 Hz, 1H), 1.33 – 1.24 (m, 1H).

¹³C NMR (151 MHz, CDCl₃): δ 164.8, 149.5, 120.9, 118.3, 76.1, 65.4, 64.7, 45.7, 43.5, 36.6, 33.6, 26.3, 25.4, 22.1, 13.1.

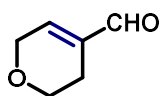
GCMS: calc. for C₁₆H₂₂O₃ [M]⁺ 262.2, found 262.1.

Compound 32



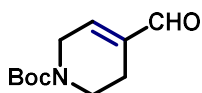
Following the general procedure C on 0.2 mmol scale of **S26** with a time of 1.5 h (2.8 F/mol), the title compound was obtained in 38% ¹H NMR yield. The NMR data were consistent with those previously reported.²²

Compound 33



Following the general procedure C on 0.2 mmol scale of **S45** with a time of 1.5 h (2.8 F/mol), the title compound was obtained in 37% ¹H NMR yield. The NMR data were consistent with those previously reported.²³

Compound 34



R_f = 0.7 (hexanes/EtOAc, 75:25 Hex:EtOAc)

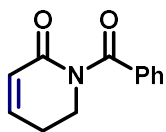
Following the general procedure C on 0.2 mmol scale of **S46** with a time of 1.5 h (2.8 F/mol). Compound **34** was p-TLC (Hex/EtOAc, 75:25) to afford 50% yield (20.9 mg, 0.0826 mmol) as a colorless amorphous solid.

¹H NMR (400 MHz, CDCl₃): δ 9.49 (s, 1H), 6.72 (br s, 1H), 4.22 – 4.18 (br m, 2H), 3.52 (t, *J* = 5.7 Hz, 2H), 2.34 (br s, 2H), 1.48 (s, 9H).

¹³C NMR (151 MHz, CDCl₃): δ 154.7, 146.0 (br), 145.2 (br), 139.8, 80.4, 44.3 (br), 43.8 (br), 40.3 (br), 39.0 (br), 28.5, 21.9. The broadened signals are likely to be attributed to a pair of rotamers.

HRMS (ESI): calcd for C₇H₁₀NO₃ [M–isobutylene]⁺ 156.0661, found 156.0660.

Compound 35

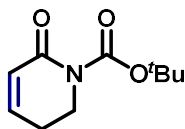


Following the general procedure C on 0.2 mmol scale of **S47** with a time of 1.5 h (2.8 F/mol). Compound **35** was purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford 58% yield (23.3 mg, 0.116 mmol) as a colorless oil. The NMR data were consistent with those previously reported.²⁴

R_f = 0.3 (hexanes/EtOAc, 7:3)

¹H NMR (500 MHz, CDCl₃): δ 7.66 – 7.53 (m, 2H), 7.53 – 7.46 (m, 2H), 7.45 – 7.38 (m, 2H), 7.00 (dt, *J* = 9.7, 4.2 Hz, 1H), 6.00 (dt, *J* = 9.8, 1.9 Hz, 1H), 4.03 (t, *J* = 6.5 Hz, 2H), 2.62 (tdd, *J* = 6.4, 4.2, 1.9 Hz, 2H).

Compound 36

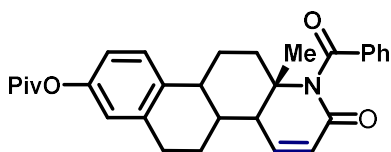


Following the general procedure C on 0.2 mmol scale of **58** with a time of 1.5 h (2.8 F/mol). Compound **36** was purified by column chromatography on silica gel (Hex/EtOAc, 7:3) to afford 69% yield (27.1 mg, 0.138 mmol) as a colorless oil. The NMR data were consistent with those previously reported.²⁵

R_f = 0.4 (hexanes/EtOAc, 7:3)

¹H NMR (600 MHz, CDCl₃): δ 6.80 (dt, *J* = 9.8, 4.2 Hz, 1H), 5.98 (dt, *J* = 9.8, 1.9 Hz, 1H), 3.88 (t, *J* = 6.4 Hz, 2H), 2.43 (tdd, *J* = 6.3, 4.2, 1.9 Hz, 2H), 1.57 (s, 9H).

Compound 37



Following the general procedure C on 0.2 mmol scale of **S48** with a time of 1.5 h (2.8 F/mol). Compound **37** was purified by column chromatography on silica gel (Hex/EtOAc, 65:35) to afford 24% yield (12.8 mg, 0.048 mmol) as a colorless oil.

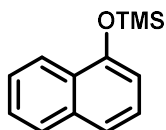
R_f = 0.3 (hexanes/EtOAc, 65:35)

¹H NMR (600 MHz, CDCl₃) δ 7.86 – 7.80 (m, 2H), 7.56 – 7.51 (m, 1H), 7.43 (t, *J* = 7.8 Hz, 2H), 7.24 (s, 0H), 6.93 (dd, *J* = 10.0, 2.2 Hz, 1H), 6.84 (dd, *J* = 8.4, 2.6 Hz, 1H), 6.82 (d, *J* = 2.5 Hz, 1H), 6.07 (dd, *J* = 10.0, 3.1 Hz, 1H), 3.24 – 2.91 (m, 3H), 2.75 (dt, *J* = 11.3, 2.7 Hz, 1H), 2.66 – 2.61 (m, 1H), 2.55 – 2.49 (m, 1H), 2.46 – 2.40 (m, 1H), 2.38 – 2.30 (m, 1H), 1.75 – 1.58 (m, 3H), 1.57 (s, 3H), 1.35 (s, 9H).

¹³C NMR (151 MHz, CDCl₃) δ 177.4, 175.6, 165.8, 149.3, 143.8, 137.6, 136.3, 136.3, 132.9, 129.2, 128.6, 126.1, 125.3, 121.4, 119.0, 63.8, 49.0, 46.1, 43.4, 39.1, 37.2, 35.6, 29.4, 27.2, 26.2, 26.1, 25.6, 17.9.

HRMS (ESI): calcd for C₃₀H₃₄NO₄ [M+H]⁺ 472.2488, found 472.2497.

Compound 47



Following the general procedure C on 0.2 mmol scale of **45** with a time of 1.5 h (2.8 F/mol). Compound **47** was purified by column chromatography on silica gel (Hex/EtOAc, 95:5) to afford 49% yield (21.1 mg, 0.098 mmol) as a colorless oil. The NMR data were consistent with those previously reported.²⁶

¹H NMR (500 MHz, CDCl₃): δ 8.23 – 8.16 (m, 1H), 7.88 – 7.82 (m, 1H), 7.56 – 7.47 (m, 3H), 7.38 (dd, *J* = 8.3, 7.5 Hz, 1H), 6.93 (dd, *J* = 7.5, 1.0 Hz, 1H), 0.40 (s, 9H).

R_f = 0.8 (hexanes/EtOAc, 95:5)

MECHANISTIC STUDY:

PROPOSED MECHANISM:

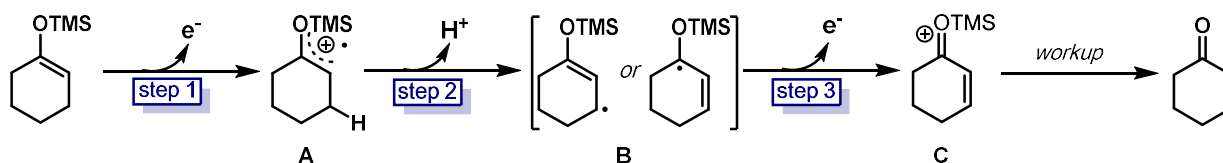


Figure S7: Proposed EDD reaction mechanism.

INTERMEDIATE A:

One of the main side products obtained during the optimization of the EDD reaction was the described 1,2-diketone **46** (Figure S8). In order to evaluate the formation pathway of side product **46**, we performed three control experiments. First, we conducted the reaction using the standard condition in presence of 10 equiv. of water (as the source of the oxygen atom). The outcome of the reaction was mainly hydrolysis product and no side-product **46** formation. Next, we performed the same reaction using the standard reaction condition under argon and under air. It was interesting to notice that under air we obtained 9% product **44**, however 4% was obtained under argon atmosphere. This result supports the hypothesis that molecular oxygen reacts with the radical cation intermediate to form the 1,2-diketone side product.

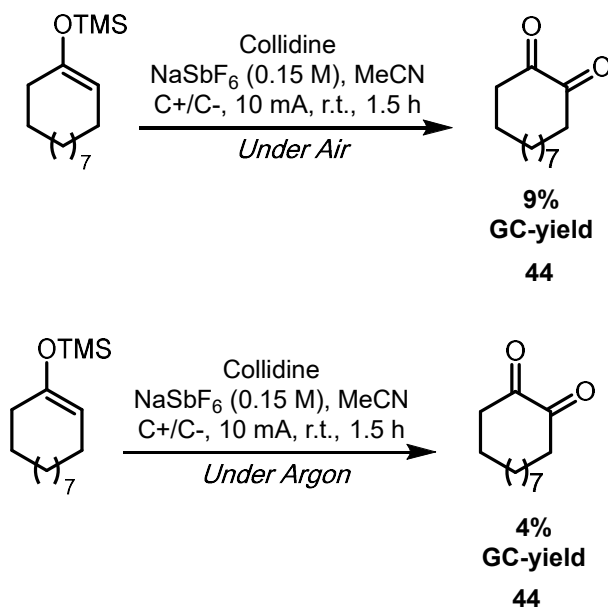


Figure S8: 1,2-diketone **44** formation.

INTERMEDIATE C:

The current experiment was conducted to validate the formation of an oxonium intermediate (Figure S7, C). Compound **48** was subjected to the reaction conditions affording the 5% LC-yield of diene-intermediate **50**. The formation of this product is in accordance with the formation of such an intermediate C (Figure S-9), which after deprotonation delivers **50**.

LCMS method:

The product separation was accomplished on a Waters I-Class LC with a Waters CORTECS C18 column (1.6 mm, 2.1x55 mm) using a 0.1% aqueous formic acid:acetonitrile gradient (0.8 mL/min, 10-99% acetonitrile over 2.5 minutes) at 55 °C. The products were detected by UV light (222 nm).

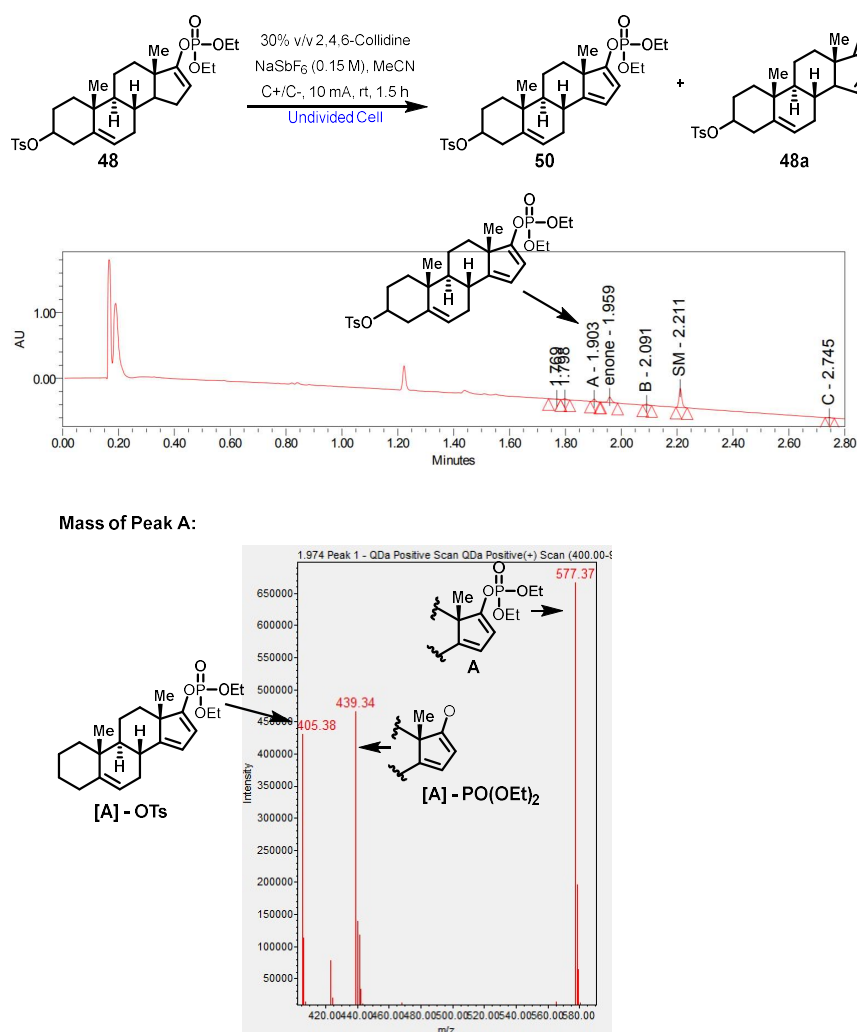


Figure S9: Diene-phosphate intermediate obtained during EDD reaction.

CYCLIC VOLTAMMETRY MEASUREMENT:

Cyclic voltammogram of the enol-ethers (10 mM in MeCN, and 0.1 M NaSbF₆ was used as an electrolyte) was recorded using Pine WaveNow potentiostat at a scan rate of 200 mV/s, with a 3.0 mm PCTFE shroud glassy carbon disk working electrode, a platinum plate counter electrode, and an Ag/AgCl (3.0 M KCl aq) reference electrode.

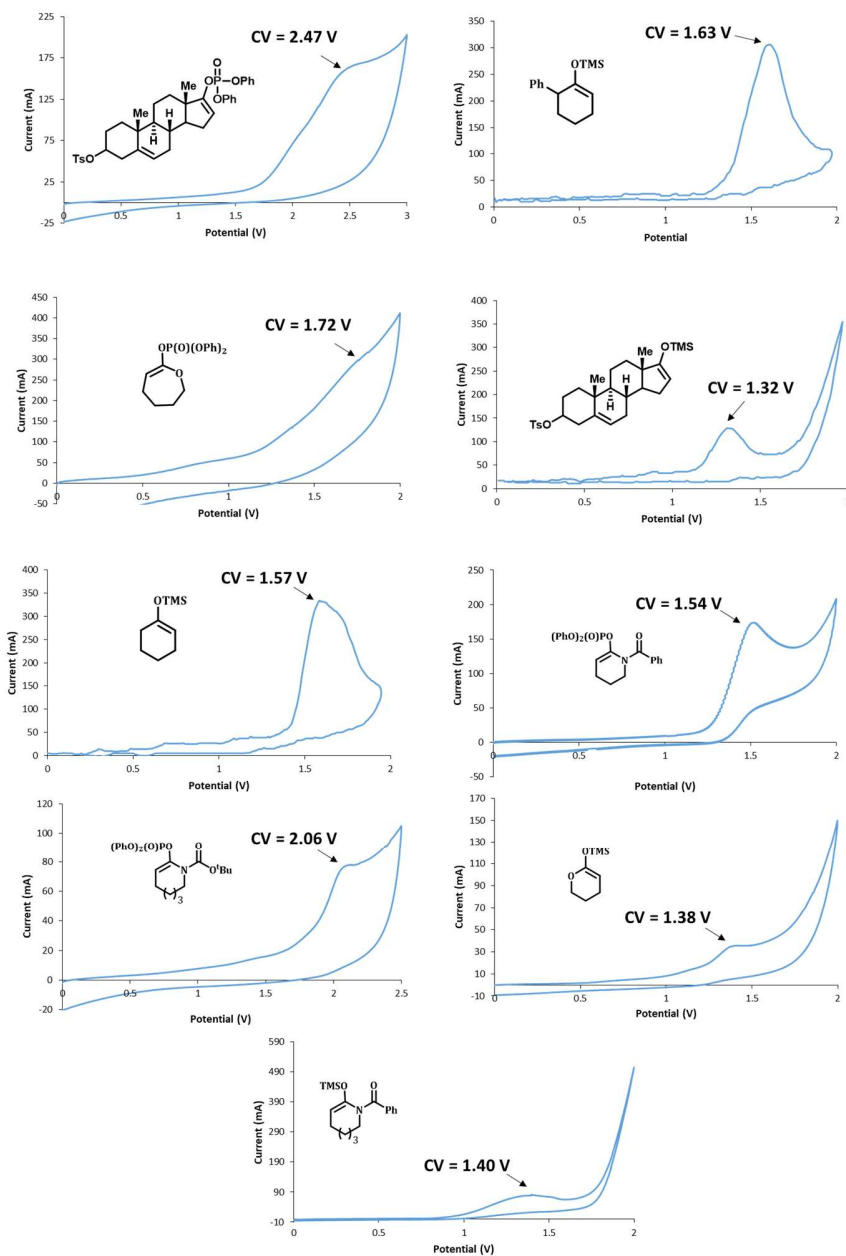


Figure S10: CV measurements of various enol-ethers.

PROCEDURES USED FOR THE CONTROL COMPARISON:

SAEGUSA-ITO PROCEDURE (PD1):

Silyl enol-ether (0.2 mmol), Na_2HPO_4 (29 mg, 0.50 mmol, 2.5 equiv.), oxone (123 mg, 0.2 mmol, 1 equiv.), and $\text{Pd}(\text{OAc})_2$ (45 mg, 0.3 mmol, 1.5 equiv.) were added to a 4 mL vial and dissolved in dry acetonitrile (2 mL). The reaction mixture was purged three times with oxygen, heated to 45 °C and stirred for under an oxygen atmosphere. After 18 the reaction was stopped, and ^1H -NMR yield was determined.

NEWHOUSE'S METHOD DESATURATION OF KETONES (PD2):

To a 0 °C solution of ketone (1.0 mmol, 1.0 equiv.) in toluene (2.5 mL, 0.40 M) was added $\text{Zn}(\text{TMP})_2$ (2.0 mL, 0.50 M in toluene, 1.0 mmol, 1.0 equiv.). The reaction mixture was stirred for 10 min. A solution of $[\text{Pd}(\text{allyl})\text{Cl}]_2$ (9.2 mg, 0.0250 mmol, 0.025 equiv.) and diethyl allyl phosphate (0.18 mL, 1.0 mmol, 1.0 equiv.) in toluene (0.82 mL) was next added at the same temperature. The reaction mixture was removed from the ice bath. The vessel was sealed with parafilm, put into a 120 °C preheated oil bath, and stirred for 2 h. The resulting mixture was removed from the oil bath, cooled to 23 °C and ^1H -NMR yield was determined.

NEWHOUSE'S METHOD DESATURATION OF ESTERS (PD2):

To a -40 °C solution of 2,2,6,6-tetramethylpiperidine (0.13 mL, 0.77 mmol, 1.5 equiv.) in THF (3.0 mL, 0.25 M) was added *n*-BuLi (2.5 M in hexanes, 0.30 mL, 0.75 mmol, 1.5 equiv.) and the resulting solution was stirred for 1 h. The corresponding ester (0.50 mmol, 1.0 equiv.) was added dropwise into the resulting solution, which was stirred for 30 min at 0 °C. ZnCl_2 (0.5 M in THF, 2.0 mL, 1.0 mmol, 2.0 equiv.) was added and stirred for 1 h at -40 °C. The stock solution of $[\text{Pd}(\text{allyl})\text{Cl}]_2$ (4.6 mg, 0.0125 mmol, 0.025 equiv.) and allyl pivalate (85 mg, 0.60 mmol, 1.2 equiv.) in THF (0.5 mL) was next added at the same temperature. After stirring for 14 h at 23 °C, the reaction was stopped, and ^1H -NMR yield was determined.

DONG'S METHOD FOR DESATURATION (Cu):

An oven-dried 4.0 mL vial was charged with the corresponding ester (0.2 mmol), CuTc (7.6 mg, 0.04 mmol, 0.2 equiv.) and CyPPh₂ (10.7 mg, 0.04 mmol, 0.2 equiv.). The vial was evacuated under high-vacuum (three times) and 2 mL of degassed benzene were added to the vial. To the resulting solution was added DTBP (^tBuO)₂ (43.9 mg, 0.3 mmol, 1.5 equiv.). The vial was tightly sealed and stirred at 80 °C for 12 h. Upon completion, ^1H -NMR yield was determined.

IBX DESATURATION:

A solution of carbonyl compound (0.1 mmol, 1 equiv.) and stabilized IBX (45% w/w, 0.13 mmol, 1.3 equiv.) in toluene/DMSO (2:1, 0.1M) was heated to 65 °C for 22 h. The reaction mixture was then filtered through Celite and diluted with MTBE. Organic phase was washed with NaHCO₃ 5%, H₂O and NaCl 10% followed by removal of solvent under reduced pressure to provide a crude mixture, which was analyzed by ¹H-NMR to determine the yield.

COMPUTATIONAL CALCULATIONS USING GAUSSIAN16

As described in the manuscript, we found an interesting correlation between the nuclear magnetic resonance chemical (^1H NMR) shift of a given enol ether's vinylic proton and the efficiency of that enol ether in the electrochemical enone formation reaction. In order to take advantage of this correlation, we developed a protocol to predict the reactivity of a compound of interest *via* prediction of its ^1H NMR shifts using quantum chemical calculations. Previous studies showed clearly that predictions using hybrid functional are more precise than pure functional. In the past, the B3LYP hybrid functional and a re-parametrized version of B3LYP, termed WP04, have been successfully used to predict NMR chemical shifts with high precision.^{27,28}

All calculations were performed using the software package GAUSSIAN16. Optimization molecules' energy-minimized geometries were performed in the gas phase using the B3LYP functional with the economical 6-31+G(d,p) basis set. NMR shielding constants were obtained using the gauge-including atomic orbital (GIAO) method in B3LYP functional with the aug-cc-pVDZ basis set. Furthermore, the same NMR shielding calculations were conducted using the GIAO method in the WP04 functional with the aug-cc-pVDZ basis set. For NMR calculations, the solvation modeling was taken into consideration by using the integral equation formalism variant of the polarizable continuum model (IEF-PCM). All NMR calculations employed the relatively unipolar and common NMR solvent, chloroform. Tetramethylsilane (TMS) served as a reference in order to determine the chemical shifts using formula 1:

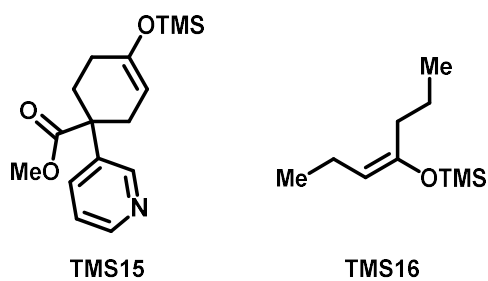
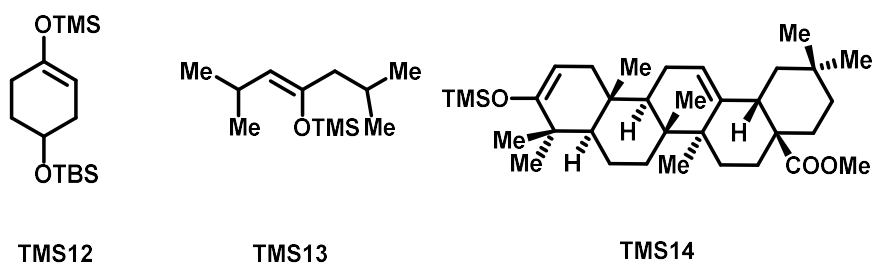
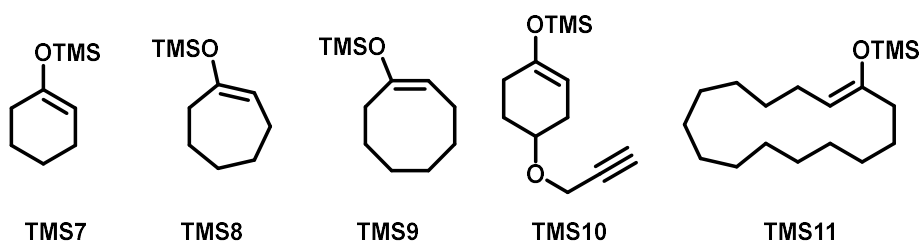
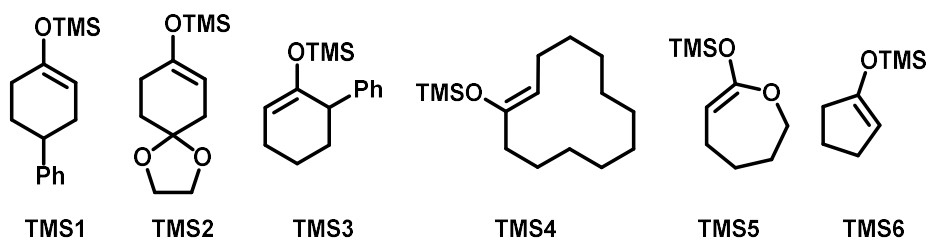
$$\delta = \text{shielding constant (TMS)} - \text{shielding constant (compound)} \quad (1)$$

Finally, the applicability of these hybrid functionals (B3LYP and WP04) was verified by calculating predictions on 16 known silyl enol ether compounds (see table below). Comparing calculated ^1H NMR shifts to those acquired experimentally, we observed root-mean-square deviations (RMSE) of 0.117 ppm (B3LYP) and 0.121 ppm (WP04) and coefficient of determinations (R^2) of 0.990 (B3LYP) and 0.988 (WP04) for the vinylic proton signals. In both methodological cases, correction term (2) can be utilized to further improve the accuracy of the calculated chemical shifts.

$$\delta = \frac{\text{intercept} - (\text{TMS})}{-st} \quad (2)$$

Note: ChemDraw and MastReNova are not precise for this kind of NMR shift prediction.

EXAMINED MOLECULES FOR GAUSSIAN NMR SHIFT CALCULATION:



CALCULATED ¹H NMR CHEMICAL SHIFTS

Table S6: Results of Calculations of ¹H NMR Chemical Shifts for TMS-protected Enols (GIAO/B3LYP/aug-cc-pVDZ//B3LYP/6-31+G(d,p)).

Compound	shielding constant	calc'd [ppm]	shift corrected [ppm]	shift exp. [ppm]	shift $\Delta(\text{calc'd} - \text{exp})$ [ppm]	$\Delta(\text{corr} - \text{exp})$ [ppm]
TMS	31.6813			0.00		
TMS 1	26.6890	4.99	4.91	4.99	0.00	-0.07
TMS 2	26.9328	4.75	4.66	4.72	-0.03	0.08
TMS 3	26.5239	5.16	5.07	5.05	0.11	0.02
TMS 4	27.1403	4.54	4.46	4.55	-0.01	-0.09
TMS 5	27.5355	4.15	4.07	4.12	0.03	-0.05
TMS 6	27.0151	4.67	4.58	4.53	0.14	0.05
TMS 7	26.7987	4.88	4.80	4.83	0.05	-0.03
TMS 8	26.5741	5.11	5.02	4.87	0.24	0.15
TMS 9	26.8280	4.85	4.77	4.80	0.05	-0.03
TMS 10	26.9403	4.74	4.66	4.73	0.01	-0.07
TMS 11	26.9563	4.73	4.64	4.63	0.1	0.01
TMS 12	26.9374	4.74	4.66	4.71	0.03	-0.05
TMS 13	26.8702	4.81	4.73	4.38	0.43	0.35
TMS 14	26.9690	4.71	4.63	4.57	0.14	0.06
TMS 15	26.7853	4.90	4.81	4.92	-0.02	-0.11
TMS 16	27.0375	4.64	4.56	4.63	0.01	-0.07

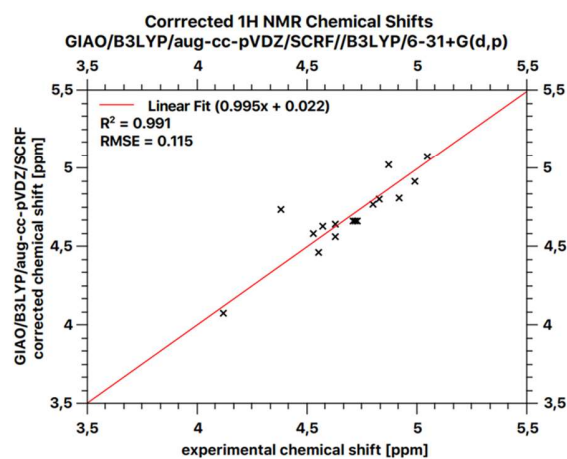
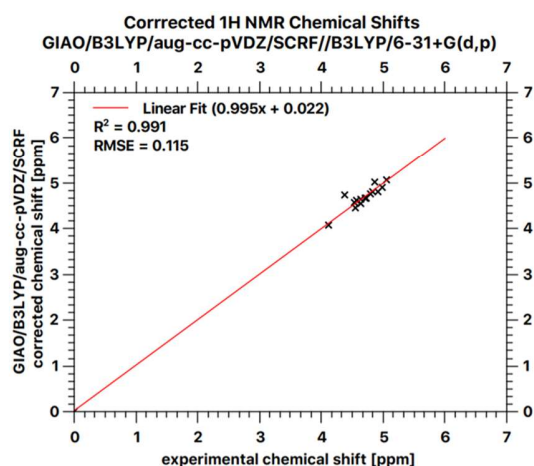
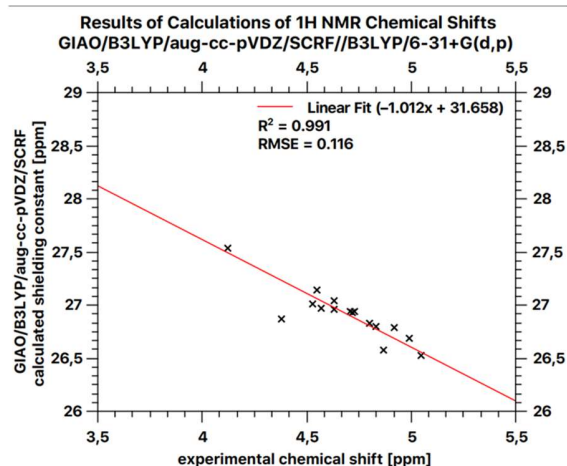
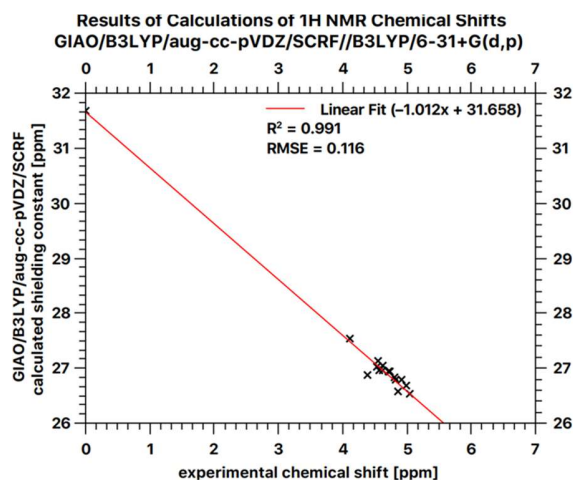


Figure S11: Graphical representation of the results from Table S6 that were obtained by optimization of the molecular structure using B3LYP functional with 6-31+G(d,p) basis set and subsequent NMR calculation using GIAO method with the B3LYP hybrid functional and aug-cc-pVDZ basis set. Solvent modeling was taken into consideration by applying the IEFPCM procedure.

Table S7: Results of Calculations of ^1H NMR Chemical Shifts for TMS-protected Enols (GIAO/WP04/aug-cc-pVDZ//B3LYP/6-31+G(d,p)).

Compound	shielding constant	calc'd [ppm]	shift [ppm]	corrected shift [ppm]	exp. shift [ppm]	$\Delta(\text{calc'd} - \text{exp})$ [ppm]	$\Delta(\text{corr} - \text{exp})$ [ppm]
TMS	31.8994				0.00		
TMS 1	27.1370	4.76		4.90	4.99	-0.23	-0.09
TMS 2	27.3431	4.56		4.68	4.72	-0.16	-0.06
TMS 3	27.0120	4.89		5.03	5.05	-0.16	-0.02
TMS 4	27.5549	4.34		4.46	4.55	-0.21	-0.09
TMS 5	27.8840	4.02		4.12	4.12	-0.10	0.00
TMS 6	27.3970	4.50		4.63	4.53	-0.03	0.10
TMS 7	27.2561	4.64		4.77	4.83	-0.19	-0.06
TMS 8	27.0813	4.82		4.95	4.87	-0.05	0.08
TMS 9	27.2838	4.62		4.74	4.80	-0.18	-0.06
TMS 10	27.3598	4.54		4.66	4.73	-0.19	-0.09
TMS 11	27.4131	4.49		4.61	4.63	-0.24	-0.02
TMS 12	27.3579	4.54		4.67	4.71	-0.17	-0.04
TMS 13	27.2748	4.62		4.75	4.38	0.24	0.37
TMS 14	27.3978	4.50		4.63	4.57	-0.07	0.06
TMS 15	27.1905	4.71		4.84	4.92	-0.21	-0.08
TMS 16	27.4984	4.40		4.52	4.63	-0.23	-0.11

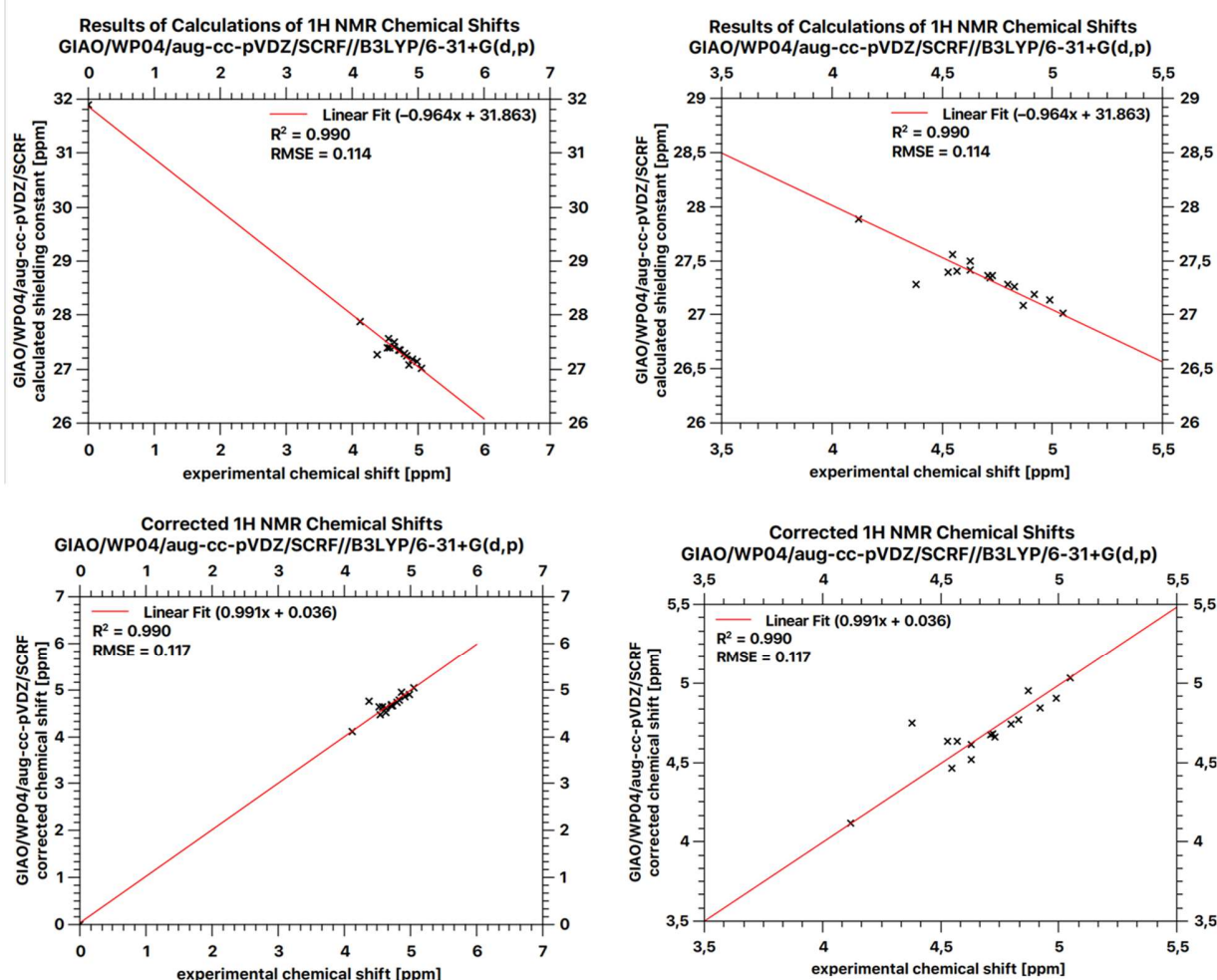
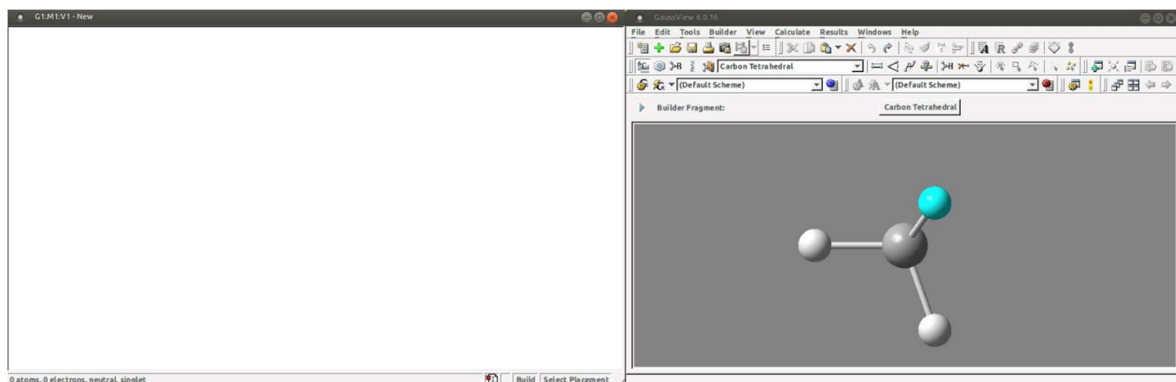


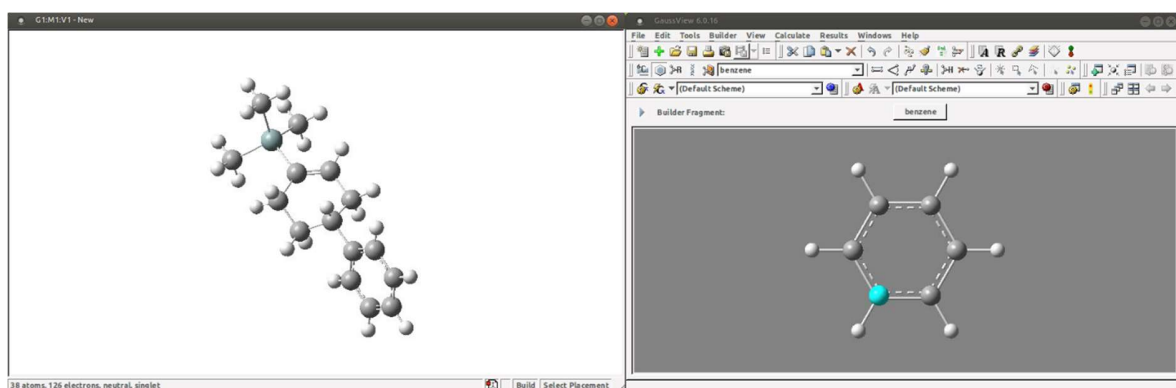
Figure S12: Graphical representation of the results from Table S7 that were obtained by optimization of the molecular structure using B3LYP functional with 6-31+G(d,p) basis set and subsequent NMR calculation using GIAO method with the WP04 hybrid functional and aug-cc-pVDZ basis set. Solvent modeling was taken into consideration by applying the IEFPCM procedure.

INSTRUCTIONS FOR CALCULATING NMR CHEMICAL SHIFTS WITH THE GAUSSIAN 16 PROGRAM PACKAGE.

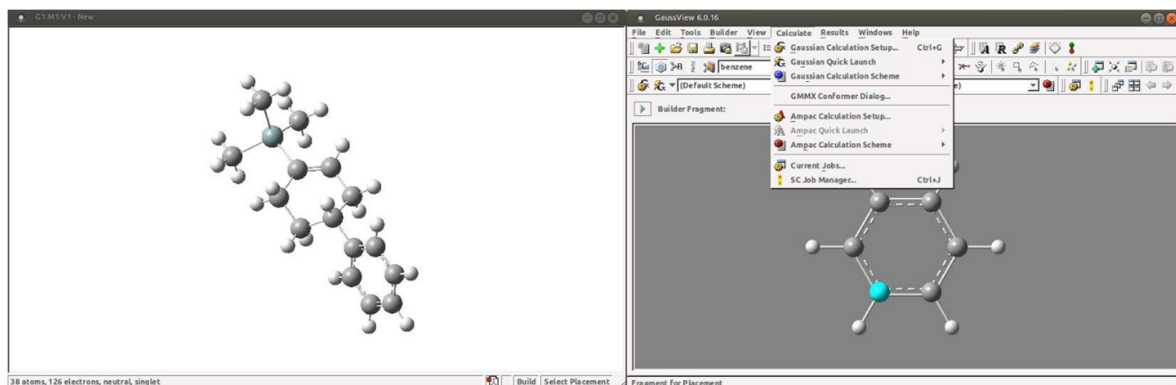
1. Open GaussView 6.



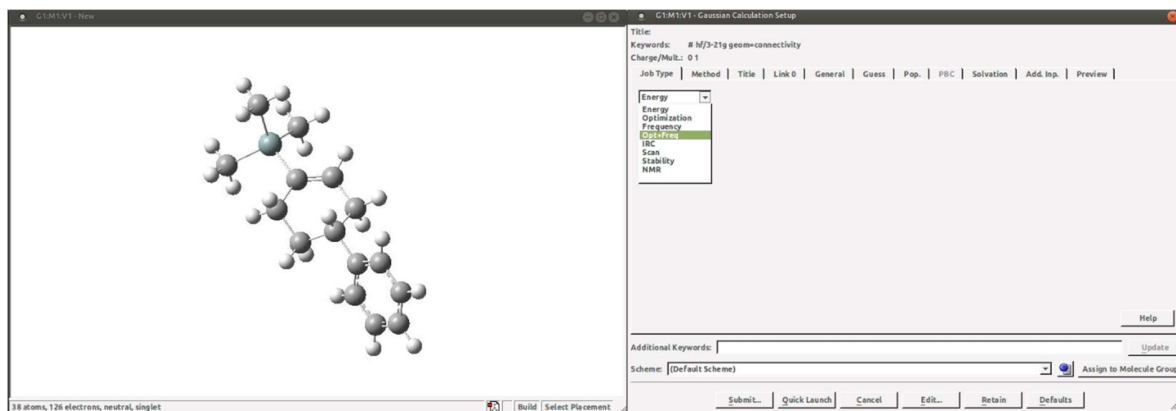
2. Use the toolbar on the top right to draw your structure of interest.



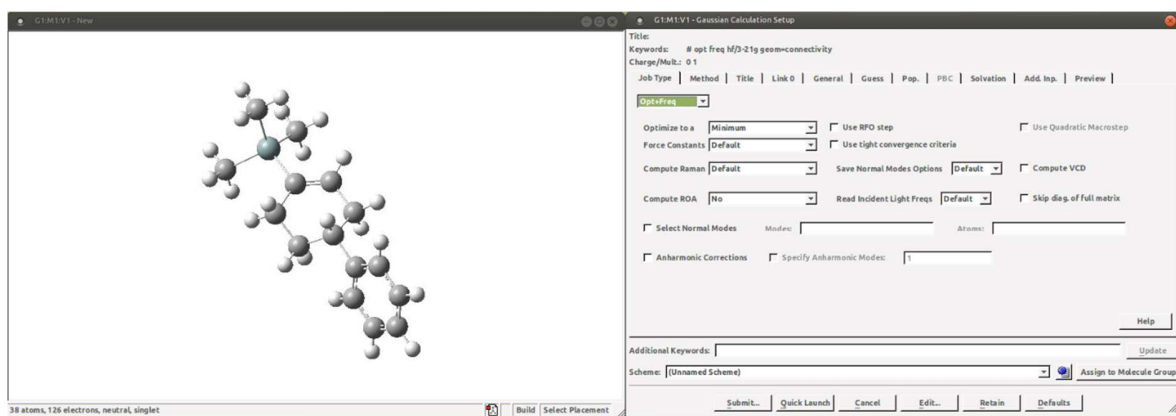
3. Once the structure is generated, click on *calculate*, then select *gaussian calculation setup* and a new window will pop up.



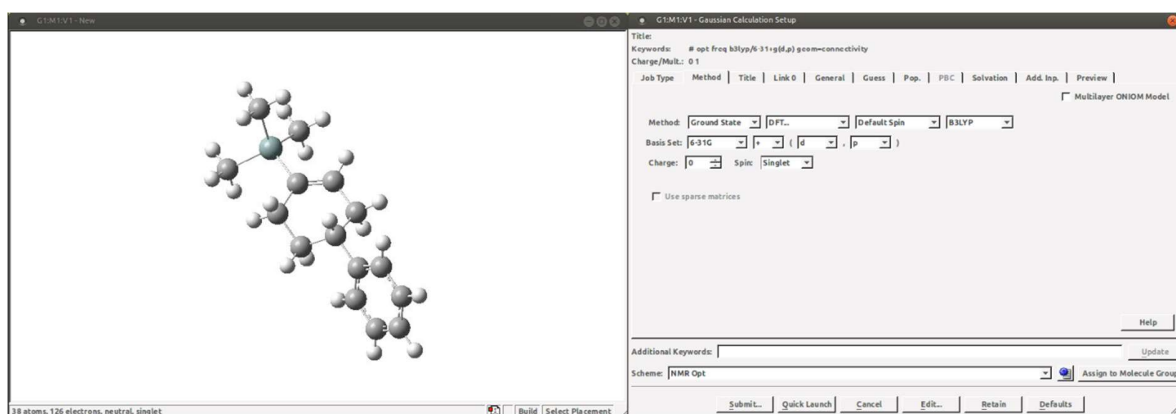
Choose *Opt+Freq* as job type



4. Select options as illustrated



5. Select method and basis set as illustrated (make sure that charge = 0 and spin = singlet, otherwise there might be a mistake in your chemical structure)

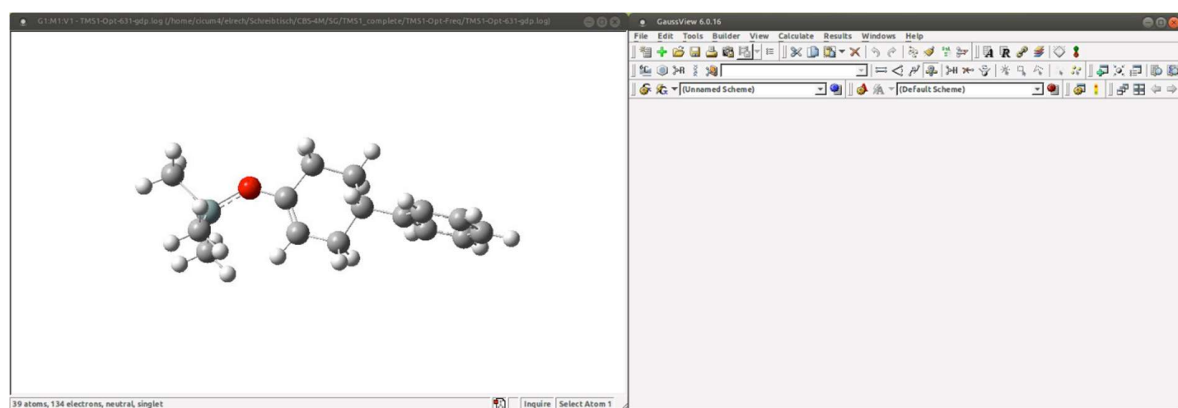


The screenshot displays the Gaussian 09 software interface. On the left, a 3D ball-and-stick model of a complex organic molecule is shown, featuring a central ring system with various substituents. On the right, the 'Gaussian Calculation Setup' window is open, showing the following details:

- Title:** Opt Test
- Keywords:** # opt freq hlyp/6-31+g(d,p) geom=connectivity
- Charge/Mult.:** 0 1
- Job Type:** Method Title Link 0 General Guess Pop. PBC Solvation Add. Inp. Preview
- Job Title:** Opt Test
- Additional Keywords:** (empty field)
- Scheme:** (Unnamed Scheme)
- Buttons:** Submit, Quick Launch, Cancel, Edit, Retain, Defaults

At the bottom left, a status bar indicates '18 atoms 126 electrons, neutral, singlet'.

- Once your optimization job has been successfully completed, open the created log-file in GaussView6.



G1M1-V1 - TMS1-NMR wPQ4.com 4/electroSchedructury CBO-WPQ4.com TMS1-NMR wPQ4.com

Title: Opt Test
Keywords: # opt freq hlyyp/j6-311g(d,p) geom=connectivity
Charge/Mult.: 0 1

Job Type | Method | Title | Link 0 | General | Guess | Pop. | PBC | Solvation | Add. Inp. | Preview |

Opt+Freq
Energy Optimization Minimum ☐ Use RFO step ☐ Use Quadratic Macrostep
Opt+Freq Default ☐ Use tight convergence criteria
IRC Default ☐ Compute VCD
Scan Default ☐ Save Normal Modes Options Default ☐
Stability
HFC

Compute ROA No ☐ Read Incident Light Freqs Default ☐ Skip diag. of full matrix

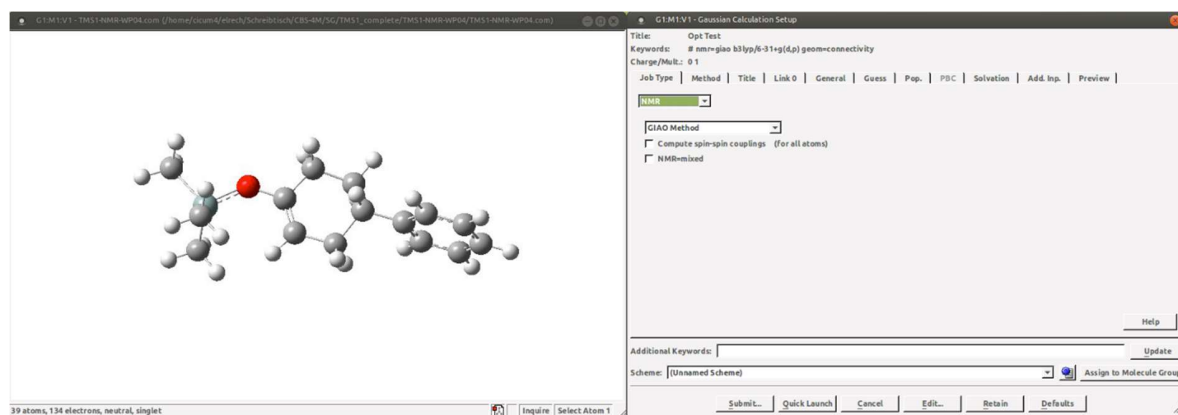
☐ Select Normal Modes Modes: Atoms:
☐ Anharmonic Corrections ☐ Specify Anharmonic Modes: 1

Additional Keywords:
Scheme: [Unnamed Scheme] Assign to Molecule Group

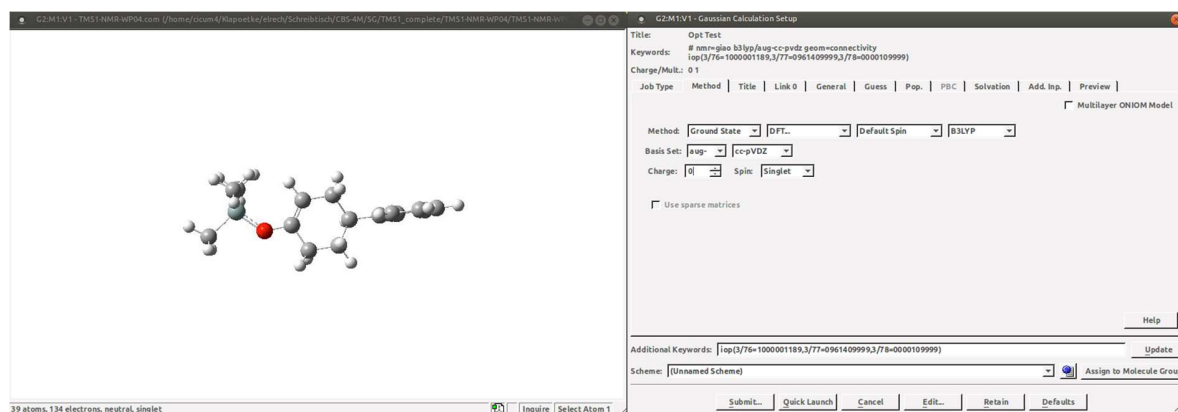
Submit... Quick Launch Cancel Edit... Retain Defaults

10 atoms 134 electrons neutral singlet

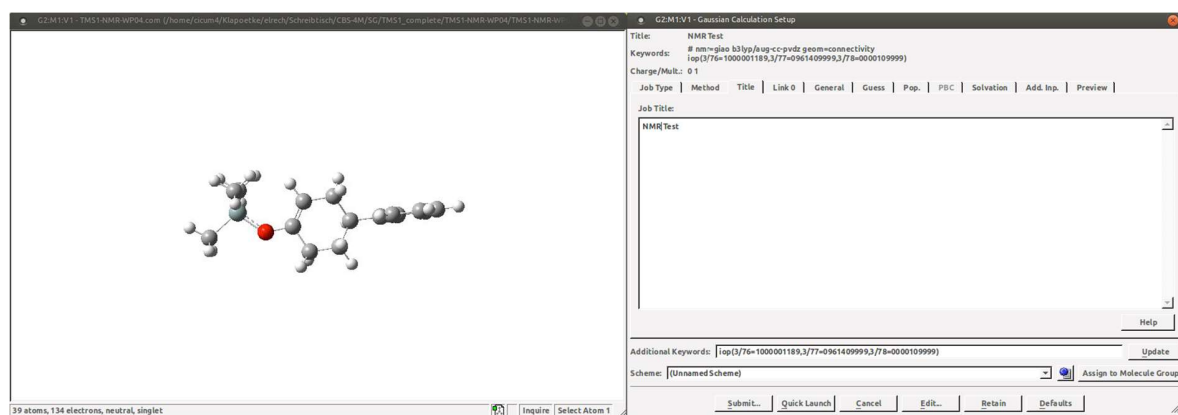
9. Select *GIAO* Method.



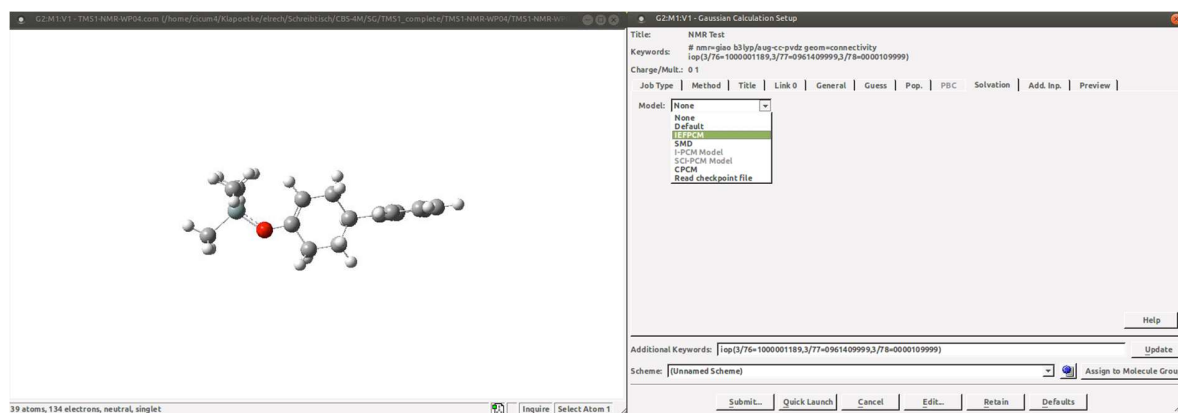
10. Select the *method* and *basis set* as illustrated (make sure that charge = 0 and spin = singlet, otherwise there might be a mistake in your chemical structure). For the *WP04* functional you have to add additional keywords (*iop(3/76=100...*)) to the field on the bottom right as illustrated bellow (*B3LYP* does not require additional keywords).



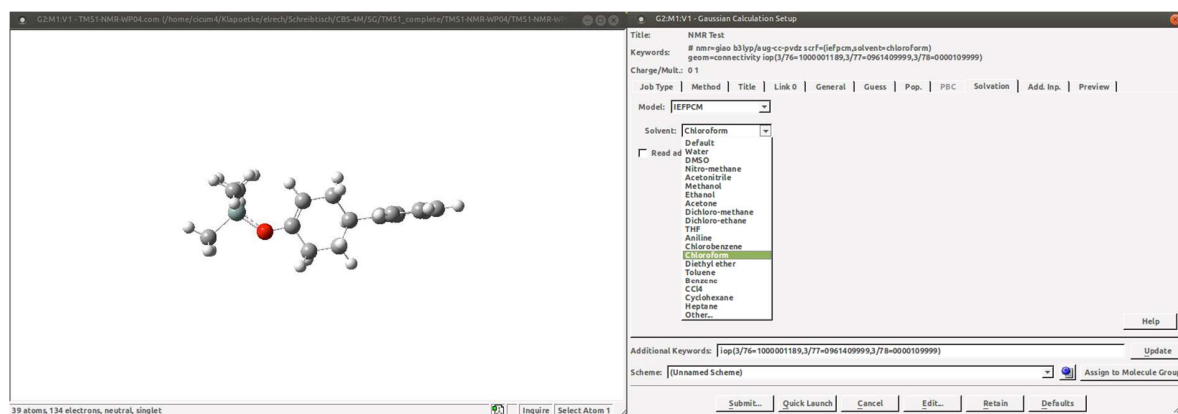
11. Enter a job title.



12. Choose *IEFPCM* as solvation model.

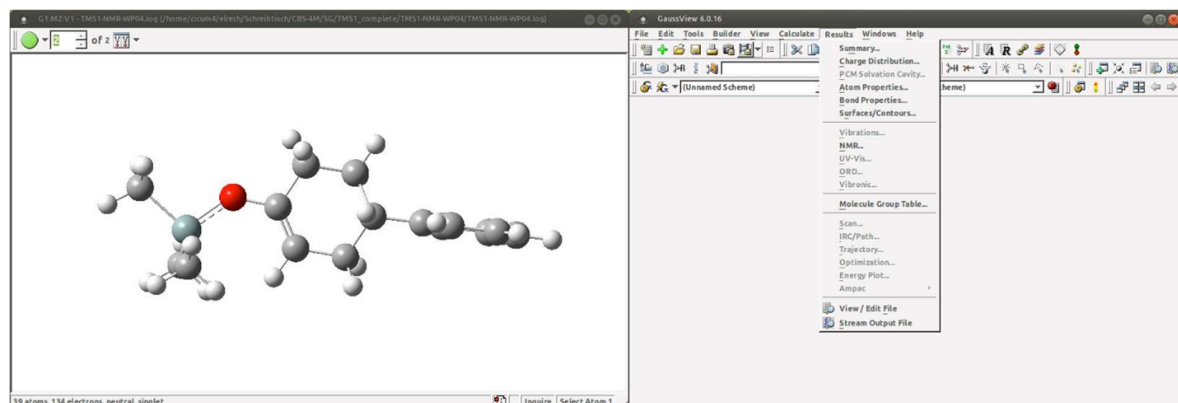


13. Choose *chloroform* as solvent.

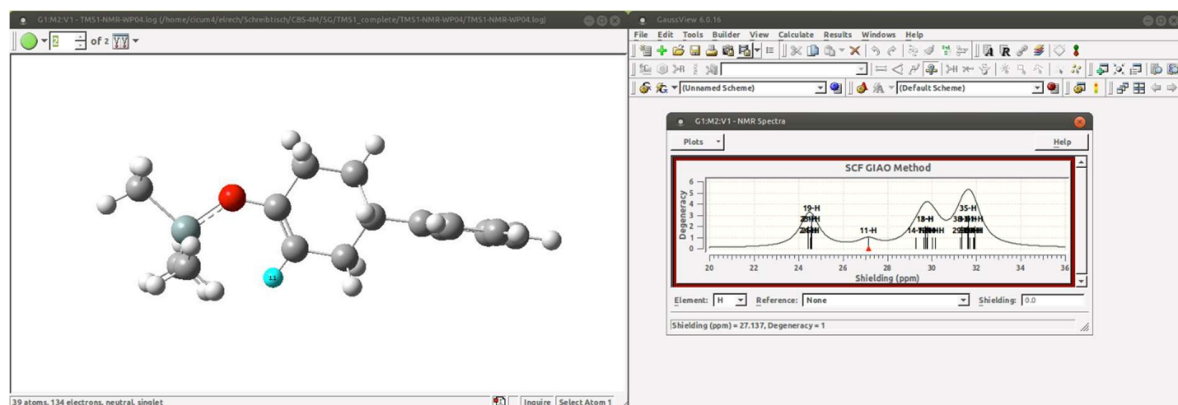


Now click on submit to run your optimization. Otherwise you could also click on “edit” to save your gaussian job on your computer and send it to your institutional cluster (if available).

14. Once your optimization job has been successfully completed, open the created log-file in GaussView6. Click on *results* and go to *NMR* and a new window will pop up.



15. Choose *H* as *element* and then select the olefinic proton and read off the corresponding shielding constant. Together with the intercept and slope of the method (see corresponding tables 1-4) place the calculated shielding constant in formula (1) to receive your corrected chemical shift (For the uncorrected chemical shift, you have to calculate tetramethylsilane using exactly the same procedure as for your compound of interest and then subtract the shielding constant of your desired molecule from the shielding constant of tetramethylsilane).



For further information visit <https://gaussian.com>

OPTIMIZED MOLECULAR GEOMETRIES:

TMS Ref

```
# opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS-Ref_631+gpd\\0,1\
Si,-1.7498322553,-3.3392519522,-0.0228478671\C,-1.1179531425,-2.445829
8788,1.5246583198\H,-1.4662524438,-1.4063193477,1.5540627218\H,-1.4678
471738,-2.9389879149,2.439602838\H,-0.0217933428,-2.4294523274,1.55498
83415\C,-3.6451791584,-3.3390922351,-0.0228796698\H,-4.0430072403,-2.3
17091222,-0.0226347102\H,-4.0430992061,-3.849833129,-0.9080713239\H,-4
.0431618769,-3.8502809298,0.8620238564\C,-1.118249571,-5.1263021843,-0
.022913849\H,-1.4672747436,-5.6716690557,-0.9080764543\H,-0.0220926824
,-5.1609281435,-0.0227345115\H,-1.4675808433,-5.6718574912,0.862011709
\C,-1.1180147218,-2.4458955326,-1.570461838\H,-0.0218576162,-2.4278678
417,-1.5998608614\H,-1.4663698475,-2.9402560184,-2.485342861\H,-1.4678
849945,-1.4069447058,-1.6009392485\\Version=ES64L-G16RevA.03\\State=1-A
\\HF=-449.2183429\\RMSD=2.449e-09\\RMSF=8.962e-05\\Dipole=0.0000293,0.0000
531,0.0000848\\Quadrupole=-0.0001005,0.0000249,0.0000756,0.0000293,0.00
01074,0.0001173\\PG=C01 [X(C4H12Si1)]\\@
```

TMS 1

```
# opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS1_Opt_Freq\\0,1
\C,-1.8592174785,-2.5308468147,0.2997463771\C,-0.3323218665,-2.3985210
632,0.2190844911\C,0.1047375924,-1.1186003018,-0.4470893554\C,-0.72804
69598,-0.0909622212,-0.681320895\C,-2.1833431067,-0.0989593211,-0.2744
087168\C,-2.5087468502,-1.2065304702,0.7525149145\H,0.1135426173,-2.44
10736349,1.2238677774\H,0.0996522531,-3.2406084079,-0.3354773717\H,-2.
2536073844,-2.8086742724,-0.6864170176\H,-2.1302149557,-3.3401386746,0
```

.9869956639\H,-0.3628389827,0.8002284234,-1.1847107757\H,-2.4554932282
,0.8763900689,0.1506102866\H,-2.8239778443,-0.2210988546,-1.1609996839
\H,-2.0315182287,-0.9201562518,1.700357626\C,-3.9993830764,-1.33352249
04,1.0172519619\C,-4.5239745831,-1.0420037287,2.2848490055\C,-4.893264
9012,-1.7435336192,0.0137782644\C,-5.892747409,-1.153710316,2.54731200
21\H,-3.8507670076,-0.7231842912,3.0774086128\C,-6.2612651941,-1.85787
9612,0.269676404\H,-4.520157297,-1.9779563034,-0.9797667711\C,-6.76791
26354,-1.5627962899,1.5390624956\H,-6.272482563,-0.9212901971,3.538498
901\H,-6.9322949218,-2.1778564321,-0.5228584086\H,-7.8320027215,-1.651
3999416,1.7383721986\O,1.4355638705,-1.1466141186,-0.7681718649\Si,2.5
016266839,0.0163440864,-1.3835759043\C,2.5765663476,1.5127903917,-0.23
83087639\H,1.6207532202,2.043356728,-0.1830851068\H,2.8505960851,1.210
9374579,0.7788154622\H,3.3333257603,2.2242027744,-0.5907910472\C,4.150
2884549,-0.8848804256,-1.4120982746\H,4.0993651753,-1.7732928884,-2.05
09783064\H,4.9478322551,-0.2379819048,-1.7960010124\H,4.4350028951,-1.
211998146,-0.4061894627\C,1.9992528553,0.5239490459,-3.1298137001\H,1.
8901114728,-0.3560395139,-3.7736949749\H,1.0528995997,1.0736891817,-3.
1528345343\H,2.768367537,1.168086959,-3.5734577765\\Version=ES64L-G16R
evA.03\State=1-A\HF=-949.691544\RMSD=3.409e-09\RMSF=1.297e-06\Dipole=0
.2598151,0.2443389,-0.1172686\Quadrupole=1.7102149,-2.5858892,0.875674
3,2.9139783,-1.10164,0.1404937\PG=C01 [X(C15H22O1Si1)]\\@

TMS 2

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS2-Opt-631+gdp\\
0,1\C,-3.7667482373,-0.4076307714,-0.7638971164\C,-2.6368254297,-1.014
9843355,0.0744587942\C,-1.8001265917,0.0740973409,0.7426894301\C,-2.66
13150024,0.9482191358,1.6636302059\C,-3.9532797636,1.3632834973,1.0076
628445\C,-4.4448485821,0.7601656461,-0.0870994032\H,-0.9815427236,-0.3

925459549,1.2998815646\H,-3.3402591505,-0.1080445953,-1.7313288126\H,-
4.4936013808,-1.2005694317,-0.9819998304\H,-2.8945637513,0.4093120276,
2.5915300968\H,-2.1134966707,1.8510510517,1.9576154828\H,-5.3774870361
,1.103376908,-0.5258106734\H,-1.3580084283,0.6854702446,-0.0524618411\
O,-4.5484068888,2.4024925073,1.6699890581\O,-1.8344961307,-1.842227703
5,-0.7826333133\O,-3.149185718,-1.8826511083,1.1000858167\Si,-6.082242
6041,3.1122562447,1.5611213097\C,-6.2990287931,3.9840659646,-0.0982922
413\H,-5.4715809337,4.6783496516,-0.283200681\H,-6.3420526296,3.284788
9287,-0.939490283\H,-7.2291949615,4.5655476189,-0.1024351562\C,-7.4249
078052,1.8156091915,1.8263217338\H,-7.2860982916,1.3028144731,2.784616
5762\H,-8.4141849884,2.2890999221,1.8399189147\H,-7.4295768132,1.05493
73911,1.0393113247\C,-6.0752075582,4.3665030093,2.960471388\H,-5.27124
84886,5.0983217784,2.8256027608\H,-7.0247434968,4.9125751738,3.0067861
881\H,-5.9206762157,3.8738202355,3.9265218452\C,-1.6704191602,-3.11368
88835,-0.1536590985\H,-1.5728447442,-3.8721087003,-0.9348607931\H,-0.7
728270726,-3.1248238432,0.4810110474\C,-2.9430220351,-3.2293960054,0.6
773743234\H,-2.8449889917,-3.855834636,1.567629512\H,-3.7881421008,-3.
5866209536,0.0708759756\\Version=ES64L-G16RevA.03\State=1-A\HF=-946.48
25546\RMSD=5.363e-09\RMSF=1.952e-06\Dipole=-0.2599619,-0.3568234,0.025
8379\Quadrupole=-0.1600077,5.6137074,-5.4536996,-4.2307546,2.1200589,0
.0246792\PG=C01 [X(C11H20O3Si1)]\\@

TMS 3

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS3-Opt-631-gdp\\
0,1\C,-4.1089729613,-2.0492854674,0.2846664318\C,-2.5813856348,-2.0734
857216,0.1845639983\C,-2.0563192483,-0.7035712237,-0.2650793441\C,-2.6
879327992,0.4197701442,0.5235405579\C,-3.8122909669,0.2775787366,1.246
6664716\C,-4.6081560373,-1.0166193785,1.3243868694\H,-0.9653564382,-0.

6613598971,-0.1477966099\H,-2.151971745,-2.324464224,1.1642087697\H,-2.2591973057,-2.8542055302,-0.5148918806\H,-4.5291439238,-1.7968460955,-0.6976738388\H,-4.5053375875,-3.0366796046,0.5478167803\H,-2.1751512155,1.3781475636,0.5196975815\H,-2.243809364,-0.5700287146,-1.3424852417\C,-6.111133382,-0.7970005857,1.1918395275\C,-6.9955376013,-1.3493219042,2.126029693\C,-6.647453901,-0.0830920852,0.10938109\C,-8.3790861909,-1.1987596839,1.9868886304\H,-6.5979784461,-1.8998407258,2.9756083568\C,-8.0268539384,0.0732310978,-0.0336472596\H,-5.9772485854,0.3624600284,-0.6217539048\C,-8.9001812335,-0.4858901948,0.905474027\H,-9.0461831286,-1.6352192177,2.7252570905\H,-8.4214617564,0.6332675438,-0.8772314794\H,-9.9739749254,-0.3644271307,0.7949016868\O,-4.357290883,1.2506212217,2.0363666602\Si,-3.9245213787,2.8433017194,2.4075843648\C,-3.9478551309,3.9136674259,0.854345659\H,-3.7691455505,4.964287856,1.1140418966\H,-3.1837858909,3.6165560727,0.1287388924\H,-4.9227113575,3.8543952235,0.3575970172\C,-2.230499936,2.8940680283,3.2372506838\H,-1.4223877102,2.5941105017,2.5625431969\H,-2.0112111388,3.9100342715,3.5879386305\H,-2.2038166514,2.2287153373,4.1075770455\C,-5.2642610985,3.3862372374,3.6067960242\H,-5.2661961717,2.7557020693,4.5025355961\H,-5.1140869557,4.4249101741,3.9240039125\H,-6.2541835374,3.3114984554,3.1441958025\H,-4.4335891824,-1.4277917534,2.3301029141\\Version=ES64L-G16RevA.03\State=1-A\HF=-949.6890195\RMSD=4.531e-09\RMSF=3.939e-06\Dipole=0.3404352,0.2342689,0.0203115\Quadrupole=-0.0029208,0.7833447,-0.7804239,0.0073656,-0.4477948,-1.0072999\PG=C01 [X(C15H22O1Si1)]\\@

TMS 4

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS4-Opt-631-gdp\\
0,1\C,-2.6924323109,-0.9761148289,-0.4023529956\H,-1.7927877849,-1.0131568945,-1.0246248858\H,-3.2581085969,-0.0923655107,-0.7326518999\C,-2

.2948395027,-0.7628397746,1.0675087238\H,-1.769412683,0.1988943454,1.1533127993\H,-3.2143501607,-0.6567396624,1.6615291292\C,-1.4271294662,-1.8462388333,1.7381327509\H,-1.4087430551,-1.6074390955,2.809731088\H,-1.9233330818,-2.8241372375,1.6697207299\C,0.0440516503,-1.9814402433,1.2762927979\H,0.6211001873,-2.3200616186,2.14476596\H,0.451528035,-0.9975848995,1.0162687045\C,-3.5500445443,-2.2260021629,-0.6521605245\H,-2.9787345147,-3.1266350443,-0.4026771353\H,-4.4020034288,-2.2139871241,0.0435449564\C,0.3464480269,-2.9812523841,0.1261177206\H,1.3157759488,-3.4526241334,0.3417777427\H,-0.3881081879,-3.7910103257,0.1313216313\C,-4.1125609563,-2.3365713533,-2.0826860142\H,-4.7391509601,-3.2378119276,-2.1490419469\H,-4.793446567,-1.4874843864,-2.2387915792\C,-3.1073551448,-2.3467579769,-3.2527890761\H,-3.6823508621,-2.1639057149,-4.1705319427\H,-2.4201120401,-1.4965676589,-3.1612663055\C,-2.2970374029,-3.6374708632,-3.4829799524\H,-1.854334975,-3.5757092736,-4.4875155797\H,-2.984046942,-4.494934495,-3.5119465496\C,0.4804356968,-2.4104676462,-1.2659274213\C,-0.1344745579,-2.8519805885,-2.3786053937\H,0.1295345548,-2.3767779826,-3.3224159678\C,-1.1555390754,-3.9570915559,-2.4902066264\H,-1.5681104778,-4.2076025008,-1.5096524065\H,-0.6665471072,-4.87657787,-2.8492184341\O,1.4010937381,-1.3888596421,-1.2749245853\Si,2.2193250817,-0.5466559219,-2.4908592358\C,3.388596188,0.569060769,-1.5307093201\H,3.9959945762,1.180674834,-2.2082185872\H,2.8327143721,1.2462118159,-0.872952347\H,4.0684922561,-0.0206830651,-0.9063447604\C,3.1858759374,-1.7431183489,-3.5827215925\H,2.5320248298,-2.4244591532,-4.136268778\H,3.7867141041,-1.1893157891,-4.31441656\H,3.8704535704,-2.3516504897,-2.9811991509\C,1.0279984261,0.4947645595,-3.5195394019\H,1.5892197954,1.1545035793,-4.1927575401\H,0.3577326257,-0.1133524876,-4.1353822106\H,0.4078992356,1.1279558015,-2.8750012774\\Version=ES64L-G16RevA.03\State=1-A\HF=-954.5087643\RMSD=5.393e-09\RMSF=1.820e-06\Dipo

le=0.1844682,0.0491232,-0.2418821\Quadrupole=-0.2006925,-0.0306258,0.2
313183,1.4425516,-1.3813001,-1.4029257\PG=C01 [X(C15H30O1Si1)]\@

TMS 5

opt freq b3lyp/6-31+g(d,p) geom=connectivity\TMS5-Opt-631-gdp\0
,1\C,-3.3896612305,-1.6318619369,0.0451623327\C,-2.3635524543,-0.99399
35046,-0.9106708872\C,-1.1611942287,-0.3455380934,-0.2696284608\C,-2.7
145562235,-2.5375316011,1.0876901263\C,-0.9570182796,-0.1178015313,1.0
357844931\C,-2.2059393082,-1.7570936664,2.3103859607\H,-3.9748606923,-
0.8547395731,0.5505276178\H,-2.0004990346,-1.7803041438,-1.5904560673\
H,-0.3533731249,-0.0428068319,-0.9296379223\H,-1.8877384822,-3.0778268
241,0.611192478\H,-1.3424412751,-2.2566747177,2.7699639963\H,-4.096943
2306,-2.2190512368,-0.5520607918\H,-2.8732484248,-0.2659123795,-1.5595
778752\H,-3.4130856842,-3.3011656663,1.4525415482\H,-2.9931681418,-1.6
724637139,3.0647387666\O,-1.8677569585,-0.3821245302,2.0345391818\O,0.
1799875064,0.4665550379,1.4897054296\Si,0.4266325731,1.320977623,2.941
9409514\C,-0.8913142818,2.6497716449,3.1460688454\H,-0.9023886932,3.32
77825951,2.2852688227\H,-1.8870106729,2.2053038261,3.2410009627\H,-0.6
993273868,3.2510593375,4.0430666484\C,0.4522094998,0.1497149626,4.4183
423679\H,1.1607746248,-0.6706324834,4.2562657491\H,0.7635480883,0.6827
256723,5.325122577\H,-0.5355098629,-0.2830164647,4.6041598698\C,2.1286
457814,2.0773830624,2.684595237\H,2.1342404718,2.7458433233,1.81685757
68\H,2.4389650528,2.6578267318,3.5614532131\H,2.8807931529,1.299641202
,2.512132432\Version=ES64L-G16RevA.03\State=1-A\HF=-793.8326983\RMSD=
9.396e-09\RMSF=2.641e-06\Dipole=-0.2577727,-0.3776551,0.3487996\Quadru
pole=-1.1468008,1.2020789,-0.0552781,2.707047,1.4894998,0.9879457\PG=C
01 [X(C9H18O2Si1)]\@

TMS 6

```
# opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS6-Opt+Freq\\0,1\
C,4.356642166,2.8448570778,-7.2767314664\C,5.7892862994,2.3986836494,-
7.0876808736\C,6.5544320845,3.1713696894,-8.2006576865\C,5.4819622953,
3.5615588124,-9.2448695206\C,4.1964690208,3.4709631796,-8.4557854825\H
,3.5693647033,2.6270523882,-6.5635006665\H,5.885796819,1.3094558901,-7
.2163462565\H,6.182469771,2.6266517745,-6.089067617\H,6.9895987313,4.0
81023297,-7.7724541833\H,7.3748138195,2.5891102885,-8.6308373948\H,5.6
303835318,4.5623375106,-9.6663888868\H,5.4474840215,2.8630810689,-10.0
938417158\O,3.079013821,3.9794618832,-9.0358092254\Si,1.4708062431,4.0
231993114,-8.4937085425\C,0.5678312263,4.8992408105,-9.8881111898\H,0.
667871582,4.3452747145,-10.8278170776\H,-0.5011498992,4.9982108624,-9.
666059993\H,0.9743883051,5.9039506709,-10.0468314353\C,1.3557624194,5.
0080366486,-6.8906678216\H,1.9049324402,4.5319720263,-6.0720753111\H,1
.7626862264,6.0167117043,-7.0233574778\H,0.309478061,5.1079777106,-6.5
771500199\C,0.8166582436,2.270255838,-8.2626031344\H,-0.2462134272,2.2
914315137,-7.9927135968\H,0.9146365525,1.6924253893,-9.1884382737\H,1.
3496682324,1.7299741297,-7.4737212808\\Version=ES64L-G16RevA.03\\State=
1-A\\HF=-679.3029227\\RMSD=8.332e-09\\RMSF=2.405e-06\\Dipole=-0.3244238,-0
.0399049,0.1483758\\Quadrupole=2.3140618,-1.0427468,-1.271315,-0.476164
6,-0.5773095,0.1668686\\PG=C01 [X(C8H16O1Si1)]\\@
```

TMS 7

```
# opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS7-Opt-Freq\\0,1\C
,-3.3213856452,-2.4488882617,-0.1716988189\C,-2.4239263329,-2.71891574
63,1.0456592971\C,-1.8549072466,-1.4470478773,1.6336113364\C,-2.326739
6885,-0.2258704993,1.3308983943\C,-3.4919864477,0.0076777549,0.4013960
392\C,-4.2750576645,-1.2804622334,0.1067062815\H,-1.0295080561,-1.5499
```

699827,2.3331487266\H,-2.9975161096,-3.2621687596,1.8136988736\H,-1.60
34196941,-3.3914121379,0.7609630997\H,-2.6927954116,-2.2014495894,-1.0
384166877\H,-3.8834843776,-3.3531163974,-0.4340110821\H,-4.1429649326,
0.7672600927,0.8514974202\H,-3.1124788313,0.4515211679,-0.5310269811\H
,-4.9046027198,-1.528999394,0.9721643254\H,-4.9523483818,-1.1192349258
,-0.7401397732\O,-1.8247792039,0.9545571901,1.8133699134\Si,-0.4511255
698,1.340280569,2.7238210135\C,-0.5713724328,0.6095486968,4.4593007751
\H,0.2494844483,0.980573082,5.085292256\H,-1.5131267883,0.9002120943,4
.9383590041\H,-0.5206678793,-0.4839858524,4.4597348204\C,1.1100015057,
0.7474213986,1.8469007676\H,1.167016335,1.1596026471,0.8331789486\H,2.
0018920804,1.0786138053,2.3927505202\H,1.154121207,-0.3433005368,1.766
6938966\C,-0.4991973715,3.2175189844,2.8010188323\H,0.3482920387,3.611
6614925,3.3740852199\H,-0.4591271242,3.6515528559,1.7960610478\H,-1.42
12429855,3.5657002527,3.2792278435\\Version=ES64L-G16RevA.03\State=1-A
\HF=-718.6266833\RMSD=5.272e-09\RMSF=3.062e-06\Dipole=0.2119871,-0.066
1139,0.0849963\Quadrupole=0.7357421,-0.65787,-0.0778721,1.2412216,1.79
09871,0.8336535\PG=C01 [X(C9H18O1Si1)]\@

TMS 8

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS8-Opt-Freq\\0
,1\C,-0.9198991096,-0.4595236618,-0.1749557576\C,0.4551600596,-0.58451
55591,-0.8611646868\C,1.36835173,0.6436486552,-0.7229320005\C,-0.89727
34214,-0.5742836328,1.3347166037\C,1.8227398073,0.9900204996,0.7034183
813\C,-0.188682642,0.230847086,2.1449948605\C,0.6834386988,1.374281044
1,1.6702059345\H,-1.3740055054,0.5016537455,-0.4596489853\H,0.96834550
05,-1.4761448971,-0.4766699847\H,0.8504508395,1.5163123041,-1.14956852
5\H,2.3833130641,0.1465807248,1.1288947861\H,-0.2327538817,0.065460300
9,3.2178621932\H,-1.5863483766,-1.2428158653,-0.5467598137\H,0.2836047

321,-0.7618488094,-1.9309538073\H,2.2588175673,0.4867242431,-1.3461114
044\H,2.5240290194,1.8332971177,0.6411294768\H,1.125196225,1.850454591
1,2.5527724078\H,0.0696667048,2.1542340656,1.1908577017\O,-1.689529209
8,-1.6051145309,1.7736961736\Si,-2.1333028171,-2.1588607037,3.31101414
12\C,-0.6258230058,-2.786909675,4.2558835195\H,-0.082785441,-3.5344266
987,3.6666354298\H,0.07661492,-1.9861188357,4.5075796597\H,-0.93746704
,-3.2635431168,5.1934132644\C,-3.0230213988,-0.8030637073,4.274262688\
H,-3.8773318409,-0.4193783184,3.7052786193\H,-3.4050502323,-1.20036829
68,5.2226400853\H,-2.369607599,0.0436393445,4.5066694859\C,-3.30541287
22,-3.5782939225,2.9314149303\H,-2.803887699,-4.3516535892,2.339421029
4\H,-3.6740830429,-4.0440279662,3.8528951889\H,-4.171711123,-3.2282686
354,2.3595723644\\Version=ES64L-G16RevA.03\State=1-A\HF=-757.9364358\R
MSD=5.113e-09\RMSF=7.145e-06\Dipole=-0.0004124,-0.0190975,0.2225592\Qu
adrapole=-0.9902779,-0.6906687,1.6809466,0.8081628,-1.1544444,-1.46124
69\PG=C01 [X(C10H20O1Si1)]\@

TMS 9

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS9-Opt-Freq\\0,1\
C,-0.7078540293,-1.0306063086,0.9852834756\C,0.7895223067,-1.261048437
8,0.9944756296\C,-0.2183071365,1.6196295134,-0.8975503296\C,1.72686447
03,-0.0181594783,1.0365446656\C,1.3209227398,1.7290642313,-0.923019143
1\C,2.1395129684,0.5590404001,-0.3384218642\H,-1.2476155579,-1.3859608
437,1.8591020284\H,1.0896848849,-1.8797998966,0.1353184267\H,1.2803985
384,0.7611002411,1.6675143026\H,-0.5867308156,1.9266993751,0.087463929
3\H,1.5979492836,2.6544223221,-0.3999876252\H,1.0091646169,-1.87147413
86,1.8775785204\H,-0.6208298718,2.3529542725,-1.6065507082\H,2.6460035
766,-0.331278855,1.5479510933\H,1.6523902673,1.865733463,-1.9617996336
\H,3.1776048258,0.9097688912,-0.2720387118\H,2.166278106,-0.2665144062

, -1.0624428645\C, -1.4079333135, -0.4270202605, 0.0087028049\C, -0.7971369
833, 0.2093960871, -1.2155924442\H, -0.0134206432, -0.4399234292, -1.620802
1806\H, -1.5776963536, 0.2800019872, -1.978008954\O, -2.7656739727, -0.2290
270596, 0.0475774665\Si, -3.9797148713, -0.6640009873, 1.1439661403\C, -5.5
438514712, -0.0137005236, 0.3292110039\H, -6.4271070533, -0.2255761933, 0.9
431737517\H, -5.4866140243, 1.0703883917, 0.1824514755\H, -5.6953199548, -0
.4766612364, -0.6519745681\C, -4.0641086921, -2.5385325019, 1.3359680803\H
, -4.1810286889, -3.0233035313, 0.3601902002\H, -3.1679560671, -2.952552344
8, 1.8086181276\H, -4.9268288244, -2.8180195224, 1.9530623558\C, -3.7084940
859, 0.1784258589, 2.810389468\H, -2.8088385441, -0.1794759083, 3.320901616
\H, -3.6132132918, 1.2630229596, 2.6860684254\H, -4.5632805983, -0.00715036
1, 3.4723321795\\Version=ES64L-G16RevA.03\State=1-A\HF=-797.2395825\RMS
D=4.675e-09\RMSF=3.376e-06\Dipole=-0.0619079, -0.0241259, 0.2104071\Quad
rupole=1.6324503, -1.5362131, -0.0962372, 0.7637441, -1.7543122, -0.7580676
\PG=C01 [X(C11H22O1Si1)]\@

TMS 10

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS10-Opt\\0,1\C, -
0.6366504562, -1.4691425818, 0.1470263338\C, 0.3345110954, -1.6365627842, 1
.3155510137\C, 0.9268168257, -0.319433366, 1.7604585204\C, 0.4159037896, 0.
8718316002, 1.4066217365\C, -0.815891777, 1.0160151322, 0.5476553447\C, -1.
5939116978, -0.3017793663, 0.4139465291\H, 1.8072931724, -0.3667968637, 2.3
947800031\H, -0.20555466, -2.1254597463, 2.1396428078\H, 1.1307755263, -2.3
319394421, 1.0228515837\H, -0.0619023111, -1.2622416334, -0.7724447275\H, -
1.45258331, 1.7957639972, 0.9821861226\H, -0.5136459757, 1.3926962221, -0.4
406128122\H, -2.1392452883, -0.5146802832, 1.3418851238\H, -2.3389269651, -
0.2102393787, -0.3841830212\O, 0.9291106733, 2.0899979533, 1.7582573953\O,
-1.3175359739, -2.7207229718, -0.0058828686\C, -1.917211311, -2.9080079615

, -1.2814718845\H, -2.7069375763, -2.1636472171, -1.4651407968\H, -1.162833
8104, -2.7866003823, -2.0766881294\C, -2.4979300271, -4.24729184, -1.363033
1851\C, -2.9888812721, -5.3475175353, -1.4629648608\H, -3.4175757552, -6.32
08367142, -1.5380244407\Si, 2.3180955434, 2.5604823161, 2.6078685609\C, 2.2
399737635, 4.4367803363, 2.5486027769\H, 1.3228788361, 4.8053851764, 3.0208
664249\H, 3.0929055075, 4.8844451556, 3.0720389052\H, 2.2517372492, 4.79659
20895, 1.5140254007\C, 2.2426984558, 1.9502526766, 4.3907880348\H, 1.313139
9546, 2.2729765156, 4.8730172259\H, 2.2955412292, 0.8593818694, 4.464814437
4\H, 3.0786467176, 2.3631327451, 4.9686337493\C, 3.8669669823, 1.9282291536
, 1.7376910866\H, 3.9337578549, 0.8357031312, 1.7437355824\H, 3.8886497314,
2.25884763, 0.6931915047\H, 4.765548579, 2.3195462376, 2.2300903827\\Versi
on=ES64L-G16RevA.03\State=1-A\HF=-909.2920511\RMSD=5.817e-09\RMSF=5.21
0e-06\Dipole=0.3912262, 0.5972894, -0.1252339\Quadrupole=1.3909317, -3.04
71576, 1.6562259, 1.089837, 3.4965279, 1.9773012\PG=C01 [X(C12H20O2Si1)]\\
@

TMS 11

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS13-Opt\\0,1\C, -
1.0759627047, -1.3943042622, 0.1234619924\C, -0.3667430171, -1.5164844422,
1.2612997008\H, -0.7637152995, -2.1315038603, 2.066288706\C, 0.9804938982,
-0.8891746498, 1.501945265\H, 1.339783328, -0.4259595038, 0.5797561066\H, 1
.7097856868, -1.6805615597, 1.7351011831\C, 1.0488221582, 0.157011767, 2.63
38171711\H, 0.882344446, -0.3382222612, 3.5996449168\H, 0.2344257239, 0.884
6173023, 2.5150397497\C, -0.6604699837, -0.5651793163, -1.0752523584\H, -1.
5638195187, -0.3585840454, -1.6594277912\H, -0.2751655843, 0.4048073716, -0
.738206402\C, 0.395291702, -1.2329961076, -1.9786560695\H, 1.3081306876, -1
.4090927208, -1.3980706405\H, 0.037258923, -2.2244519039, -2.2860737368\C,
0.7249790992, -0.4036483628, -3.2309379723\H, 0.8773595851, 0.6472976621, -

2.9497714537\H,-0.1567841,-0.4079149086,-3.8851663965\C,1.9561394514,-
 0.9122782997,-4.0192867893\H,1.7389884515,-0.8510152042,-5.0933678454\
 H,2.1009236374,-1.9820084498,-3.8093579675\C,3.2926968919,-0.172987701
 1,-3.7951052344\H,4.0096858879,-0.5979442176,-4.5099057728\H,3.1708619
 226,0.8796361851,-4.090192257\C,3.9342191663,-0.2258480541,-2.38836110
 89\H,3.7485004567,-1.2088766508,-1.9324178556\H,5.0243774579,-0.157190
 9639,-2.5079907888\C,2.4054221367,0.8873578649,2.6360295662\H,3.201470
 6657,0.1355456965,2.5403467701\H,2.5689563914,1.3711806959,3.606955254
 8\C,3.5055693589,0.8885869249,-1.4177105126\H,2.4300038181,0.819930265
 3,-1.2201287198\H,3.6612740024,1.8608633224,-1.9083053512\C,4.28503815
 81,0.8736689245,-0.0917302883\H,4.1295166364,-0.0907533645,0.412076067
 1\H,5.3588212786,0.9208264168,-0.3203486286\C,2.5397196619,1.945579630
 6,1.5127278436\C,3.9373182555,2.0292582565,0.8688608906\H,4.6926126028
 ,2.0726820256,1.6659170504\H,4.0248963302,2.9761819571,0.3180587322\H,
 1.7980226523,1.7492923579,0.7283964058\H,2.2745077626,2.9291926619,1.9
 204058027\O,-2.2755723664,-2.023868996,-0.1020942464\Si,-3.1832372997,
 -3.1509242829,0.7754267193\C,-3.7858691221,-2.4061408395,2.4007998492\
 H,-4.4850375167,-3.0913798184,2.8956568229\H,-2.9685433153,-2.20312120
 36,3.1000008288\H,-4.3141295152,-1.4627826087,2.2221811779\C,-2.181707
 7465,-4.7207499747,1.0780324477\H,-1.8093752173,-5.132299867,0.1331538
 486\H,-1.3193831813,-4.5483181709,1.7296663473\H,-2.8097784132,-5.4857
 380533,1.550777608\C,-4.6390918094,-3.5047958243,-0.3597761979\H,-5.32
 48417352,-4.2315525326,0.0913994376\H,-5.2049187374,-2.5898432568,-0.5
 665607787\H,-4.2984015095,-3.9114122699,-1.3182149379\\Version=ES64L-G
 16RevA.03\State=1-A\HF=-1072.459777\RMSE=4.568e-09\RMSF=1.790e-06\Dipo
 le=-0.0019025,-0.1723894,0.119909\Quadrupole=0.0543838,0.2359057,-0.29
 02894,2.8192247,-1.6040992,-1.5435307\PG=C01 [X(C18H36O1Si1)]\\@

TMS 12

```
# opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS14-Opt\\0,1\C,-2
.8273659424,-1.5405688568,0.1398841482\C,-1.4988278214,-1.8379034439,0
.8430468231\C,-0.8676130989,-0.5942949353,1.4259001564\C,-1.5477210417
,0.5487779924,1.6176289806\C,-3.0118761621,0.7032062406,1.2879452297\C
,-3.7004130853,-0.6431674727,1.0192784177\H,0.1834353144,-0.6524736593
,1.6946688711\H,-1.6923275369,-2.5871476432,1.6249696029\H,-0.81036393
45,-2.3136055869,0.1326695886\H,-2.6120364711,-1.0039898462,-0.7989772
602\H,-3.5004513917,1.228120399,2.1176348769\H,-3.1049839413,1.3693690
265,0.4175112212\H,-3.8864737355,-1.169574623,1.9640928385\H,-4.673661
3159,-0.4863003641,0.5417358765\O,-1.0196588545,1.7082631951,2.1177754
094\Si,0.5508312184,2.1703128368,2.5529211034\C,1.1697996352,1.1352695
501,4.003367777\H,0.4599617975,1.1723874285,4.8373813837\H,1.316948126
9,0.0836429184,3.7374860062\H,2.1296173441,1.5241303188,4.364976709\C,
0.3433091696,3.9655794054,3.0671881159\H,1.3000758601,4.4001299816,3.3
797376119\H,-0.0469612371,4.5674665931,2.2393267334\H,-0.3572714804,4.
0540771725,3.9046523833\C,1.7123854232,2.0294048755,1.0736944554\H,1.8
392227662,0.9948770897,0.7393888641\H,1.3340629993,2.6108497075,0.2254
136433\H,2.7042980104,2.4207866855,1.3305886407\O,-3.5023335516,-2.768
637276,-0.1361148721\Si,-4.0131600112,-3.3044658265,-1.6455475804\C,-4
.8346609015,-4.9975623646,-1.2992329263\C,-5.2311255042,-2.0660598507,
-2.3976817297\H,-6.1152771518,-1.9296604175,-1.7659050757\H,-4.7594882
678,-1.0844018915,-2.5258724552\H,-5.5707635882,-2.3931043013,-3.38737
68755\C,-2.5298812901,-3.4591554914,-2.8107802557\H,-2.0350633029,-2.4
896468499,-2.9434667813\H,-1.7833698391,-4.1626273068,-2.4270346422\H,
-2.8389506683,-3.803126261,-3.8047389806\C,-6.0161272535,-4.8159898737
,-0.3203176868\H,-6.4799423874,-5.788654152,-0.1021689631\H,-5.6878714
903,-4.3812930157,0.6294184304\H,-6.7983335998,-4.169533353,-0.7353235
```

822\C,-5.3577153614,-5.6112741408,-2.617358688\H,-5.8295281597,-6.5842
 989518,-2.4206385477\H,-6.1125215659,-4.977085592,-3.0973167248\H,-4.5
 523311855,-5.7829452996,-3.3413619275\C,-3.8050586188,-5.9592342356,-0
 .665190452\H,-4.2768284121,-6.9276565975,-0.445263487\H,-2.9589929858,
 -6.1549779288,-1.3343655416\H,-3.4073821678,-5.559911938,0.2734777972\
 \Version=ES64L-G16RevA.03\State=1-A\HF=-1320.5196697\RMSD=2.394e-09\RM
 SF=1.351e-06\Dipole=0.4083037,0.3432332,-0.1850041\Quadrupole=2.309687
 7,-2.4036983,0.0940105,1.787347,2.9409499,1.7043186\PG=C01 [X(C15H32O2
 Si2)]\@

TMS 13

opt freq b3lyp/6-31+g(d,p) geom=connectivity\\TMS15-Opt\\0,1\C,-1
 .8064858528,-1.0954228539,0.0290622754\H,-2.1404631575,-0.4548354142,0
 .8540330834\C,-2.9528342253,-1.1640012723,-1.0007068871\H,-3.189998740
 9,-0.1672461637,-1.3911767533\H,-2.6742399966,-1.7984367991,-1.8512659
 614\H,-3.8608368508,-1.5835794443,-0.5558003065\C,-0.5570484525,-0.443
 4563939,-0.5971920082\H,-0.7887425581,0.5523160537,-0.9933669021\H,0.2
 471783604,-0.3401291716,0.1387788821\H,-0.1754703999,-1.0517589796,-1.
 4267753803\C,-1.4850764472,-2.471150835,0.5633180739\H,-1.15585935,-3.
 1959069889,-0.1812576756\C,-1.5808938724,-2.8972408405,1.8345341047\O,
 -1.2975747022,-4.2132266563,2.1602154365\Si,0.2096927446,-4.9731787267
 ,2.2452329633\C,1.3793432937,-3.9457880914,3.3117541002\H,1.0027964588
 , -3.8430935264,4.335560786\H,2.3688419568,-4.4155967654,3.3651242107\H
 ,1.5140144573,-2.9395103303,2.8989688045\C,0.9567284761,-5.207019666,0
 .5285632144\H,1.8877532186,-5.7835865268,0.594308601\H,0.272393159,-5.
 7522440371,-0.1311459268\H,1.1936055176,-4.2487077457,0.0542107799\C,-
 0.1651827105,-6.6371156326,3.0338037995\H,-0.8774779554,-7.2052535149,
 2.4254316806\H,0.7450436885,-7.2393766891,3.1371751032\H,-0.6027478651

, -6.5108245226, 4.0299746319\ C, -2.0641637336, -2.0848131829, 3.0152263209
 \ H, -1.7863075578, -1.0345293267, 2.8744937268\ H, -1.5347898969, -2.4343935
 15, 3.9110050071\ C, -3.5910584905, -2.1510634765, 3.2802195536\ H, -4.093272
 0174, -1.8052997419, 2.3652978611\ C, -3.9686234892, -1.1916129522, 4.419415
 3594\ H, -5.0506715601, -1.1930882782, 4.5927208903\ H, -3.4824295232, -1.487
 89223, 5.3577806284\ H, -3.6657685471, -0.1616377884, 4.1972569988\ C, -4.081
 0909806, -3.5754678665, 3.5779710573\ H, -3.6090840675, -3.9671324832, 4.487
 9022868\ H, -5.1661123143, -3.5841587806, 3.733942841\ H, -3.8454297859, -4.2
 643752033, 2.7625953085\ \ Version=ES64L-G16RevA.03\ State=1-A\ HF=-837.782
 5646\ RMSD=8.666e-09\ RMSF=1.737e-06\ Dipole=0.3357628, 0.1147244, 0.054227
 2\ Quadrupole=0.0986548, 0.5080055, -0.6066603, -2.5524399, 0.3330115, -0.03
 45388\ PG=C01 [X(C12H26O1Si1)]\ \@

TMS 14

opt freq b3lyp/6-31+g(d,p) geom=connectivity\ TMS17-Opt\ 0, 1\ C, -3
 .517353437, -3.3215383626, -0.2243848951\ C, -2.8763644746, -2.1816119857, -
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TMS 16

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TROUBLESHOOTING AND FREQUENTLY ASKED QUESTIONS

Q. What can I do when the yield of the reaction does not match the one reported in the paper?

A. Check the voltage of the reaction. From our experiences, if the cell voltage is too low (below 4.0 V at 10 mA on 0.1–0.2 mmol scale without a reference electrode), this reaction does not proceed efficiently, and a certain amount of starting material remains unchanged after general reaction conditions. Normal operational voltage range for this reaction is approximately 4.5–5.5 V and reaction mixture turns brownish color from colorless during electrolysis. Additionally, a gas evolution from cathode surface is likely to be a good indicator for the desired reactivity: when you observe a constant cathodic gas evolution that might be a good sign to get the corresponding desaturation product.

When a low voltage is noted:

- It is worth trying that you may run a reaction under constant potential mode at 5.0 V. This is an alternative electrolysis mode to get desired reactivity, especially for the one-pot procedure described in this paper, which tends to result in a lower voltage.
- You may apply a higher voltage, but we strongly recommend maintaining a suitable range of current (10–50 mA on 0.1–0.2 mmol scale reactions). We observed a degradation of anodic material with an exotherm when we apply a 100 mA current on 0.2 mmol scale reaction and thereby resulting in a deleterious yield.

When a high voltage is noted:

- Ensure there is sufficient contact between the electrode and ElectraSyn cap to avoid undesired increase of resistance in the circuit.
- Increasing the amount of electrolyte helps to reduce the resistance of the cell.
- Reducing the current value also helps to decrease the reaction potential. Please note that longer reaction time is required in this case to ensure the passage of the same amount of electricity.
- Using alternating polarity – sometimes the build-up on the electrodes increases the voltage.

Q. Where can I get the electrode materials?

A. We purchased a graphite electrode from IKA but could be obtained from multiple suppliers since this material is very common. See “electrode materials/dimensions” section for details in this Supporting Information.

Q. Is the pre-stirring described in the General Procedures prior to electrolysis is essential?

A. No - However, our preliminary experiments showed that the pre-stirring helps dissolving NaSbF₆ and make the reaction more reproducible. See also relevant FAQ described below.

Q. What are the suitable current values for reactions on different scales?

A. We typically use 10 mA on 0.1–0.2 mmol scales and gives us an operational voltage of approximately 4.5–5.5 V. The submerged exterior surface area of electrode is approximately W7 × D1.5 × H20 mm. The current values and exterior area of electrodes may be adjusted proportionally for other scales to maintain similar levels of current density (mA/cm²).

Q. We notice that NaSbF₆ is not completely soluble in MeCN/2,4,6-collidine system. Can we electrolyze this heterogeneous solution as is?

A. Yes—Our preliminary experiments showed that solubility of NaSbF₆ in MeCN/2,4,6-collidine varies on its manufacturer, batch number, and crystal shape/size, etc. Qualitatively, 0.10–0.15 M NaSbF₆ gives a homogeneous system whereas NaSbF₆ remained insoluble at higher concentrations. Even on the latter case, NaSbF₆ dissolves gradually during electrolysis so you can electrolyze it as is. Please note that a powdered NaSbF₆ ground with a mortar and pestle is a good option to improve its solubility.

Q. We notice that a starting material which we plan to use is not soluble in MeCN. Can we electrolyze this heterogeneous solution as is?

A. You may use a small amount of DCM as a co-solvent to dissolve your starting material. As discussed in Table S2 (optimization table), our preliminary studies showed a comparable result when we used a DCM as a co-solvent (see, entries 1). Alternatively, you may check solubility of the starting material in 2,4,6-collidine. If it dissolves, you can prepare a solution of your starting material in 2,4,6-collidine to make it homogeneous before adding MeCN.

Q. Is this reaction sensitive to water?

A. A small amount of water does not significantly affect the outcome. This allows you to use commercial NaSbF₆ without any precaution. However, large amount of water should be avoided since this could hinder the desaturation. Please note that silylation step in the one-pot procedure (see General procedure D) is a water-sensitive reaction. You

need to use a flame-dried glassware and dry 2,4,6-collidine (3 Å molecular sieves is a suitable desiccant) to achieve full conversion into the corresponding TMS enol ether. A large excess amount of TMSOTf may help to obtain better conversion, but this tends to a lower voltage in the subsequent e-desaturation step and results in a deleterious yield.

Q. How air sensitive is the reaction?

A. This reaction is not significantly sensitive to air and no rigorous degassing is required. However, we recommend you perform this reaction under an inert atmosphere. See “optimization table” in this Supporting Information.

Q. Is this reaction sensitive to stirring rate?

A. Stirring rate (400–1,500 rpm) unlikely to affect the outcome significantly. Please note that this protocol, however, generally gives a turbid reaction mixture and a buildup formation on the cathode surface after electrolysis, and we usually applied a faster stirring at a rate of 1,500 rpm.

Q. Is the one-pot protocol disclosed in this work capable of not only ketone also esters or aldehydes?

A. No - The protocol is currently optimized for ketones.

Q. What are typical byproducts for this protocol?

A. It depends on a substrate which you plan to use. For the reaction of TMS enol ether of ketone, for example, we have detected parent ketone, dimers of ketone, and α -carbonylated ketone as byproducts.

Q. What can I do if a significant amount of starting materials remains after electrolysis?

A. Please check the voltage. If you note a low voltage (<4.0V), it is worth applying a constant potential mode electrolysis at 5.0 V as described above. If you note a suitable range of voltage (approximately 4.5–5.5 V), prolonged reaction time might be beneficial to obtain better conversion. Indeed, some compounds in this work requires a larger amount of passing current to get a reasonable conversion.

Q. Can I reuse the electrodes, if yes, how should I wash them for the next reaction?

A. After the desaturation, graphite electrodes used are not very dirty so you can reuse them after a simple cleaning as follows:

1. Wash vigorously with water and soap.
2. Wash the surfaces of the electrode three times with acetone and three times with DCM.
3. Heat the electrode to 150 °C, using hot plate for 5 min on each side.
4. Scratch the electrode surface to get a clean dark gray color.

Q. How stable is the TMS-enol?

A. The TMS-enol starting material is stable and could be purified by silica gel chromatography. In addition, the latter could be stored for days in 0 °C, and for months in -20 °C.

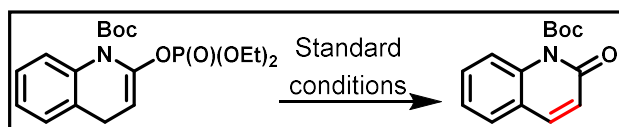
Q. What can I do if the TMS-enol is stable for silica gel purification?

A. Usually if the TMS-enol is stable under silica gel purification, this means that you are using wet silica gel, which accelerate the hydrolysis of the product.

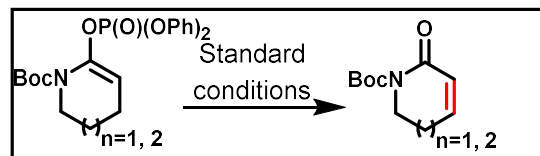
Ways to avoid the hydrolysis during purification:

1. You can pre-treat the reaction with 5% triethylamine in hexane, and then adding 0.5% triethylamine to your eluent.
2. You can use basic alumina to avoid the hydrolysis.

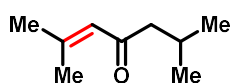
UNSUCCESSFUL AND LOW CONVERSION SUBSTRATES FOR E-CHEMICAL DESATURATION REACTION



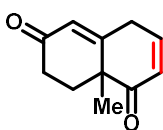
traces - $^1\text{H-NMR}$ shift is 5.6 ppm



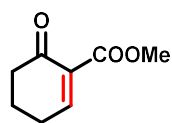
No product - $^1\text{H-NMR}$ shift is:
n=2 - 5.4 ppm, n=3 - 5.5 ppm



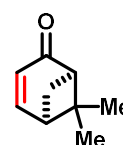
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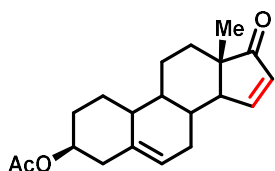
Decomposition



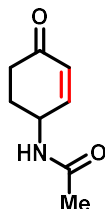
Starting material



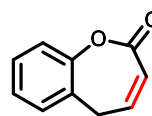
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7% - $^1\text{H-NMR}$ shift is 4.5 ppm

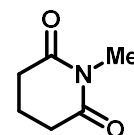
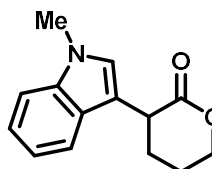
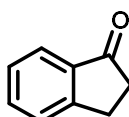
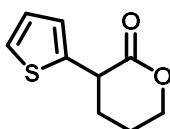
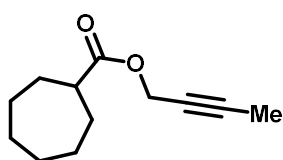


Decomposition



20%

UNSUCCESSFUL SUBSTRATES FOR ENOL-ETHER PREPARATION REACTION



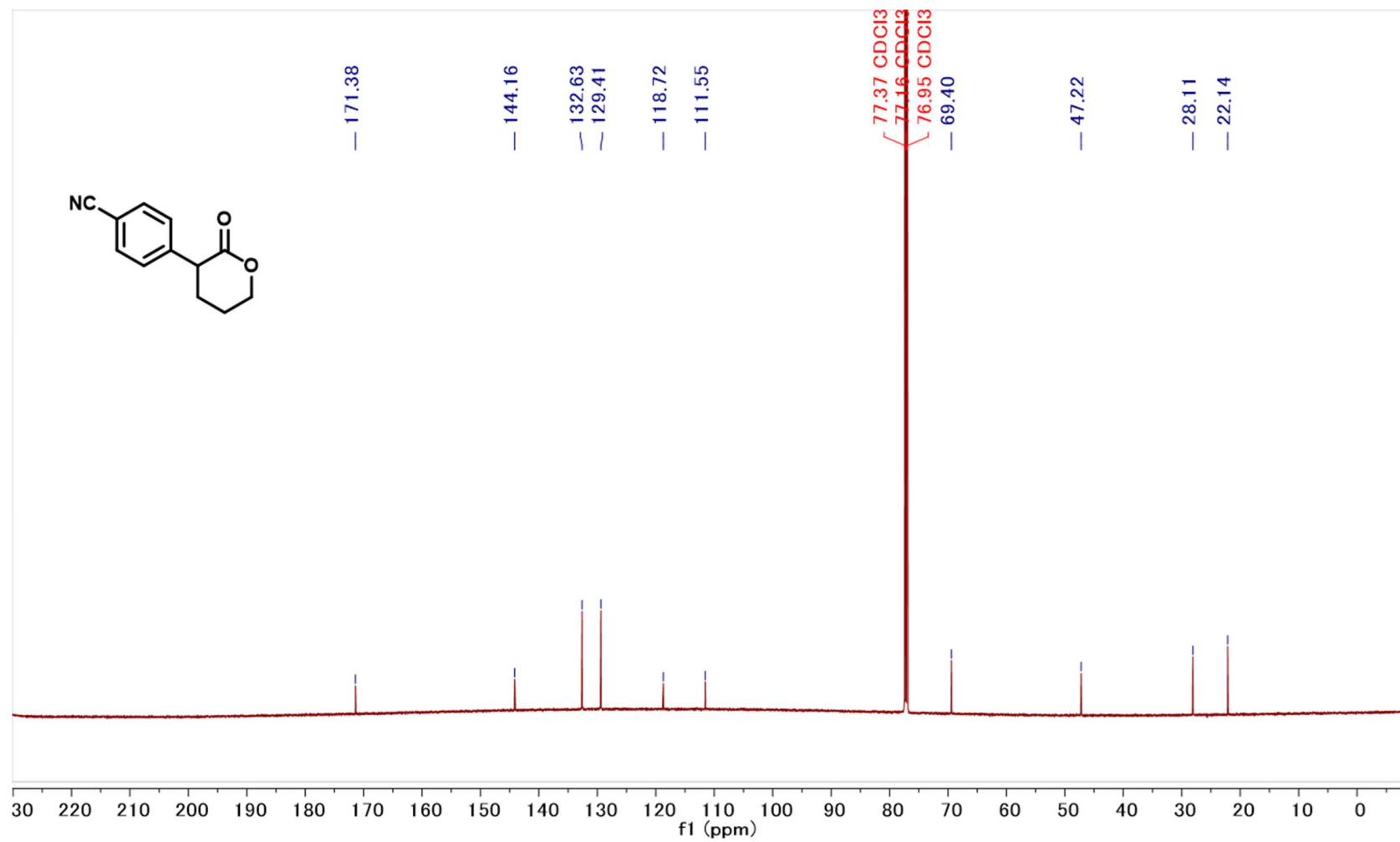
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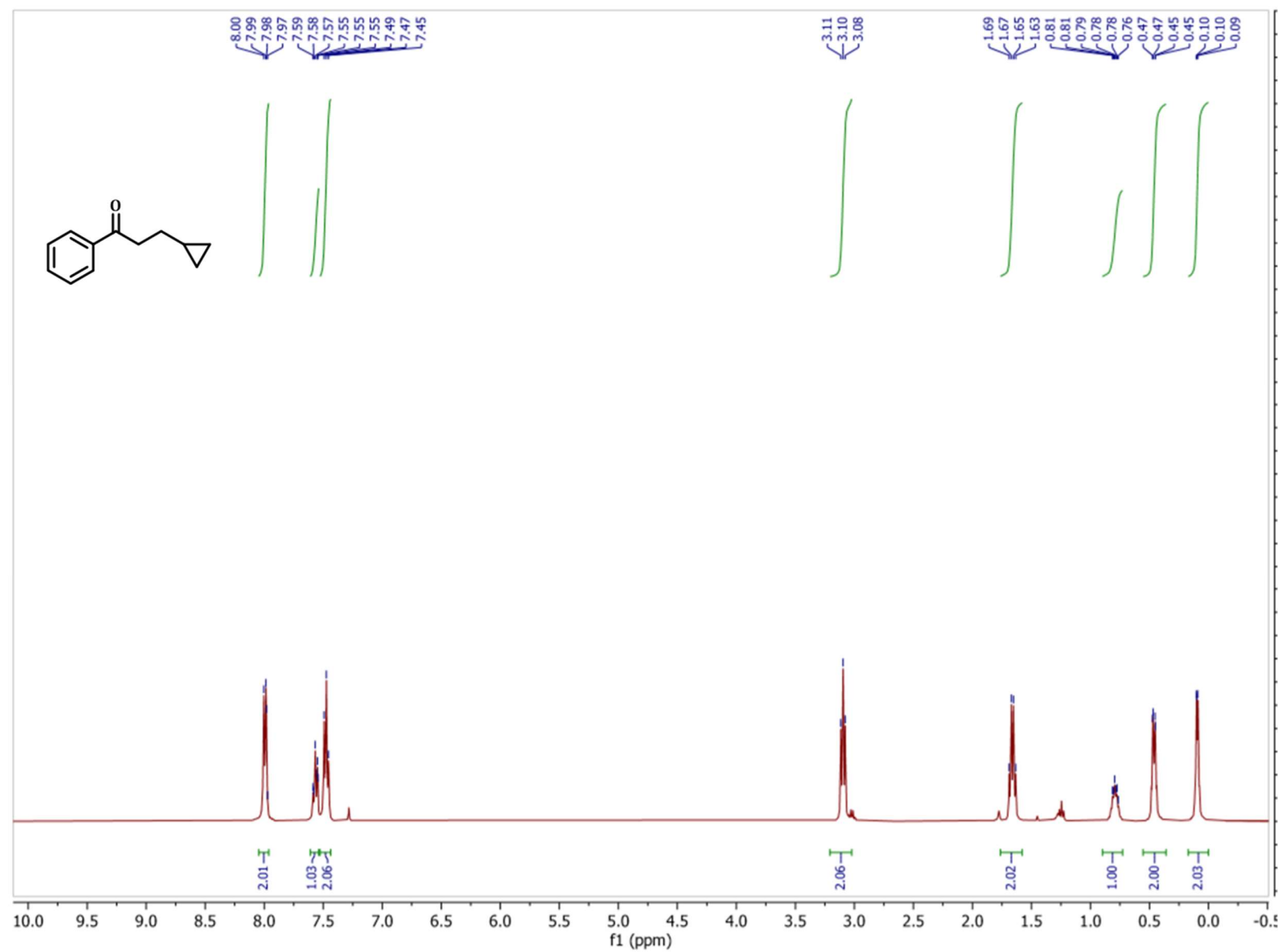
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¹H NMR (400 MHz, CDCl₃) OF COMPOUND **S16**

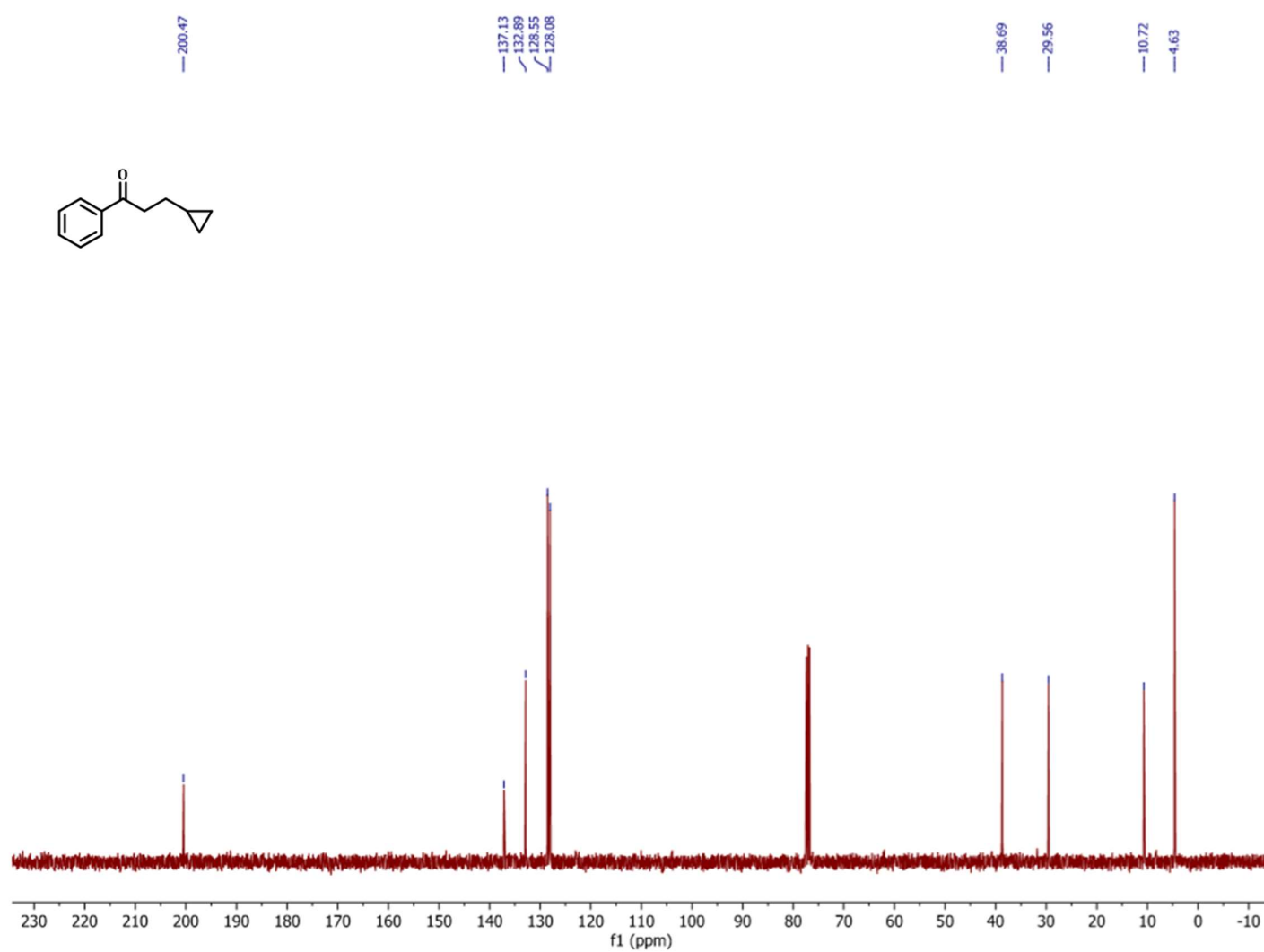
^{13}C NMR (151 MHz, CDCl_3) OF COMPOUND **S16**



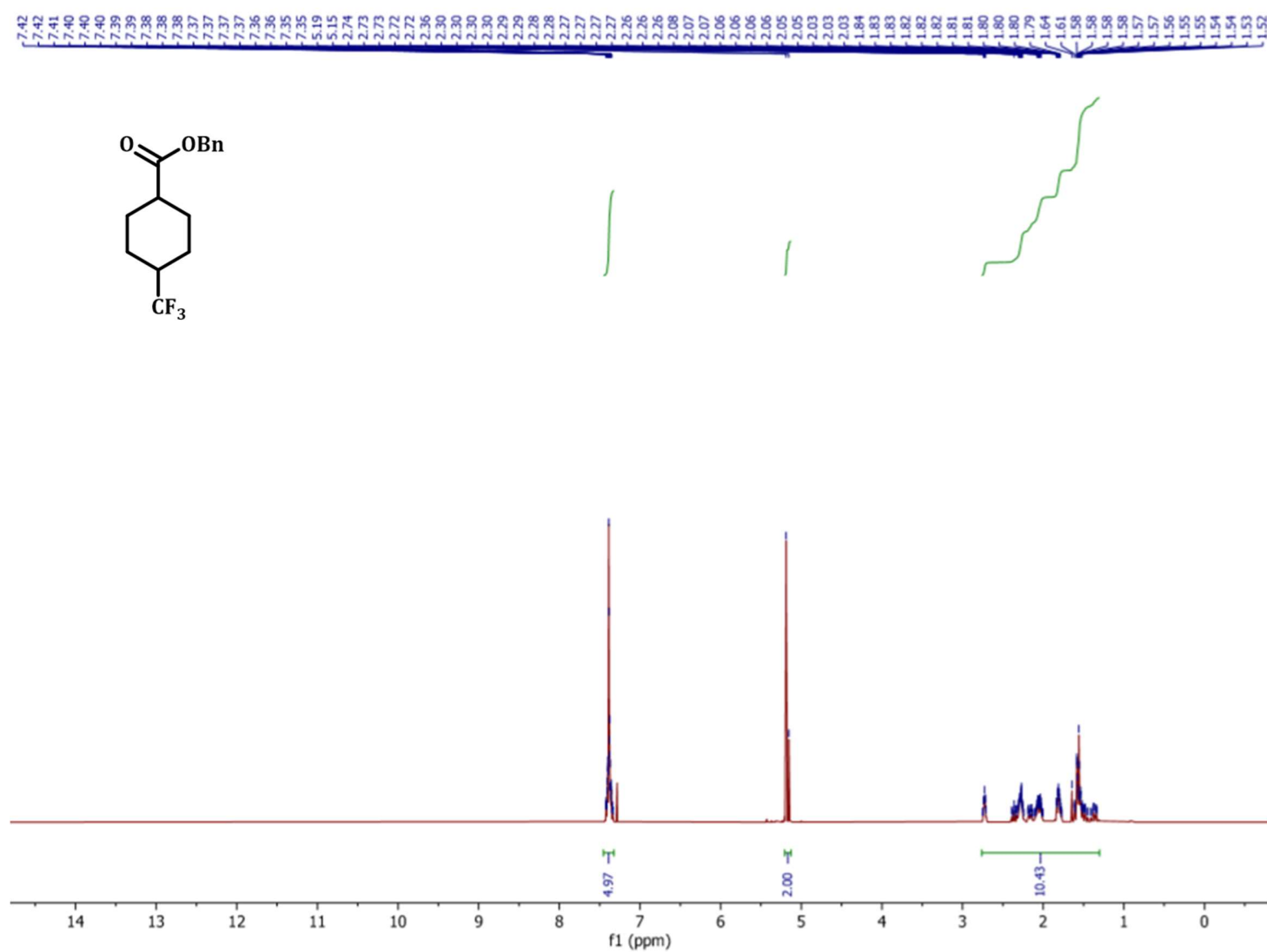
^1H NMR (400 MHz, CDCl_3) OF COMPOUND **S17**



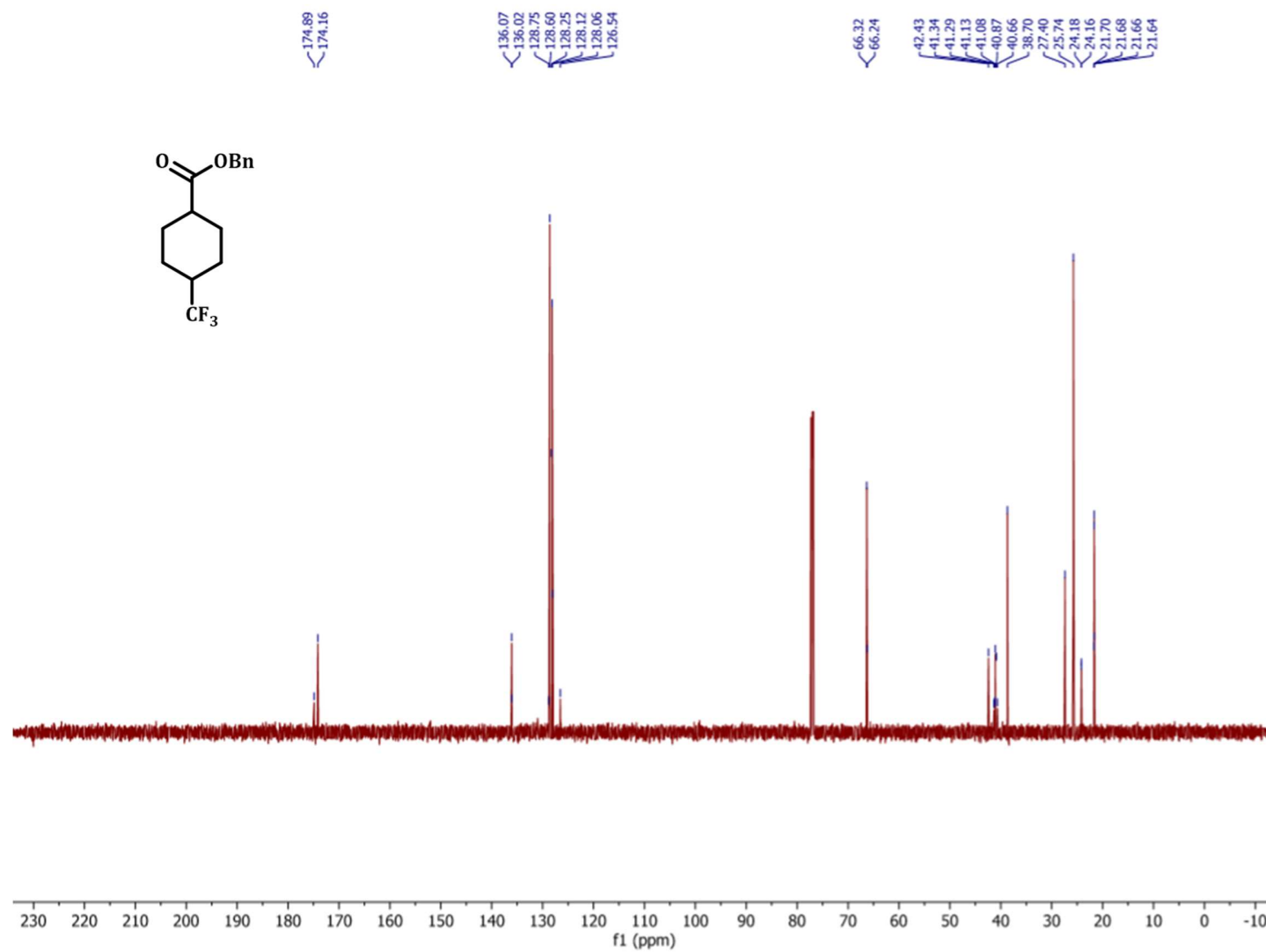
^{13}C NMR (101 MHz, CDCl_3) OF COMPOUND **S17**



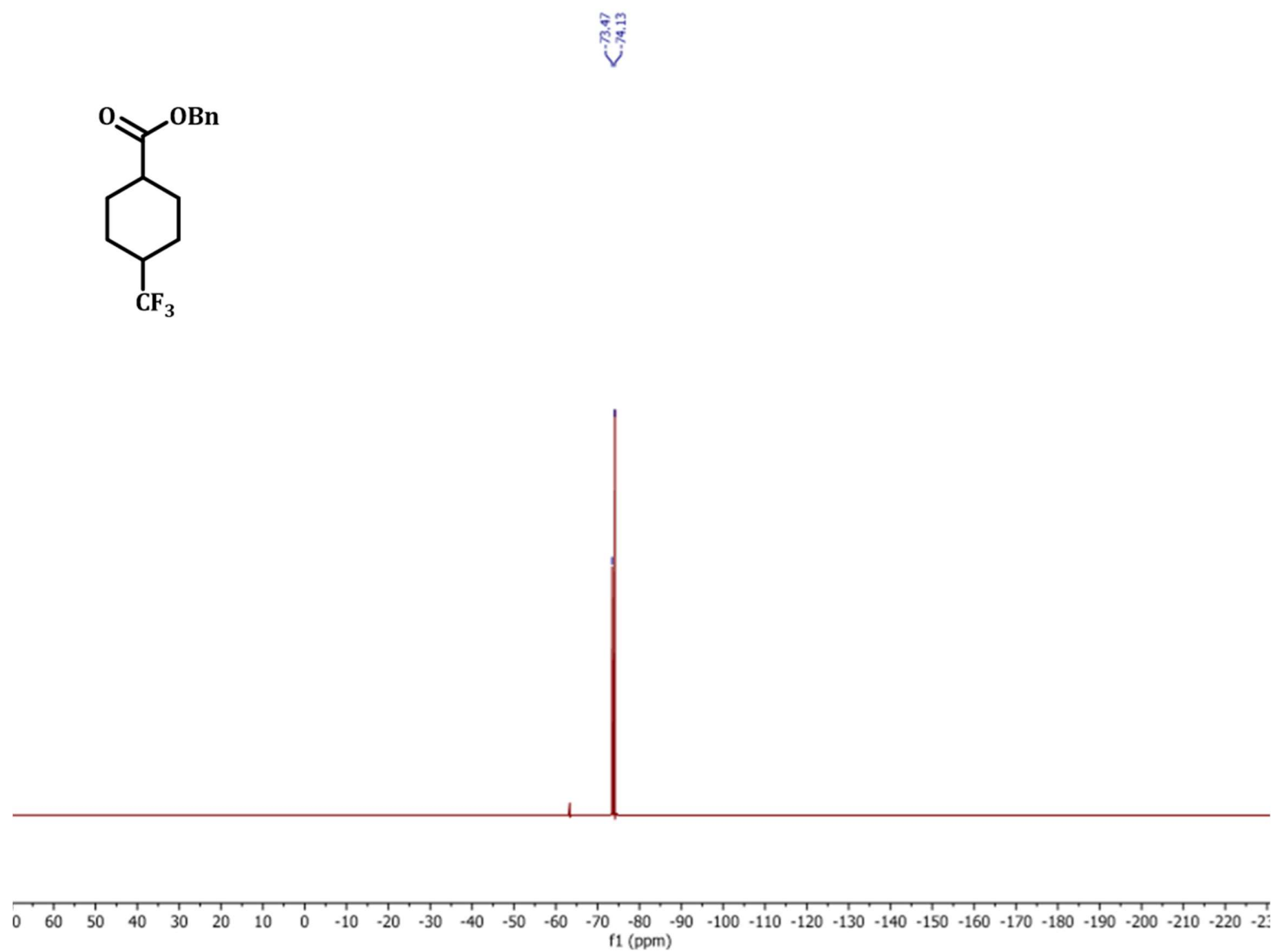
^1H NMR (400 MHz, CDCl_3) OF COMPOUND **S18** (MIXTURE OF ISOMERS)



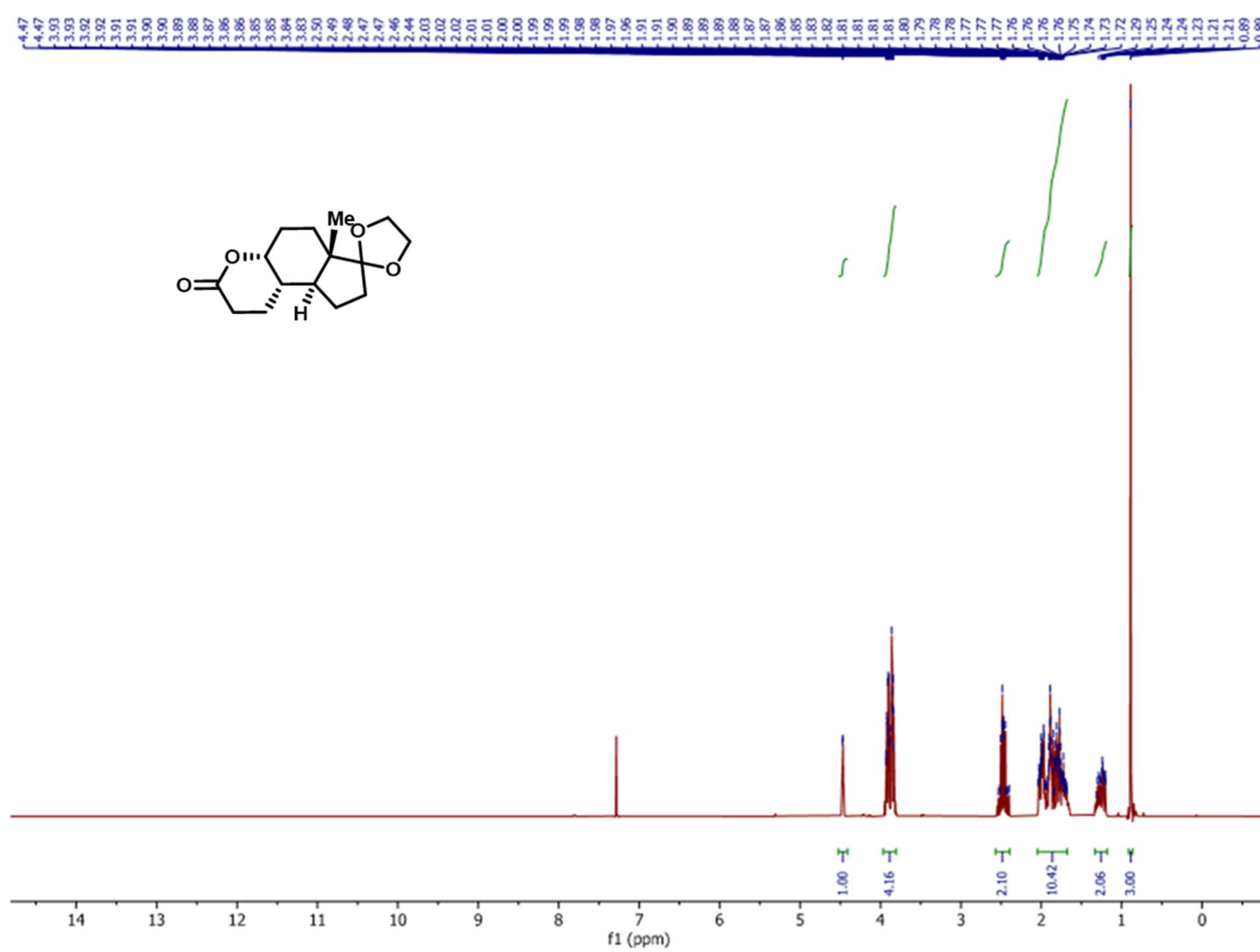
^{13}C NMR (126 MHz, CDCl_3) OF COMPOUND **S18**



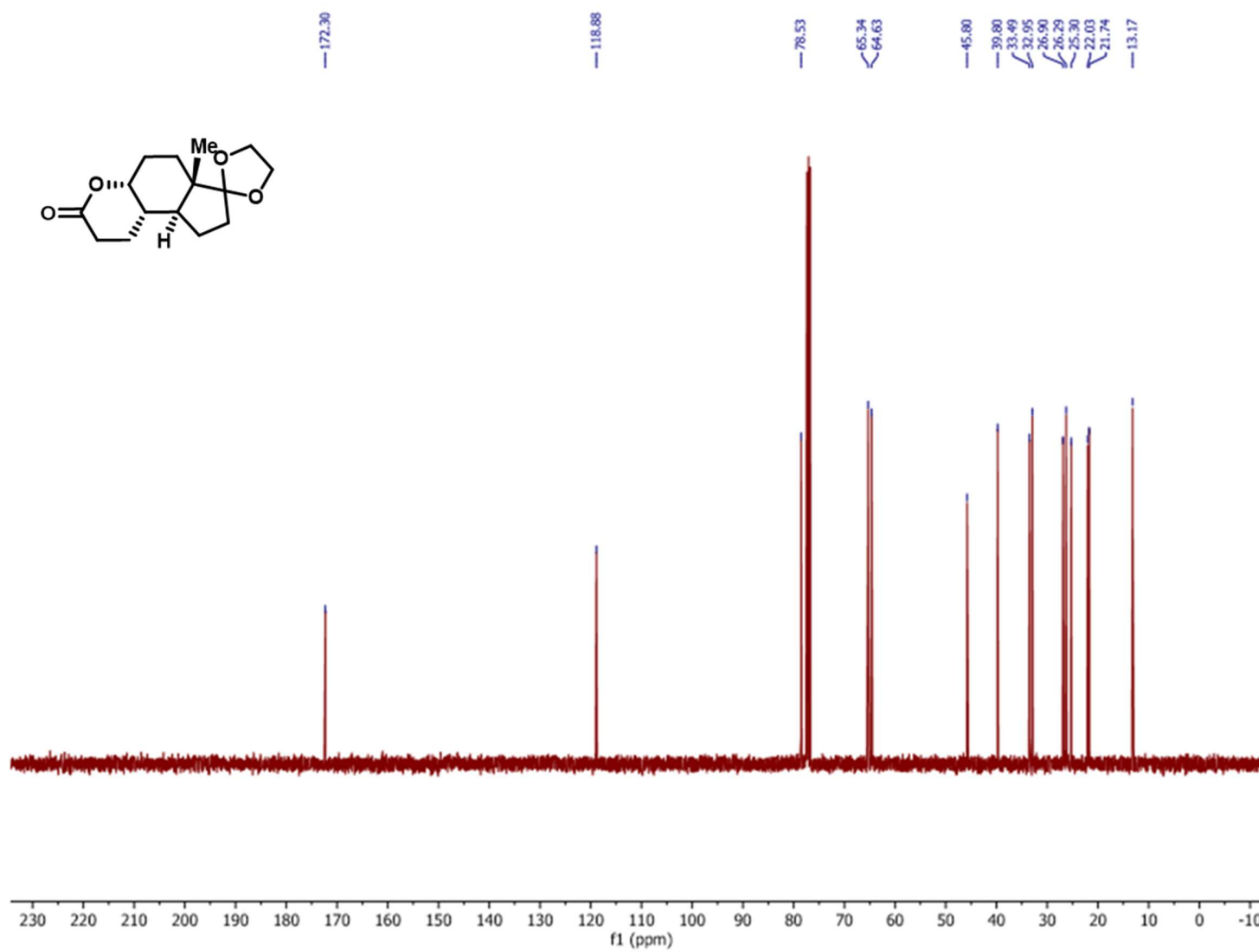
^{19}F NMR (376 MHz, CDCl_3) of compound **S18**



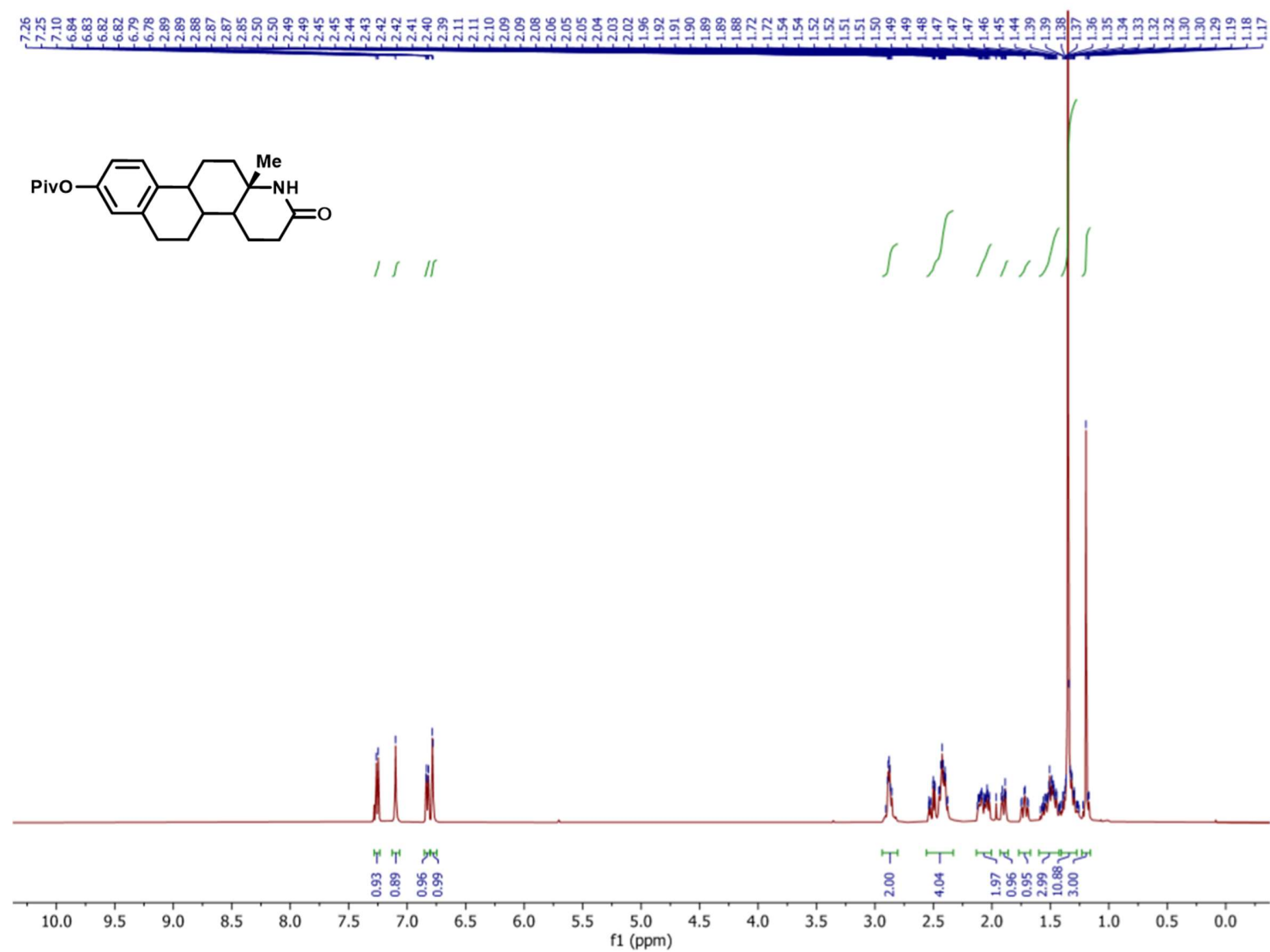
^1H NMR (400 MHz, CDCl_3) OF COMPOUND **S19**



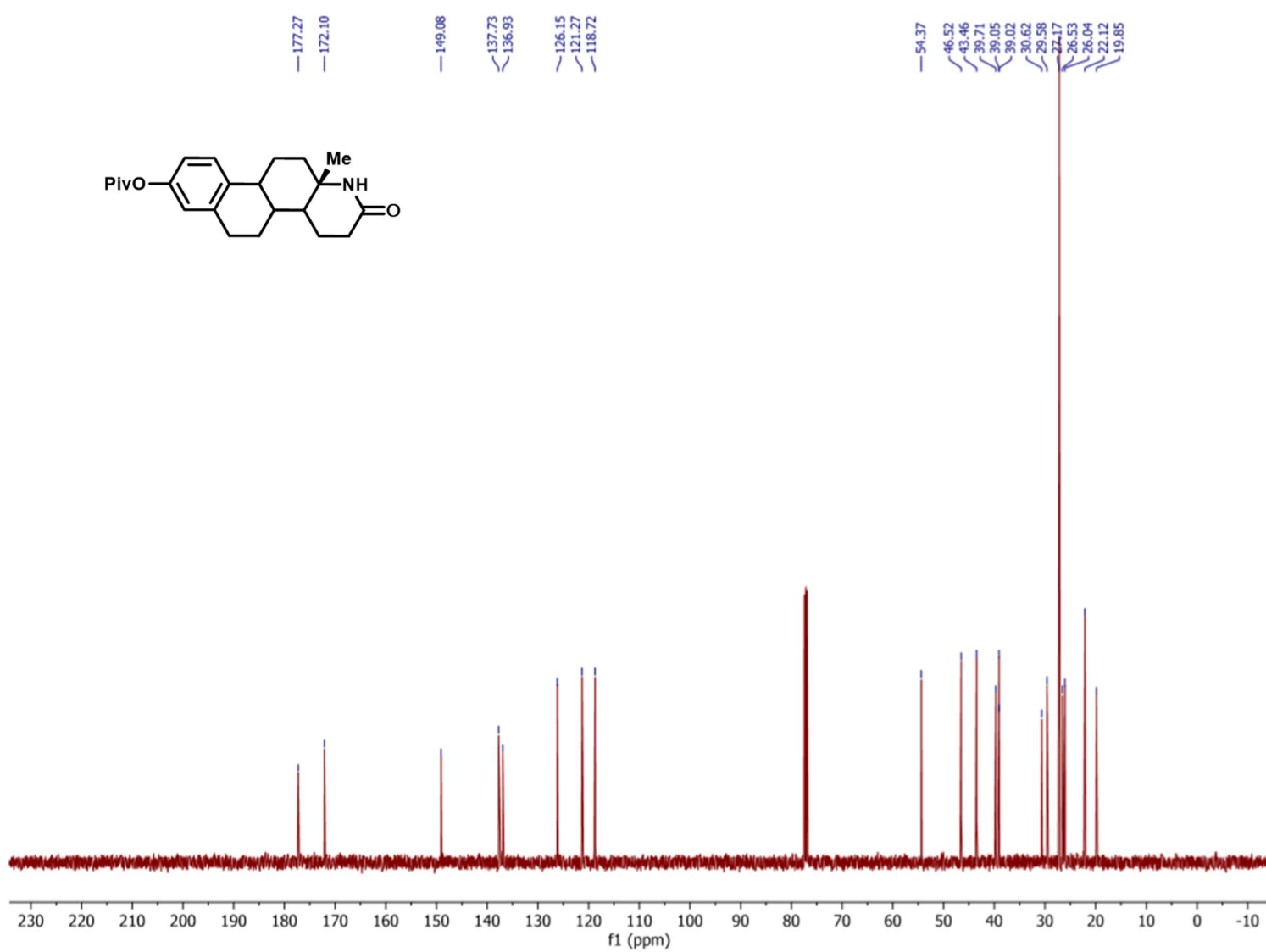
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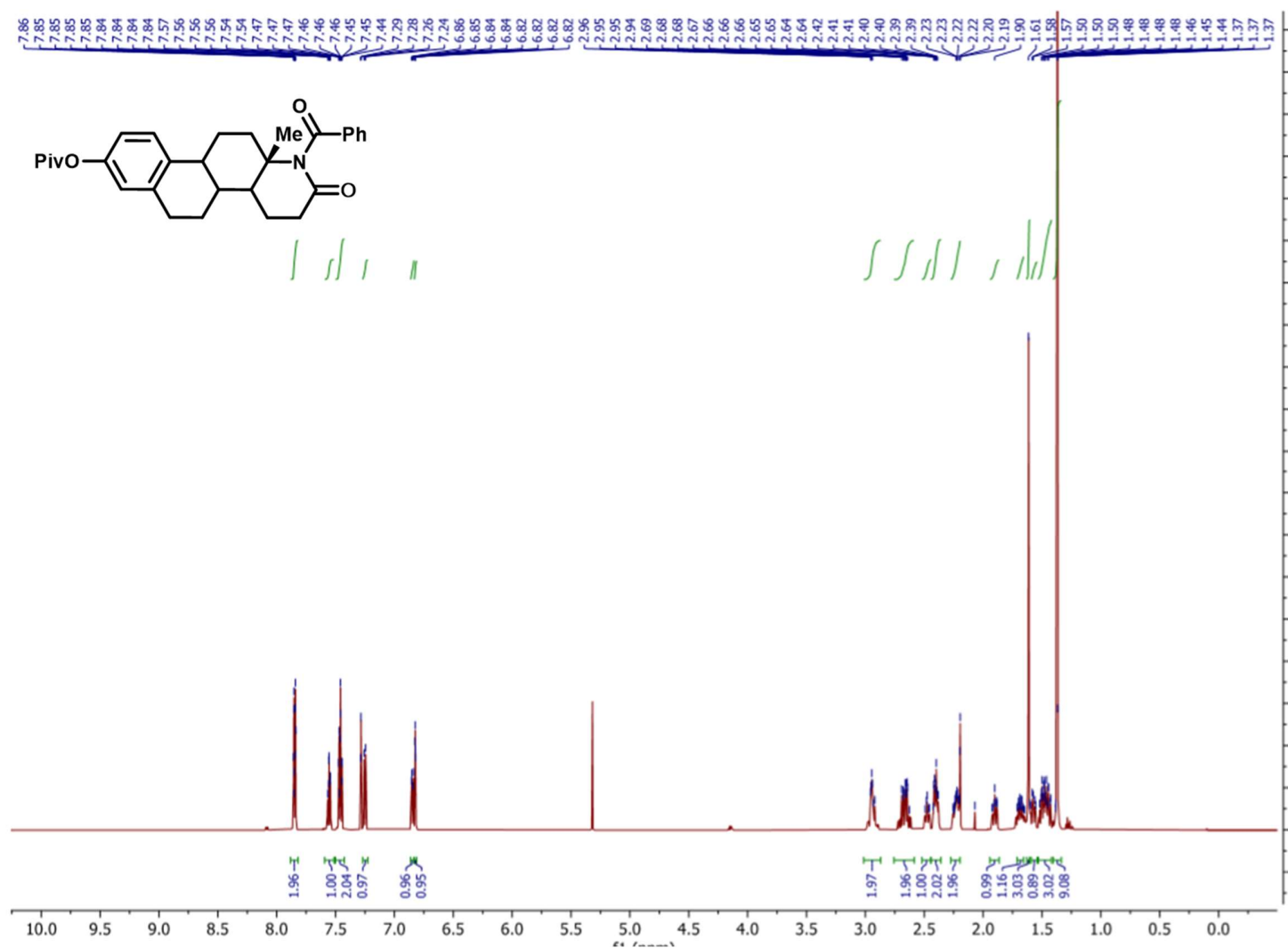
^1H NMR (400 MHz, CDCl_3) OF COMPOUND **S20c**



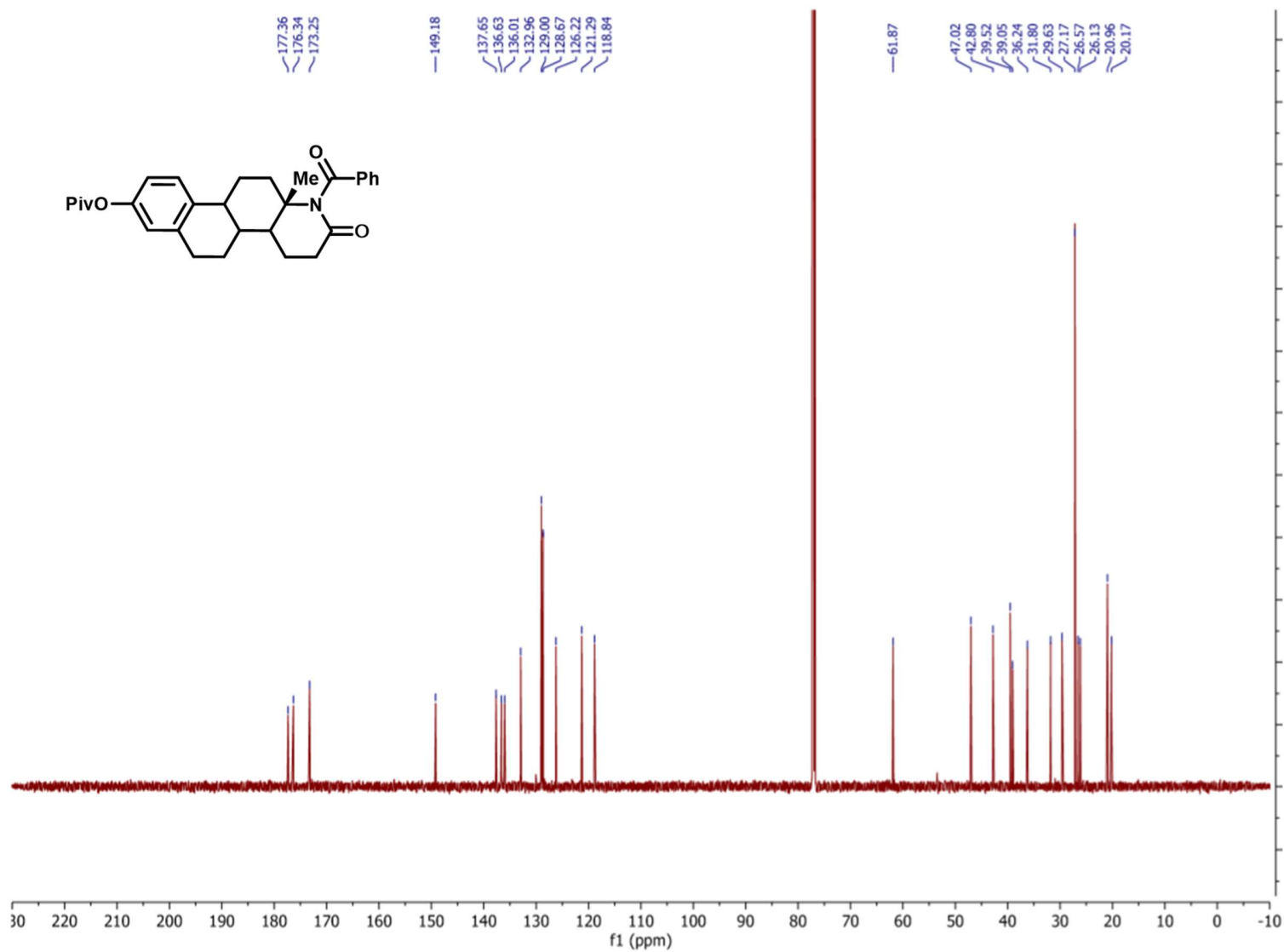
^{13}C NMR (101 MHz, CDCl_3) OF COMPOUND **S20c**



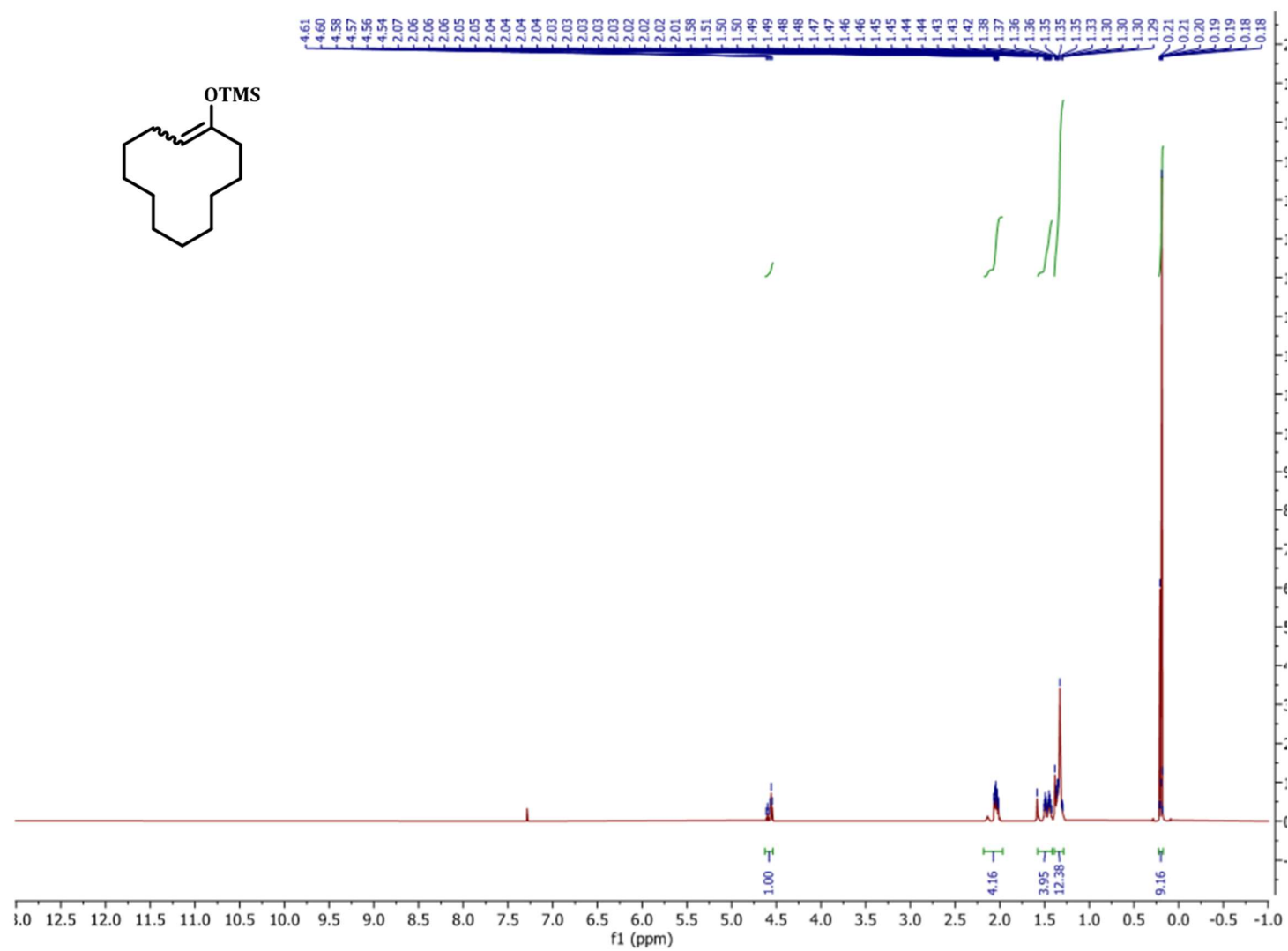
^1H NMR (600 MHz, CDCl_3) of compound **S20**



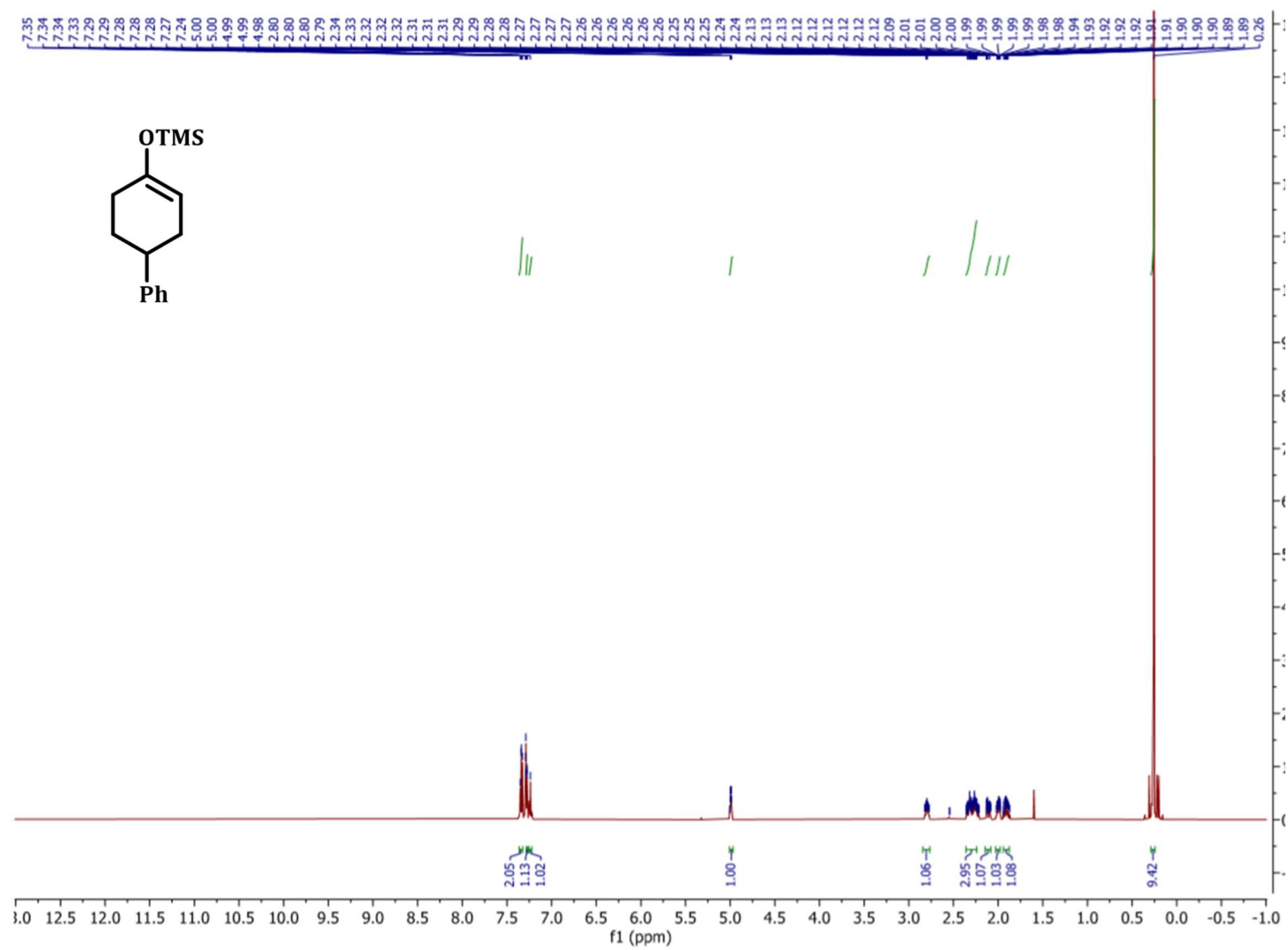
^{13}C NMR (151 MHz, CDCl_3) OF COMPOUND **S20**

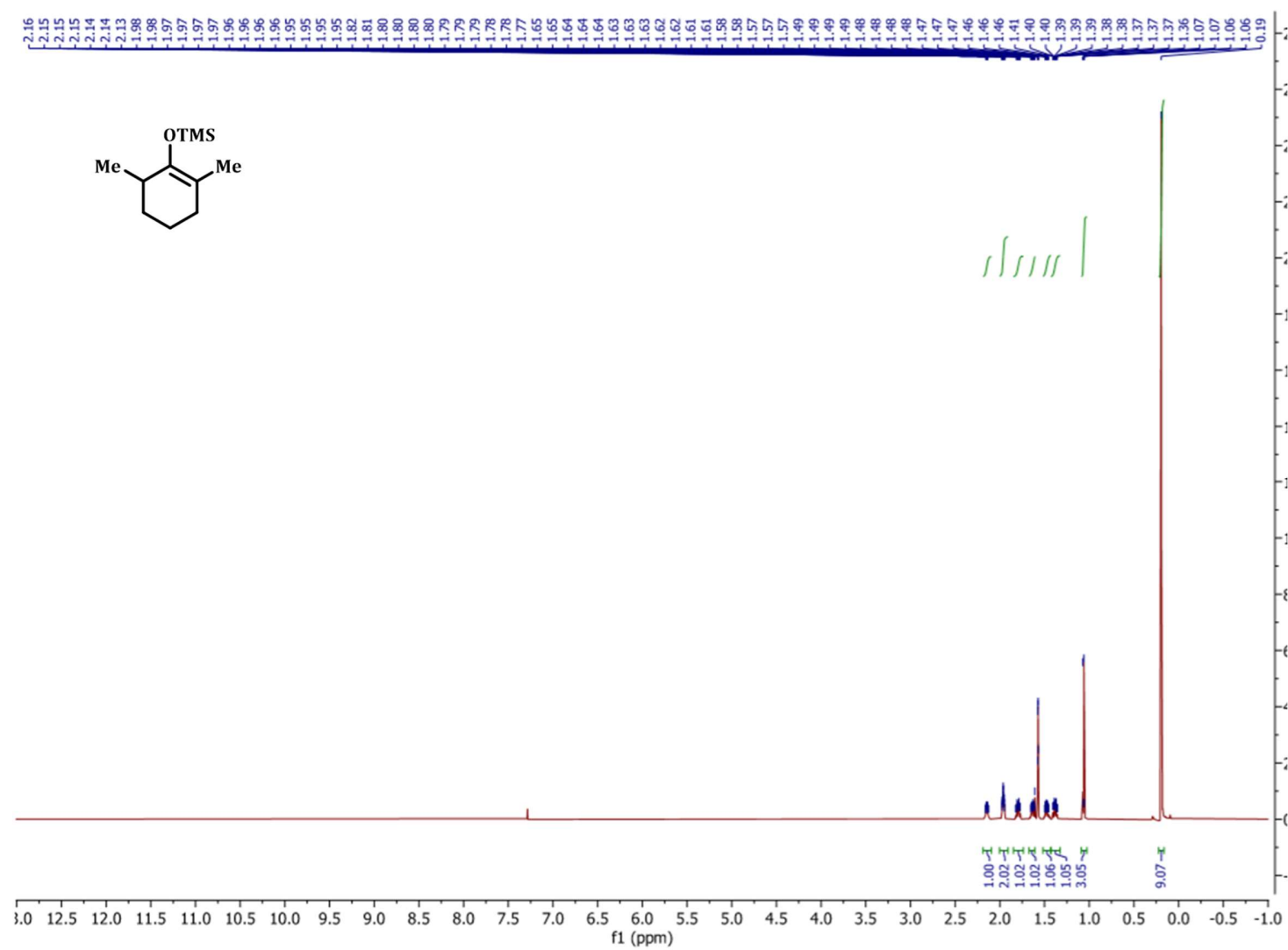


^1H NMR (600 MHz, CDCl_3) of compound **1**

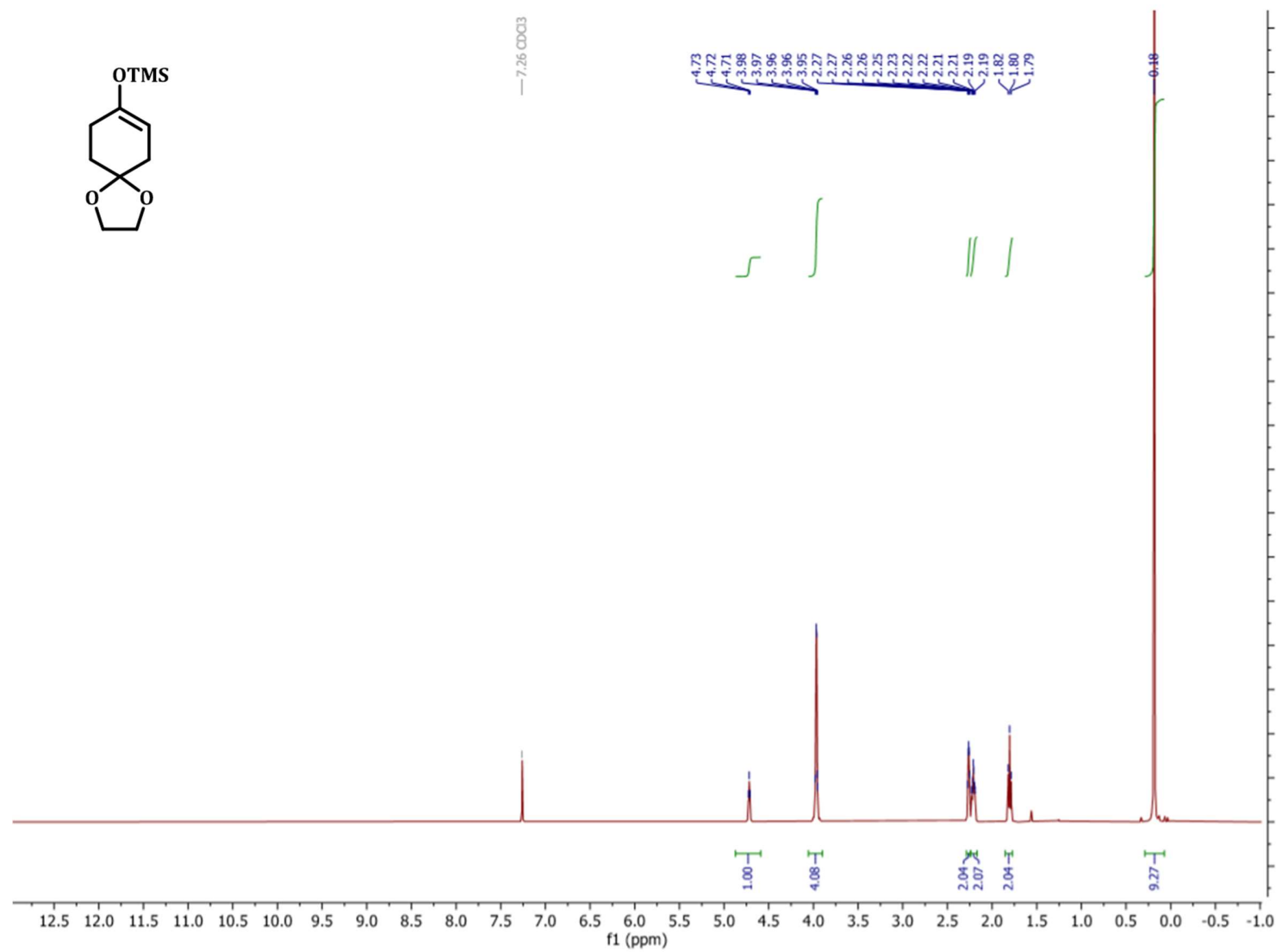


^1H NMR (600 MHz, CDCl_3) of compound **60**

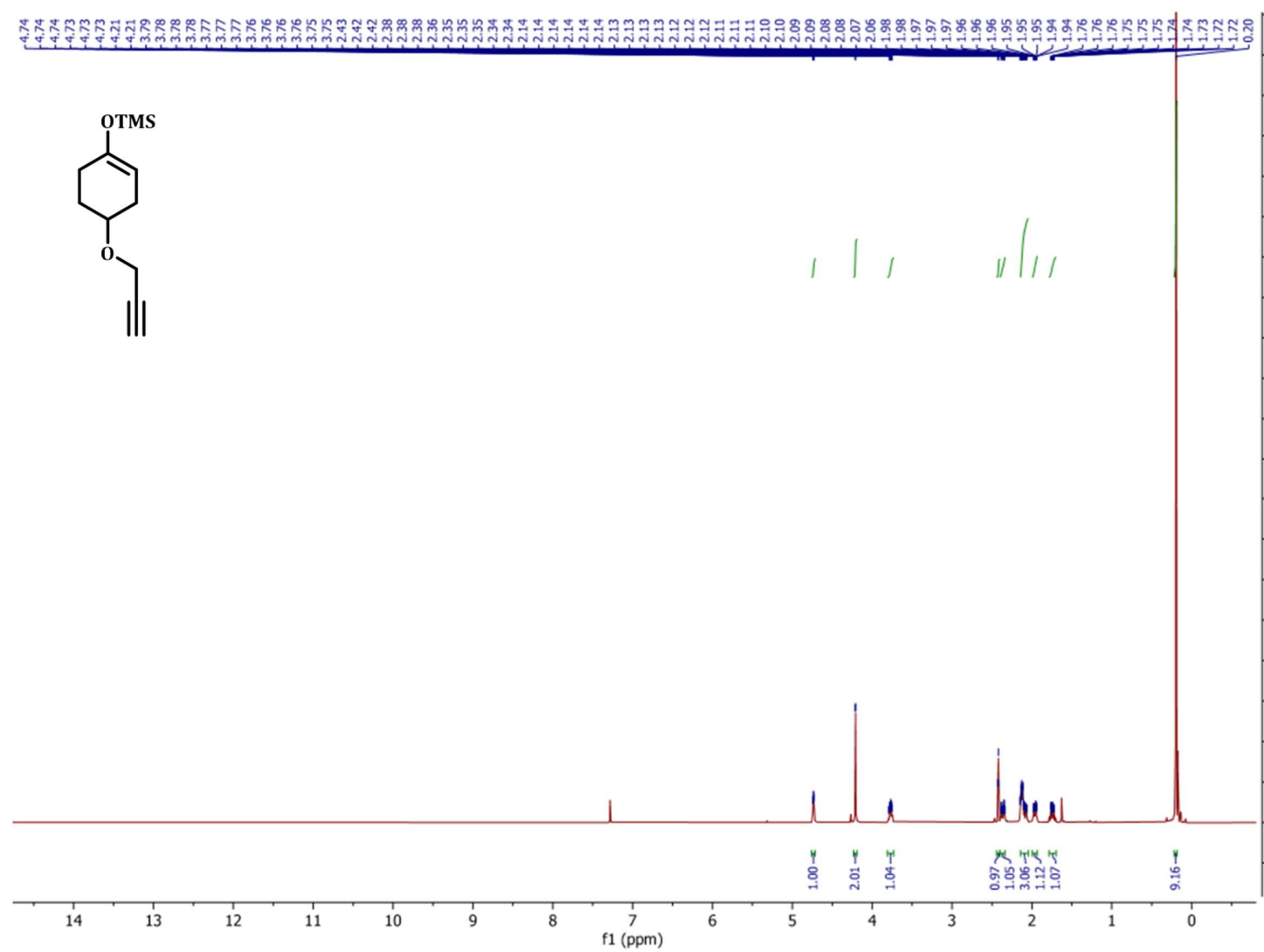


¹H NMR (600 MHz, CDCl₃) of compound **S27**

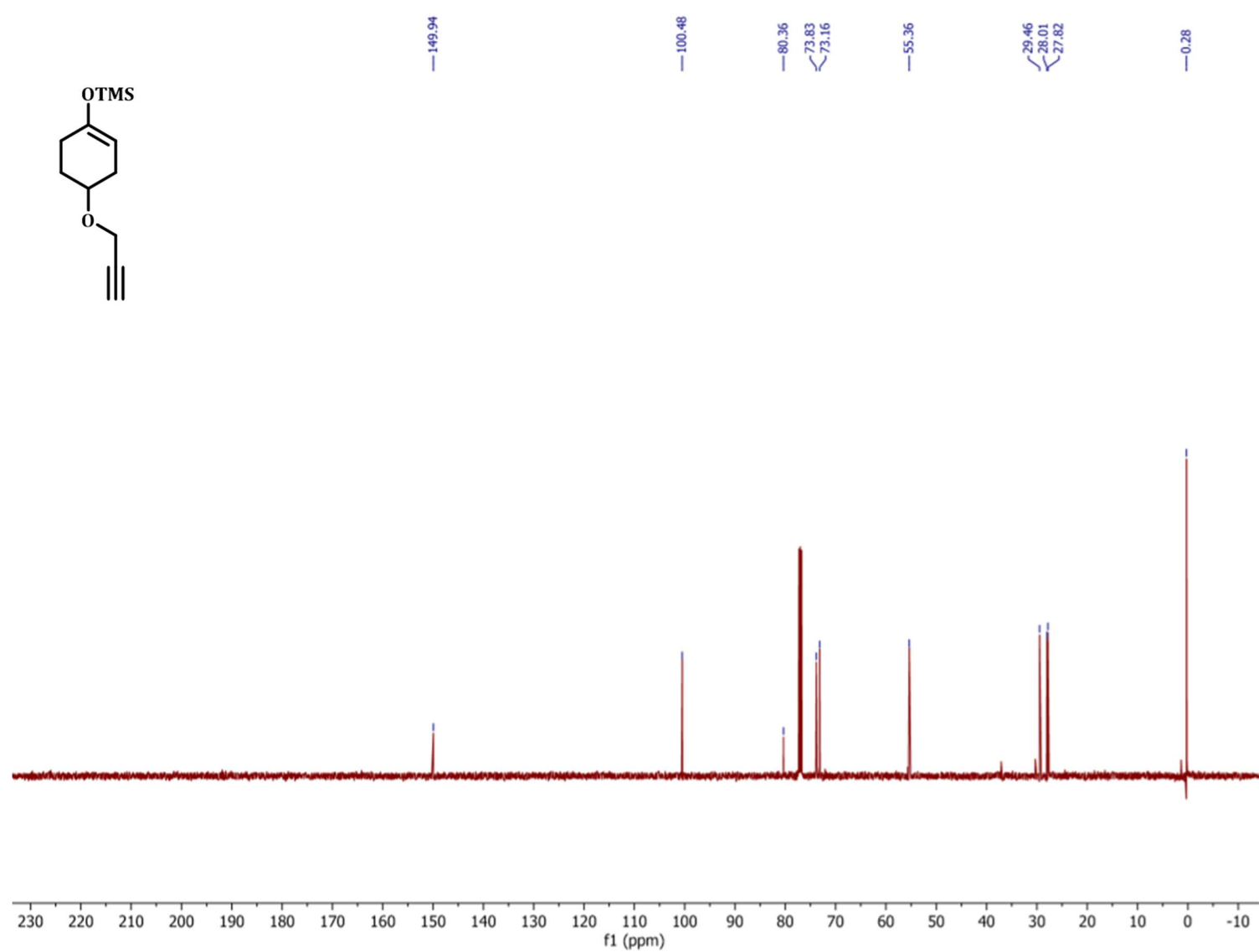
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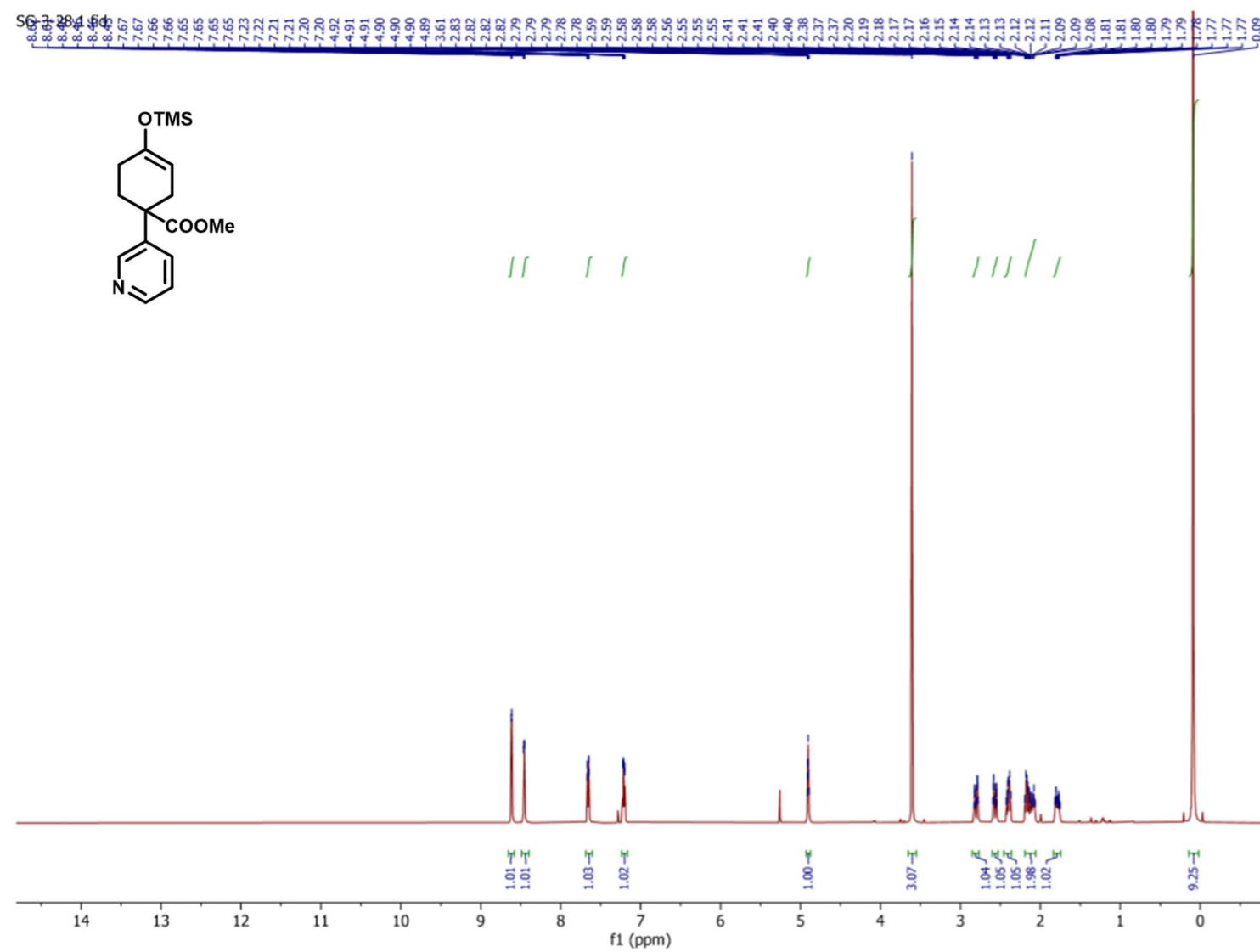


^1H NMR (500 MHz, CDCl_3) of compound **S29**

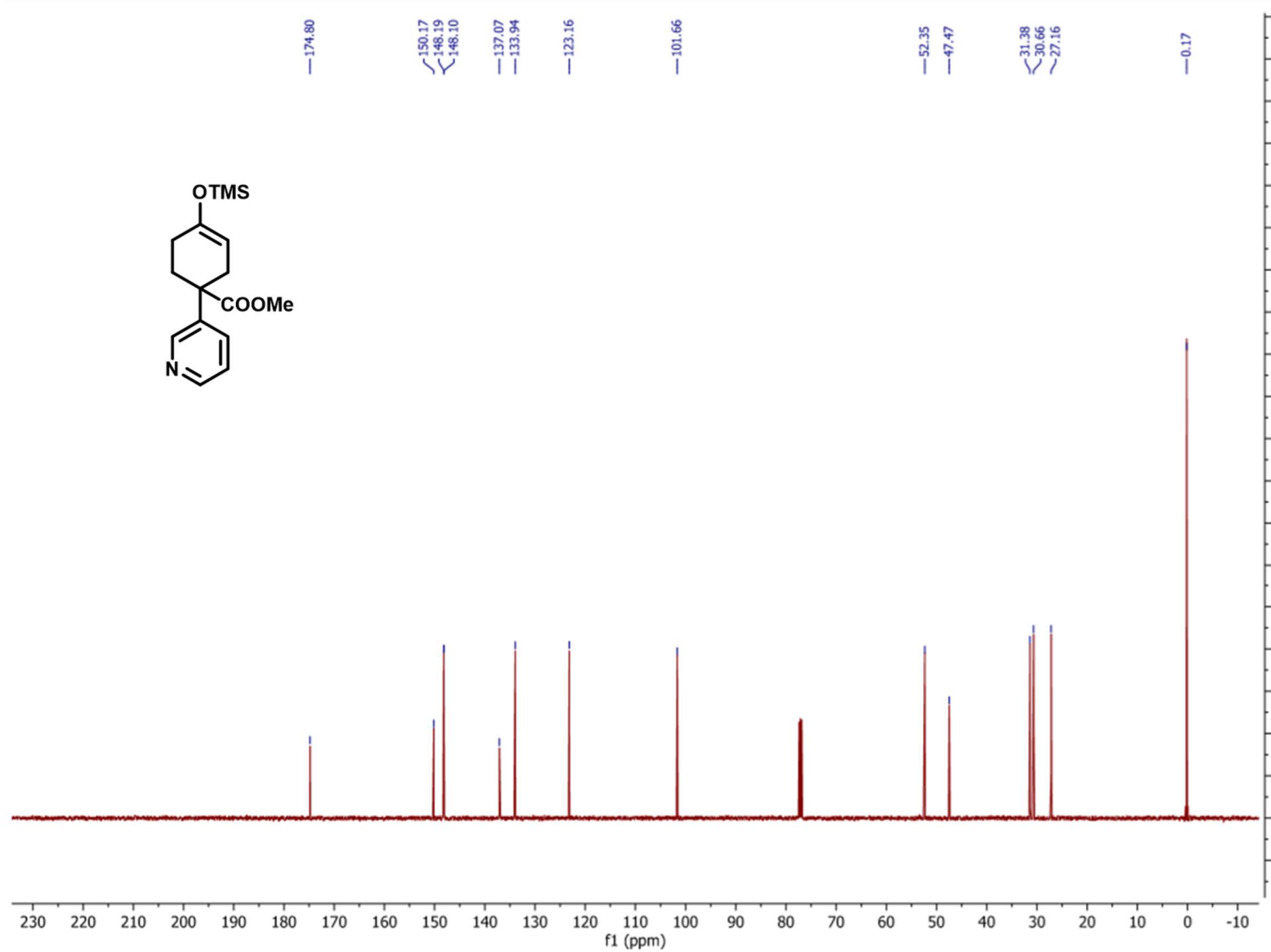


^{13}C NMR (126 MHz, CDCl_3) OF COMPOUND **S29**

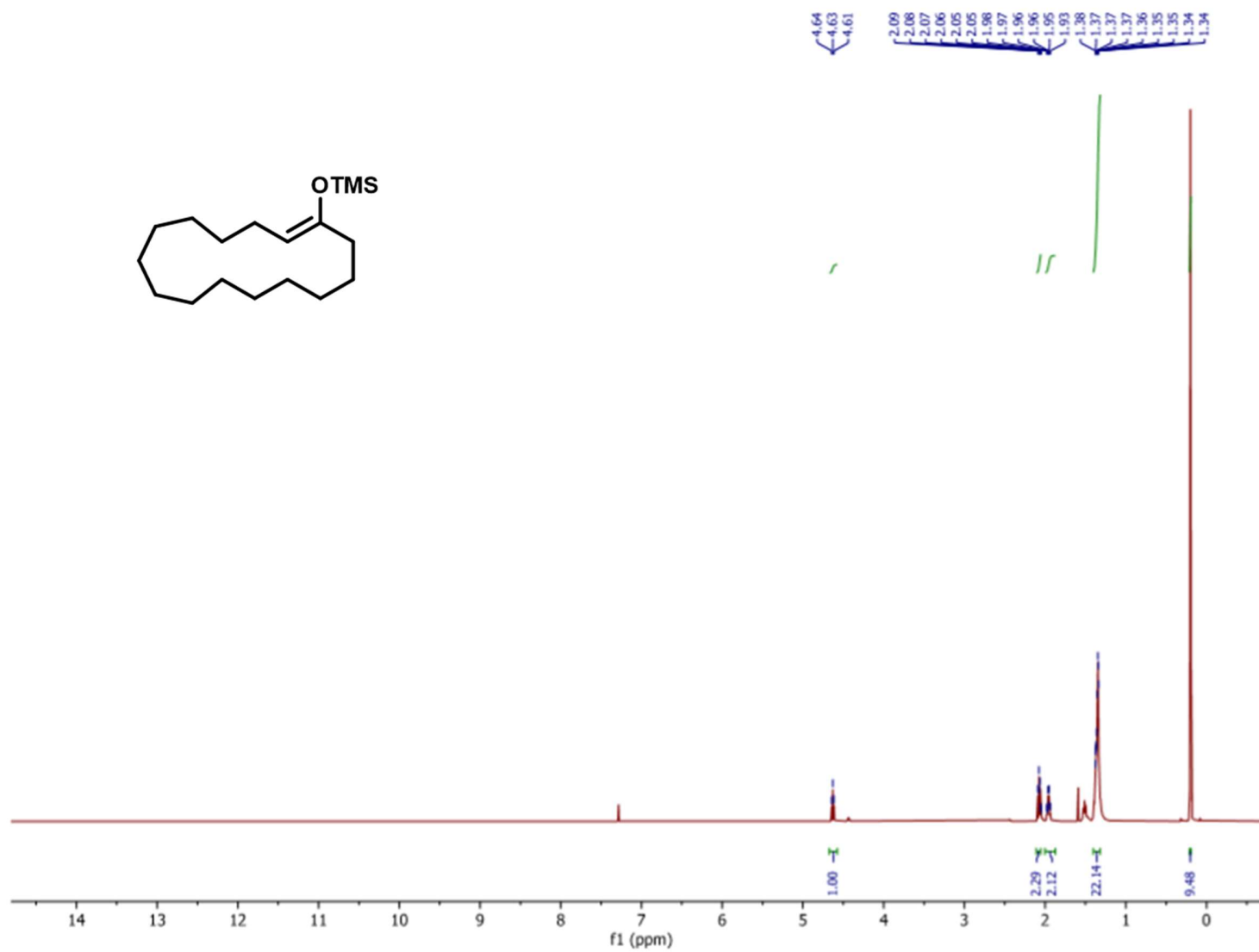


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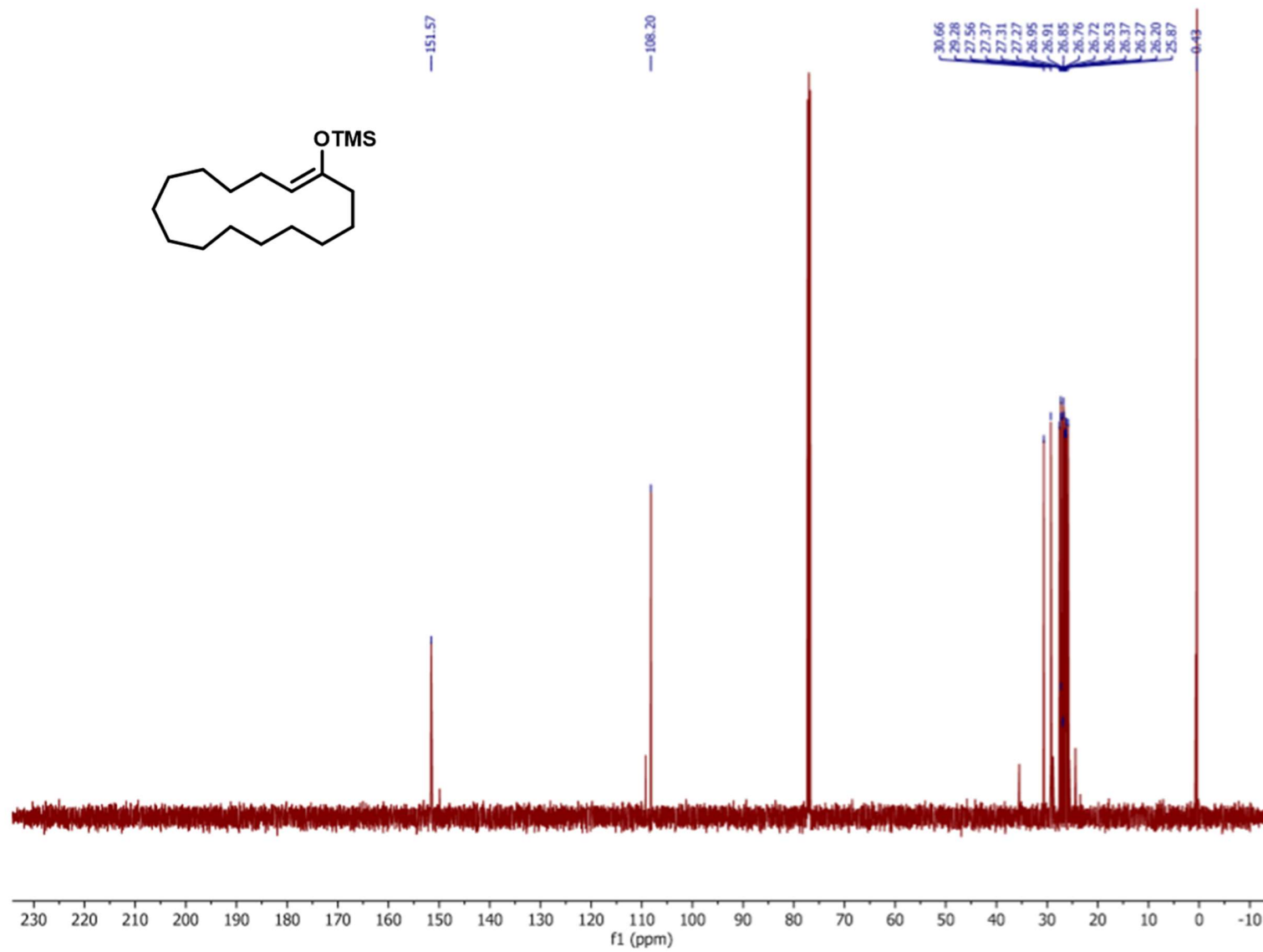
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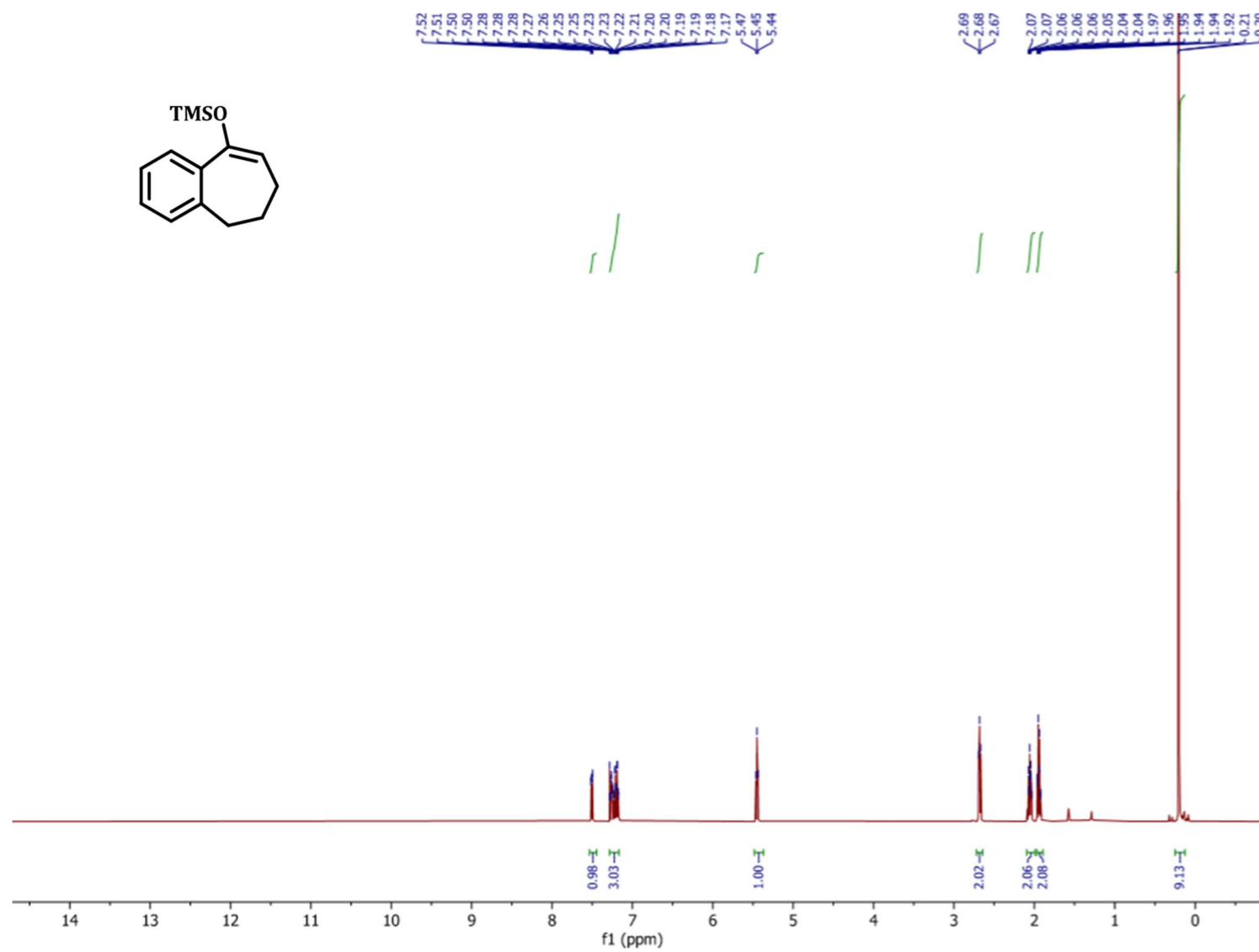
^1H NMR (500 MHz, CDCl_3) of compound **S31**



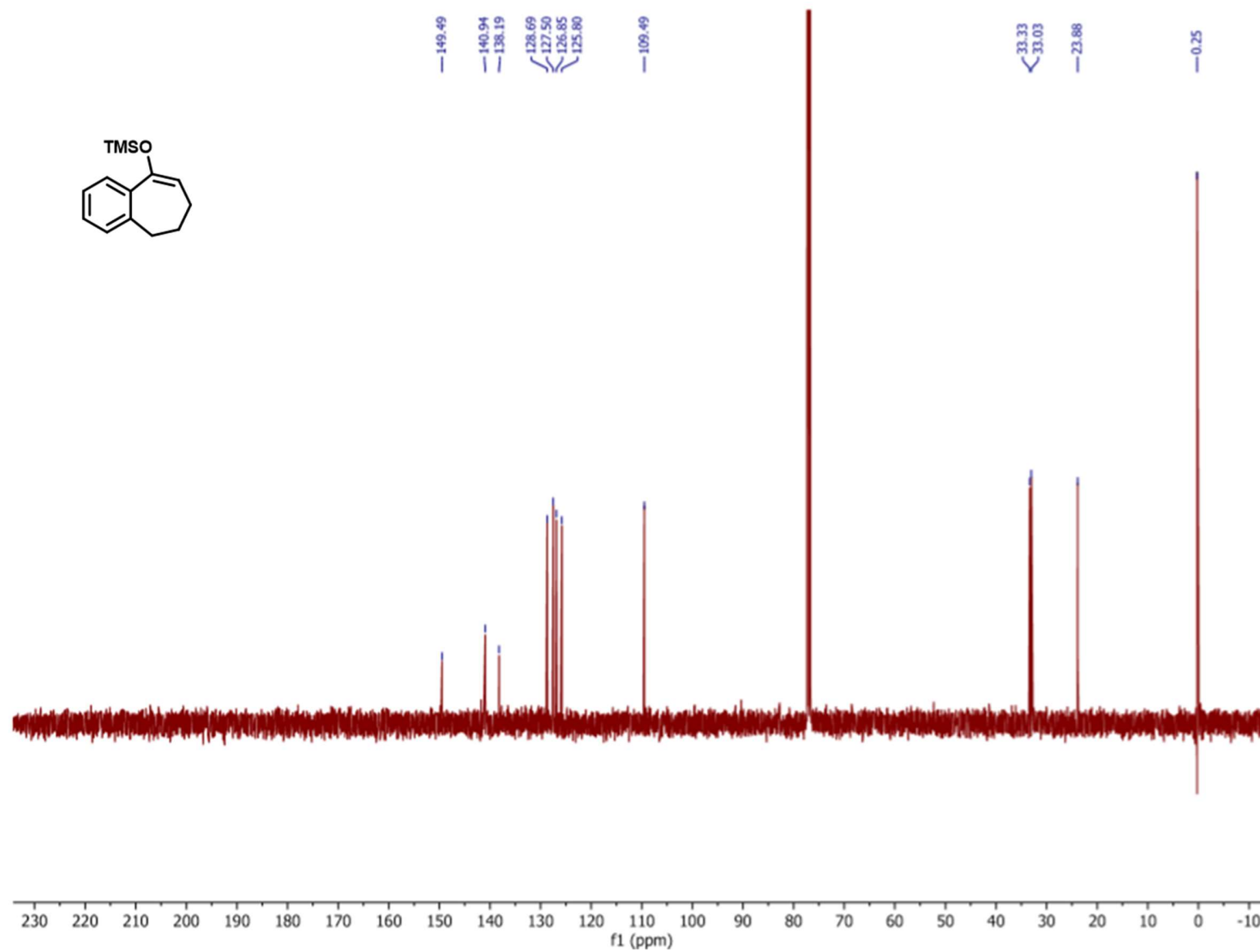
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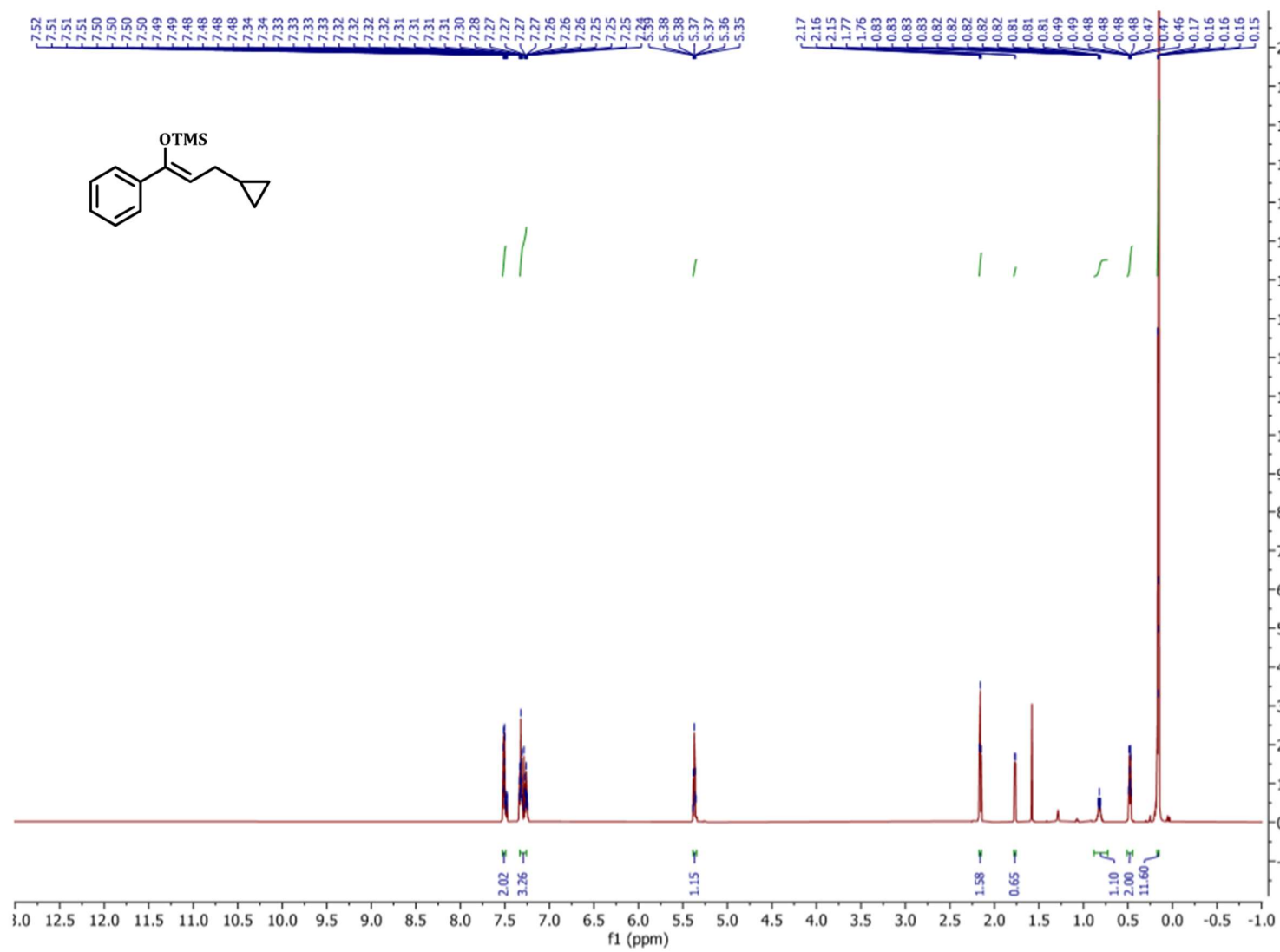


^1H NMR (500 MHz, CDCl_3) of compound **S32**

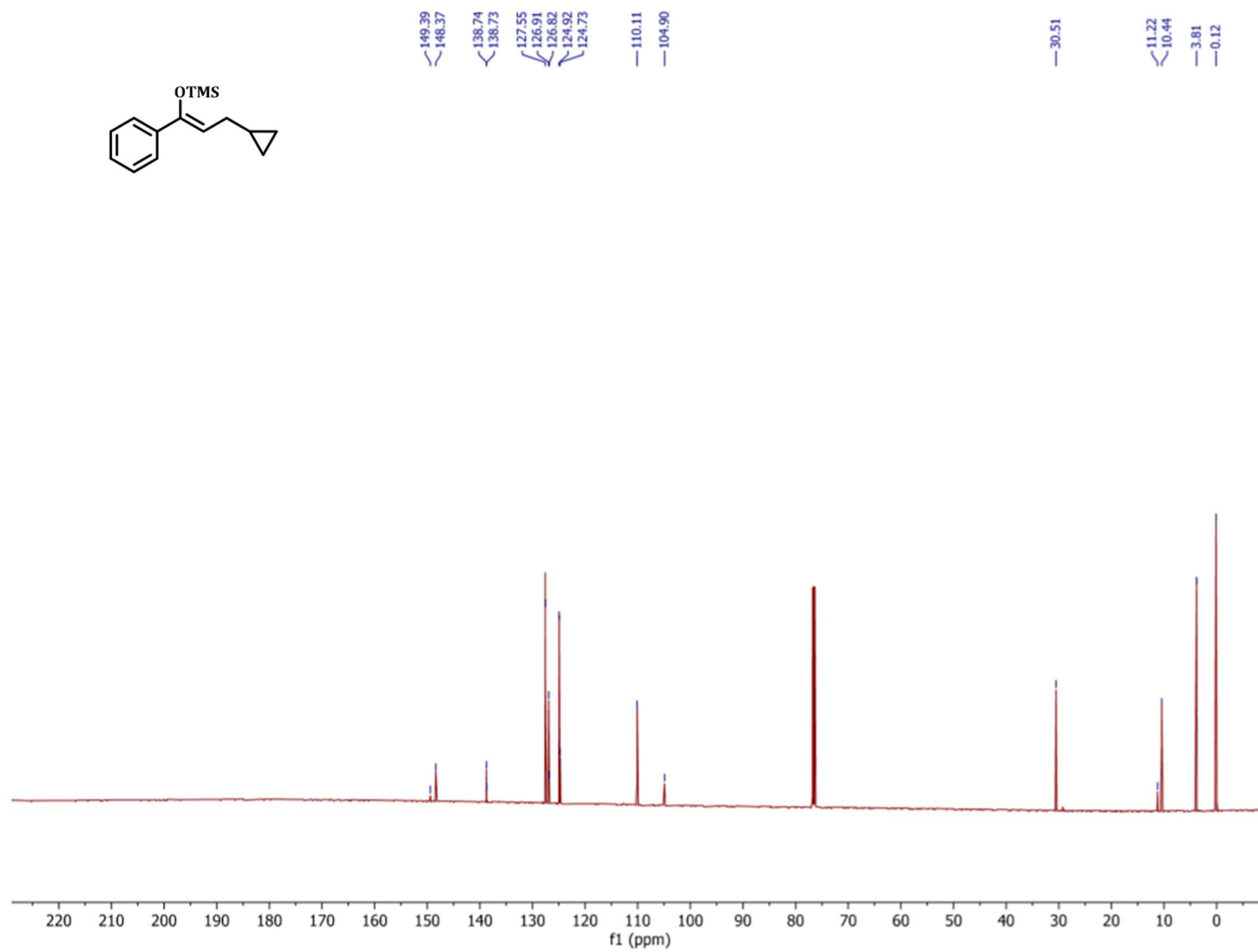


^1H NMR (500 MHz, CDCl_3) of compound **S32**

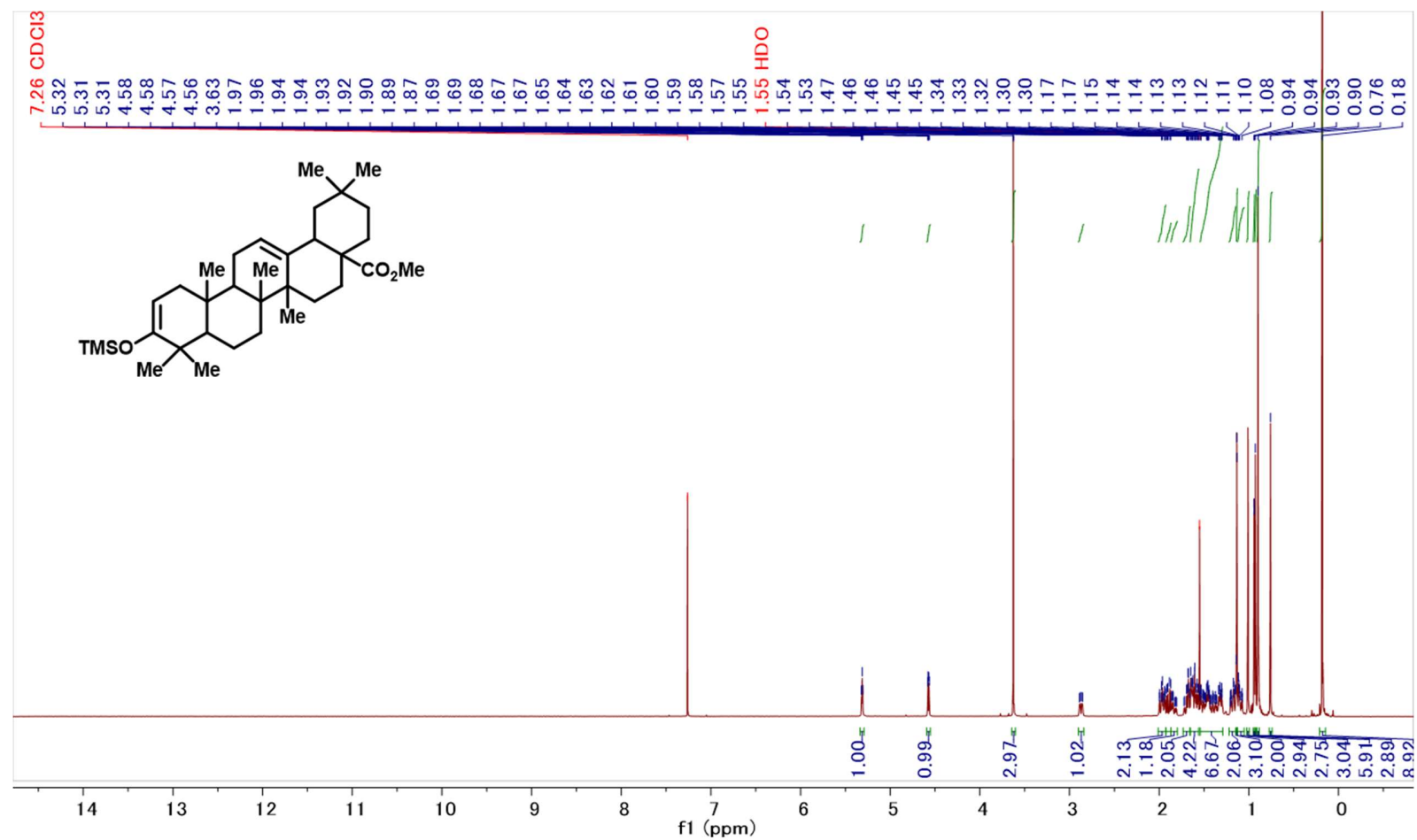


¹H NMR (600 MHz, CDCl₃) of compound **S33**

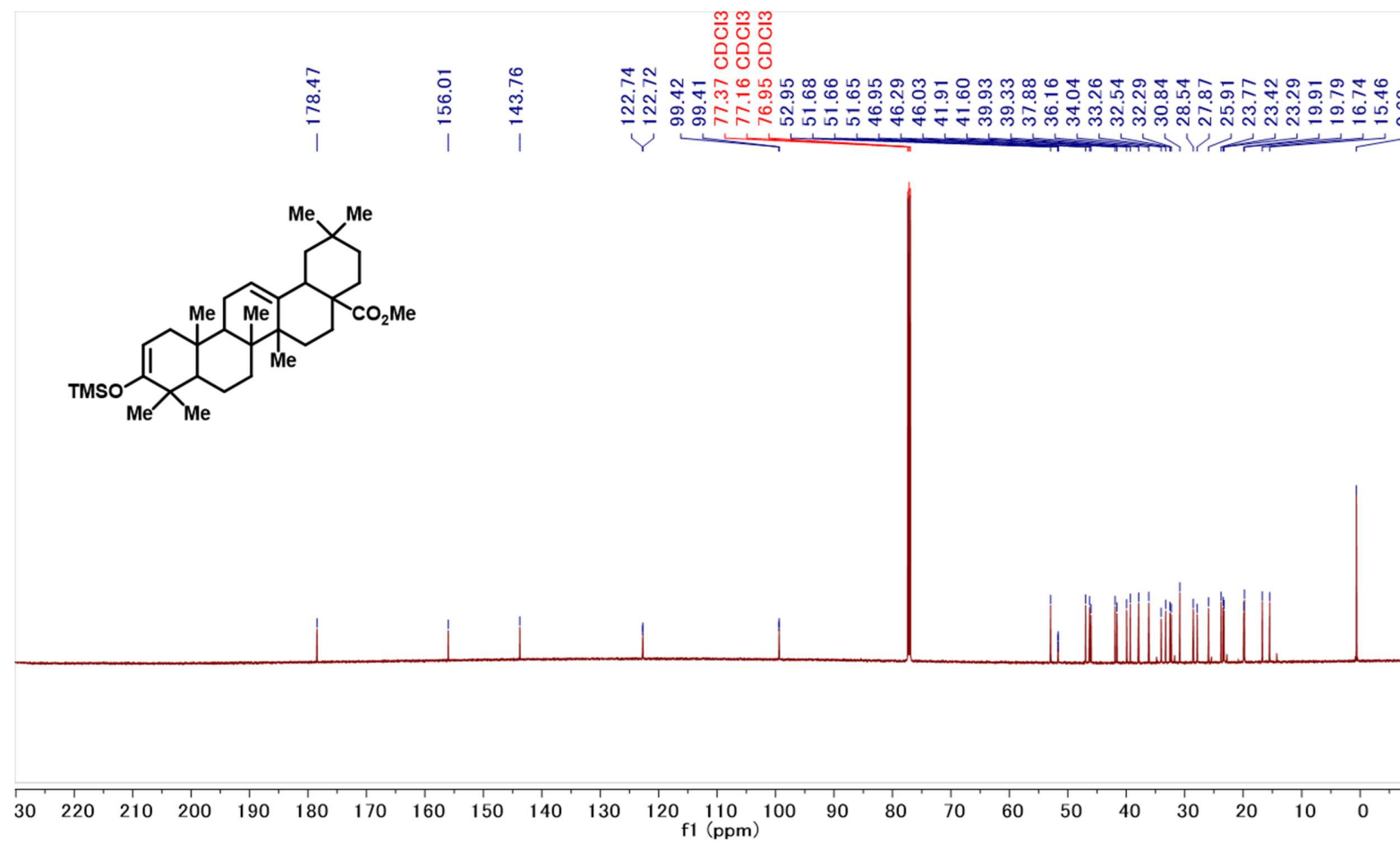
^{13}C NMR (151 MHz, CDCl_3) of compound **S33**



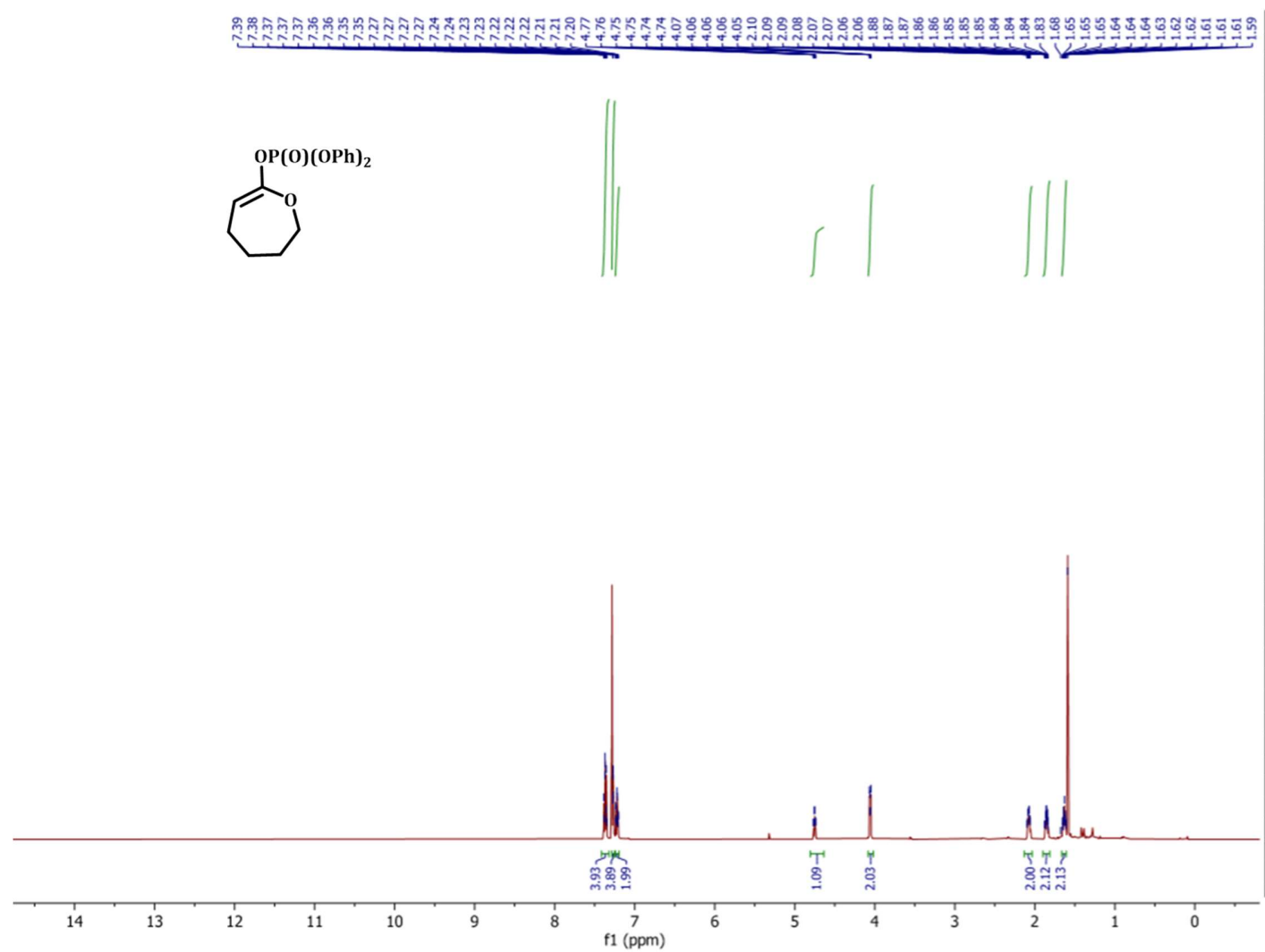
^1H NMR (400 MHz, CDCl_3) of compound **62**



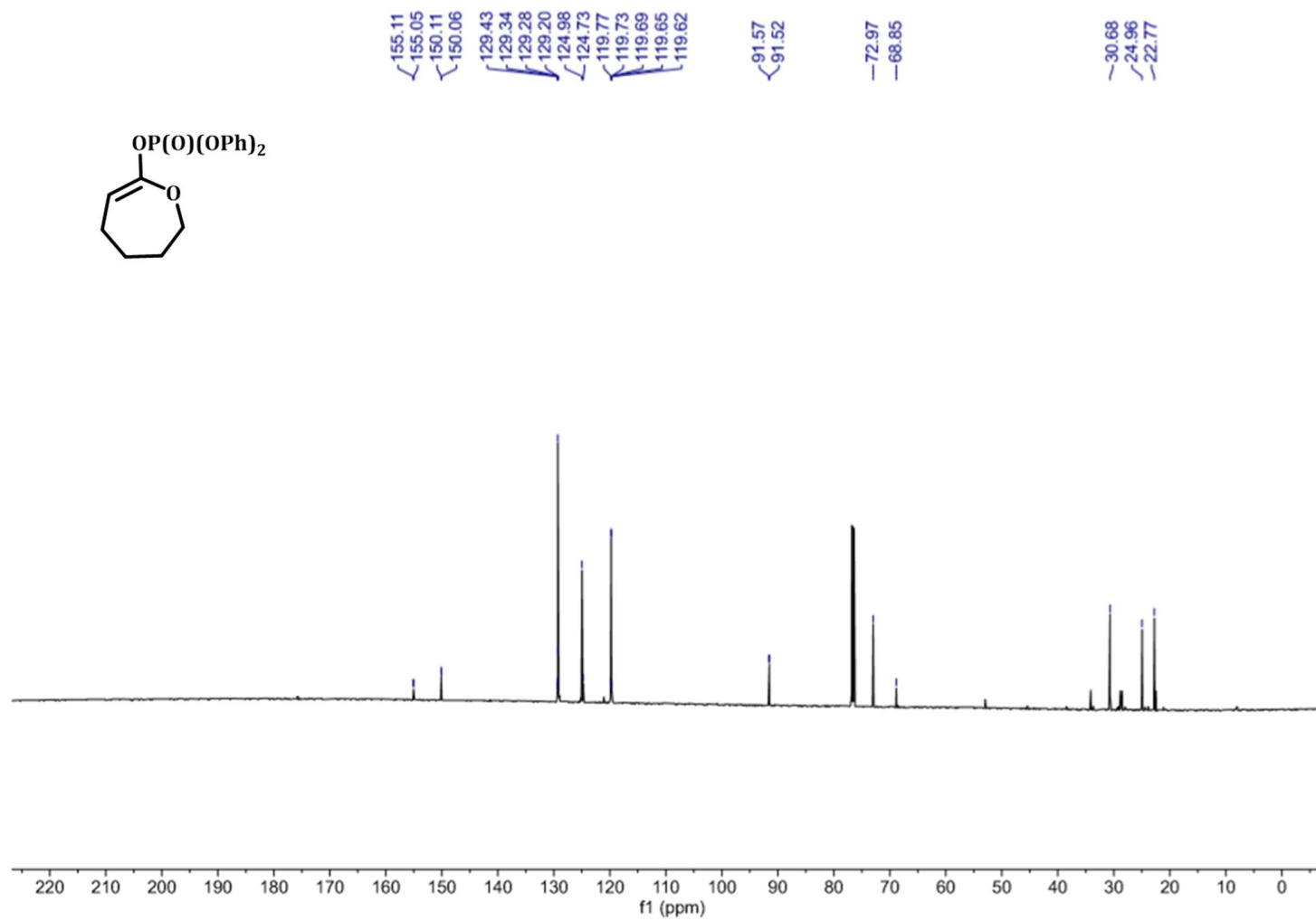
^{13}C NMR (101 MHz, CDCl_3) of compound **62**



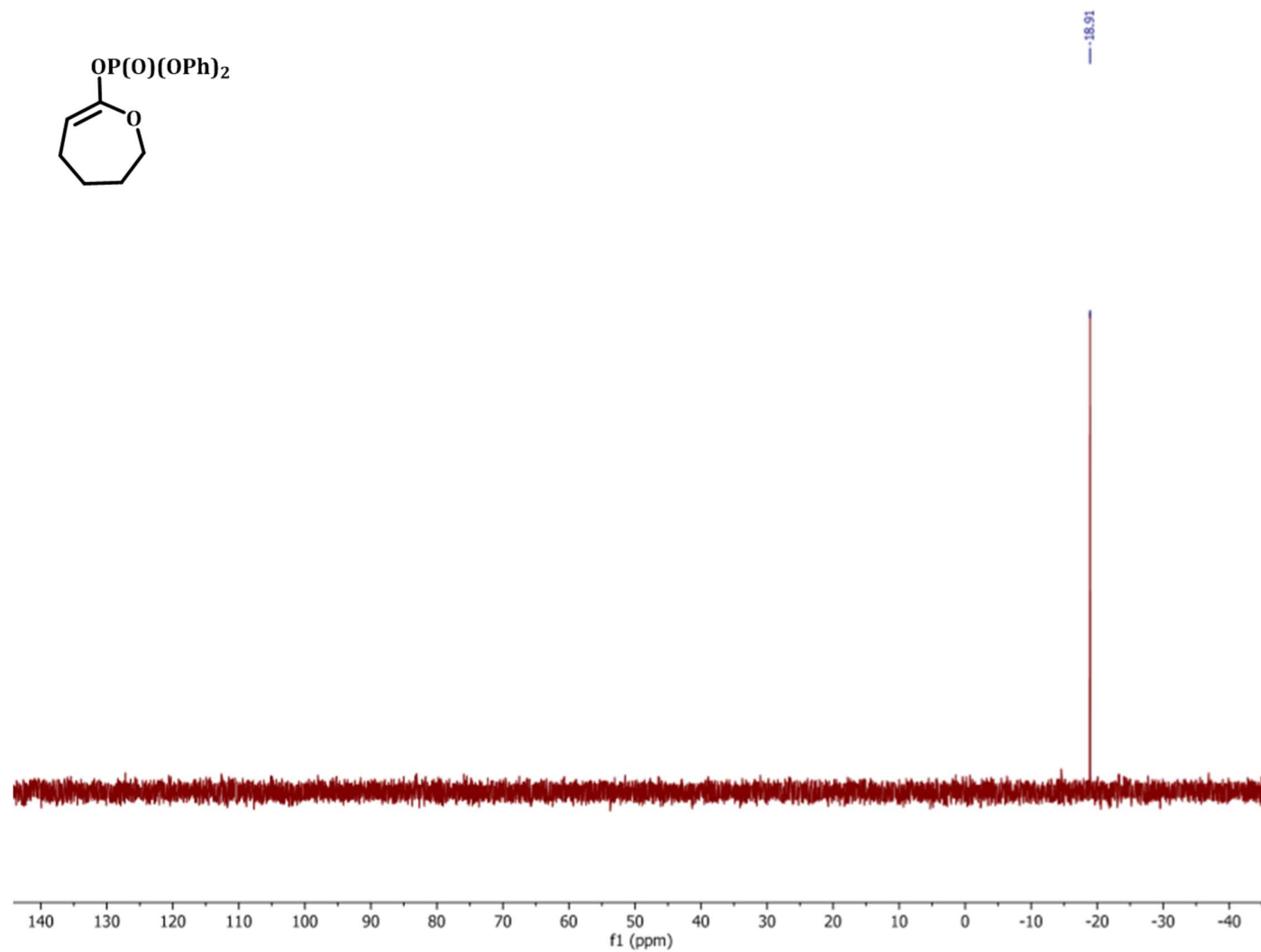
^1H NMR (400 MHz, CDCl_3) of compound **55**



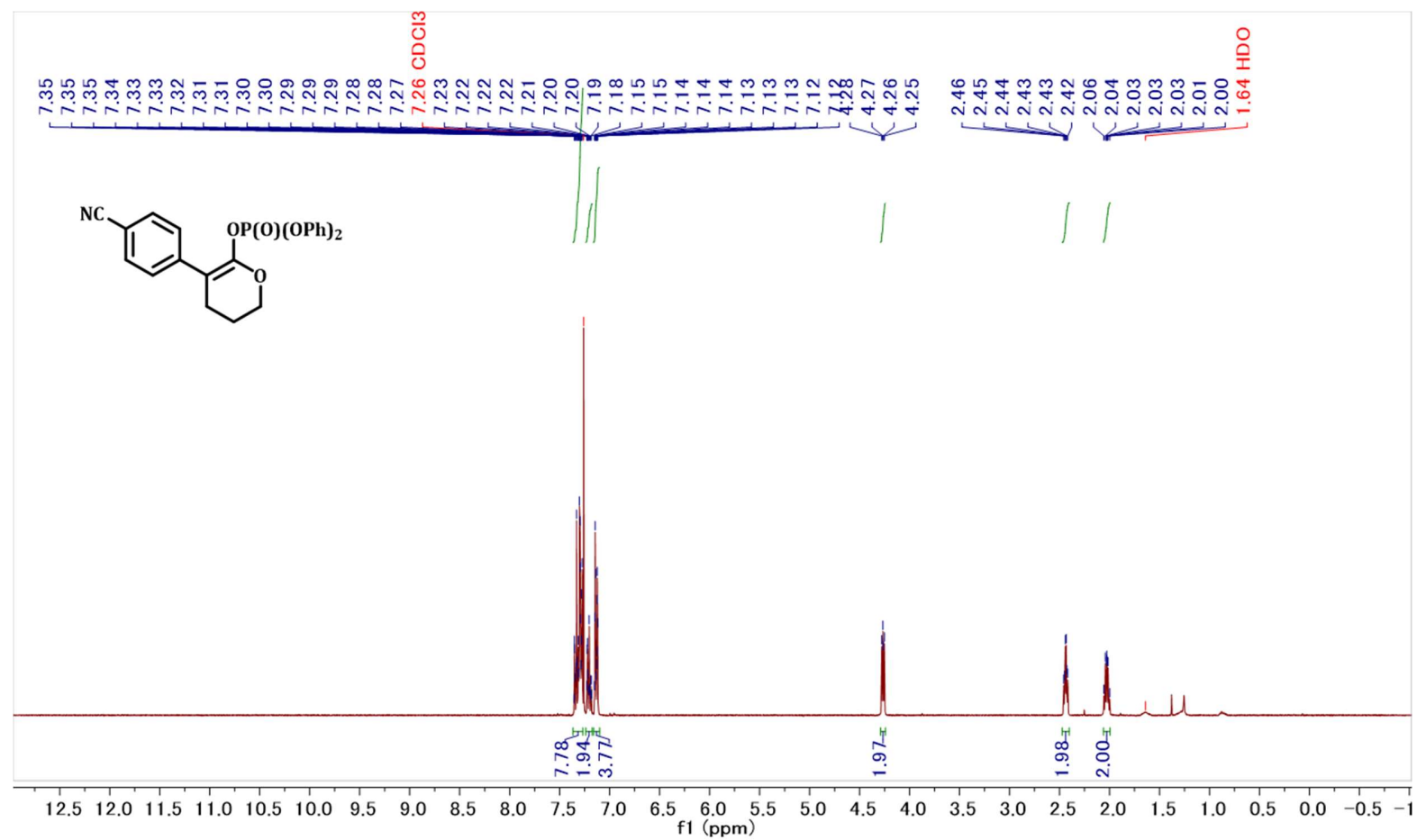
^{13}C NMR (151 MHz, CDCl_3) of compound **55**



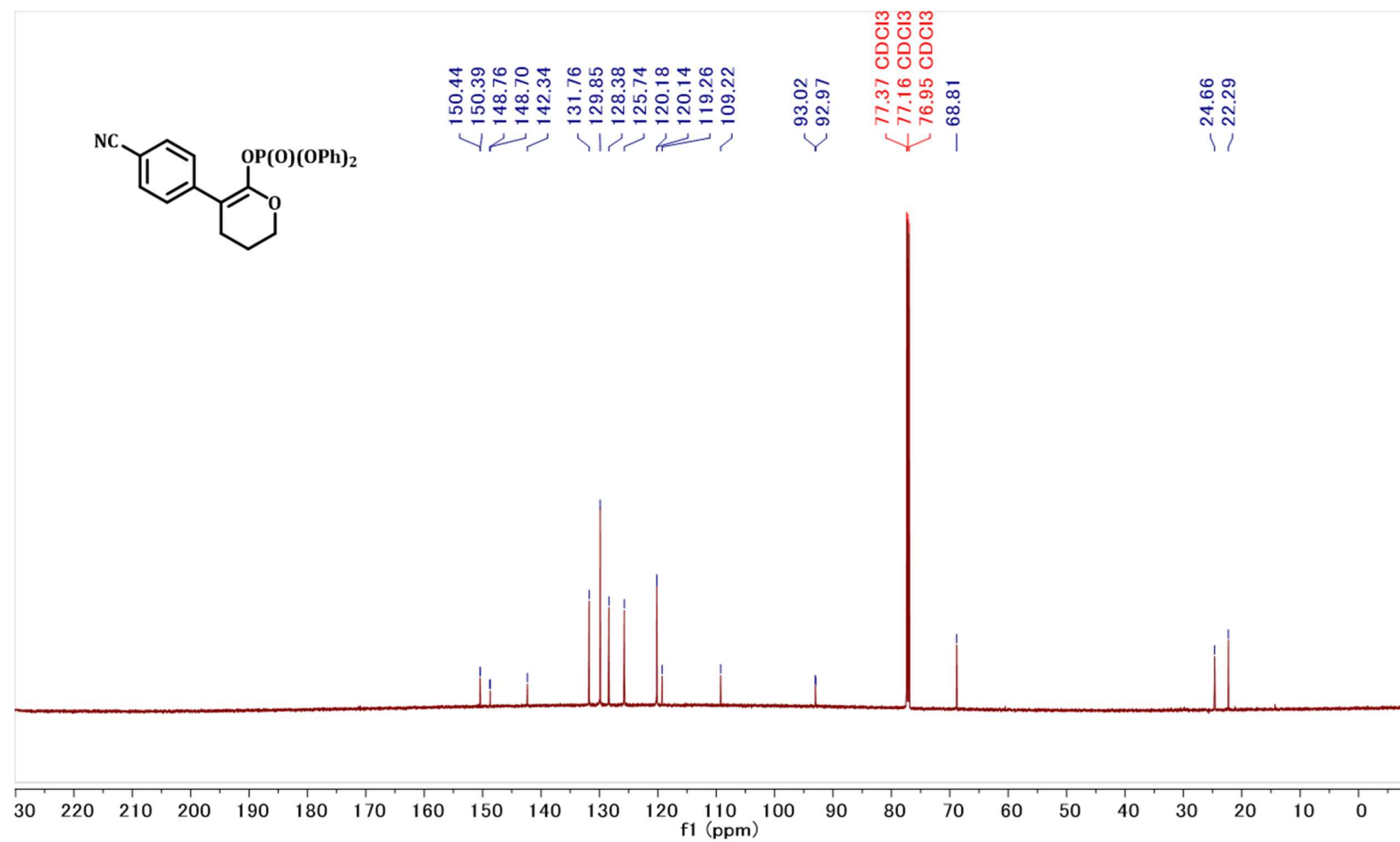
^{31}P NMR (162 MHz, CDCl_3) of compound **55**



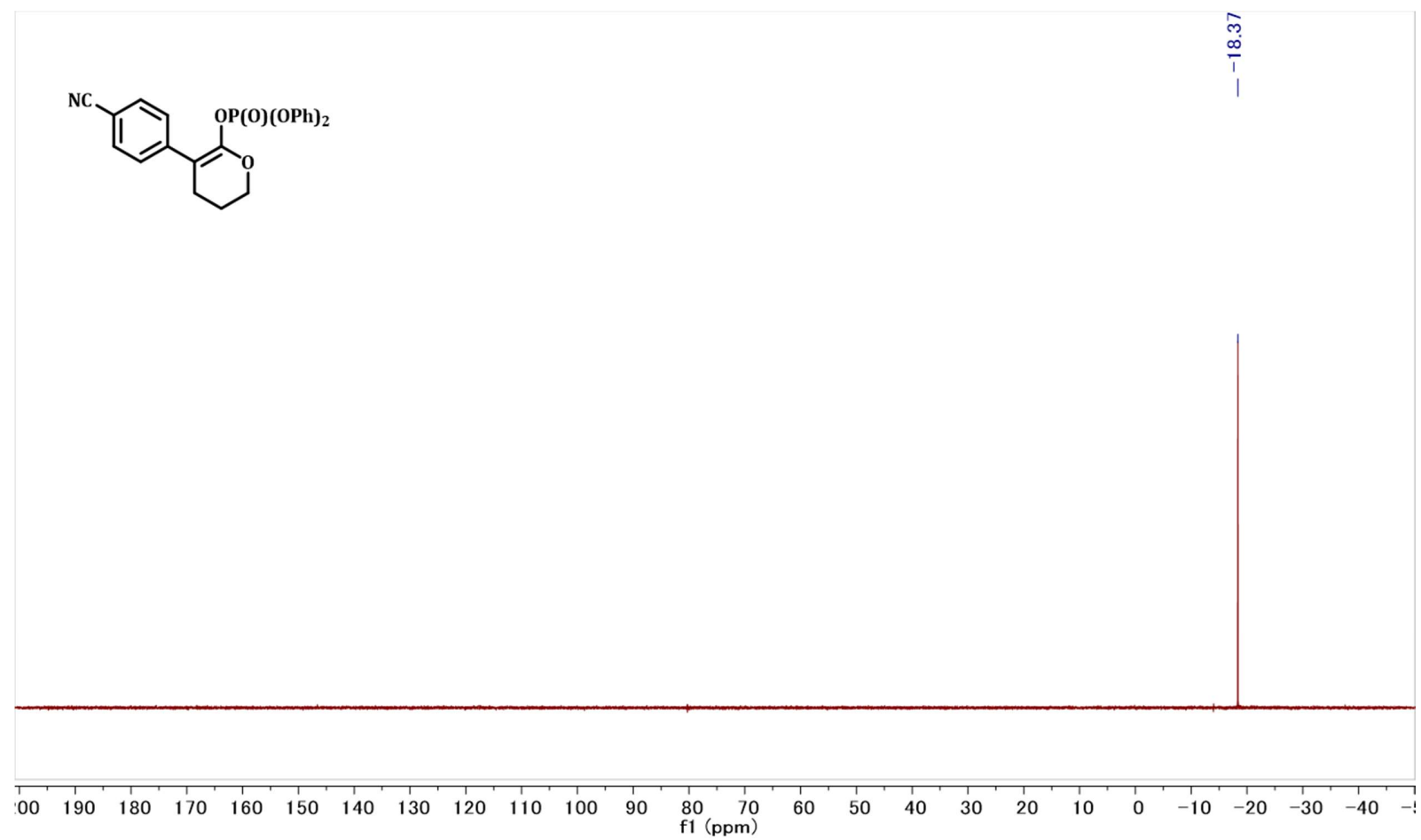
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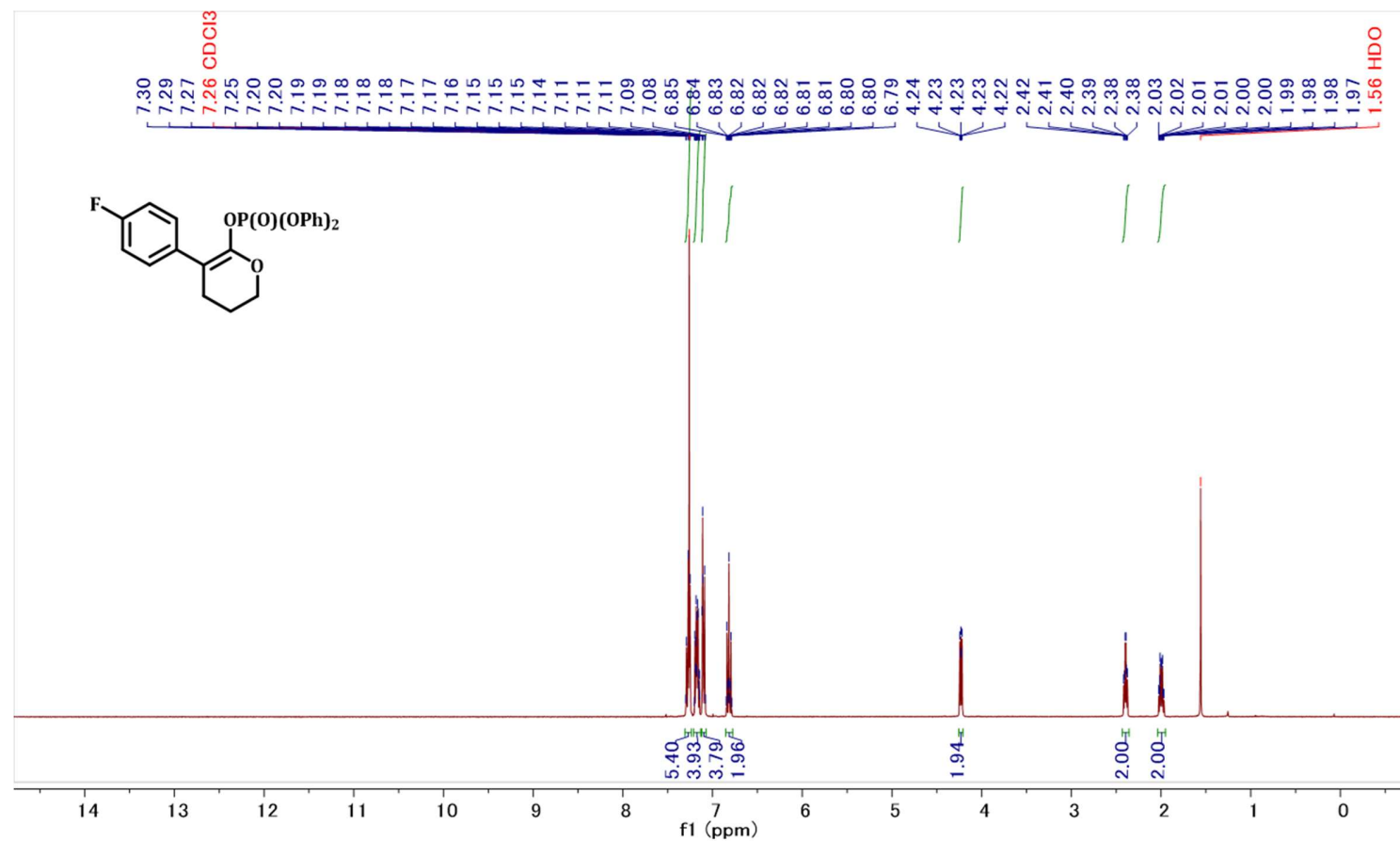
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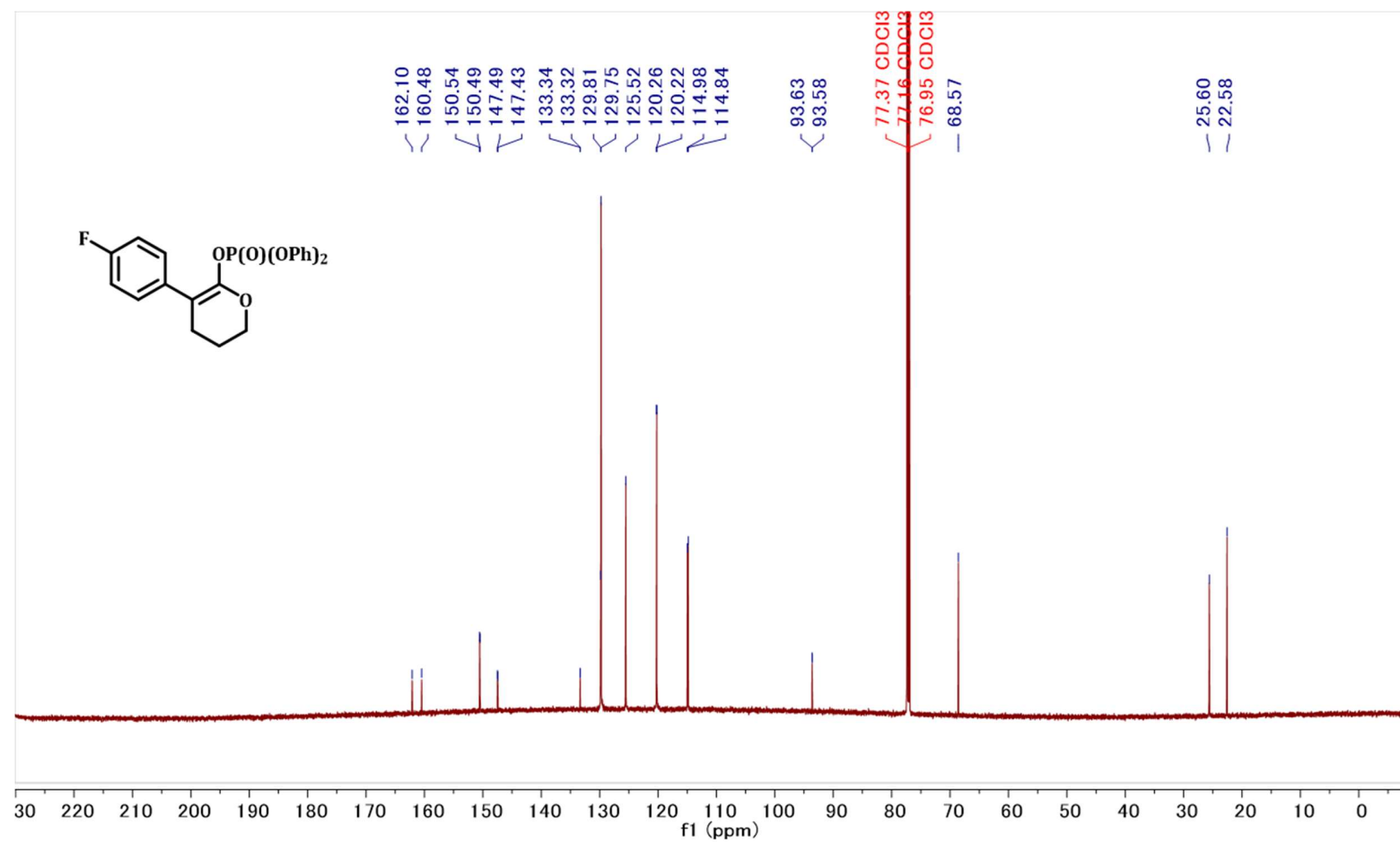
^{31}P NMR (162 MHz, CDCl_3) of compound **S34**



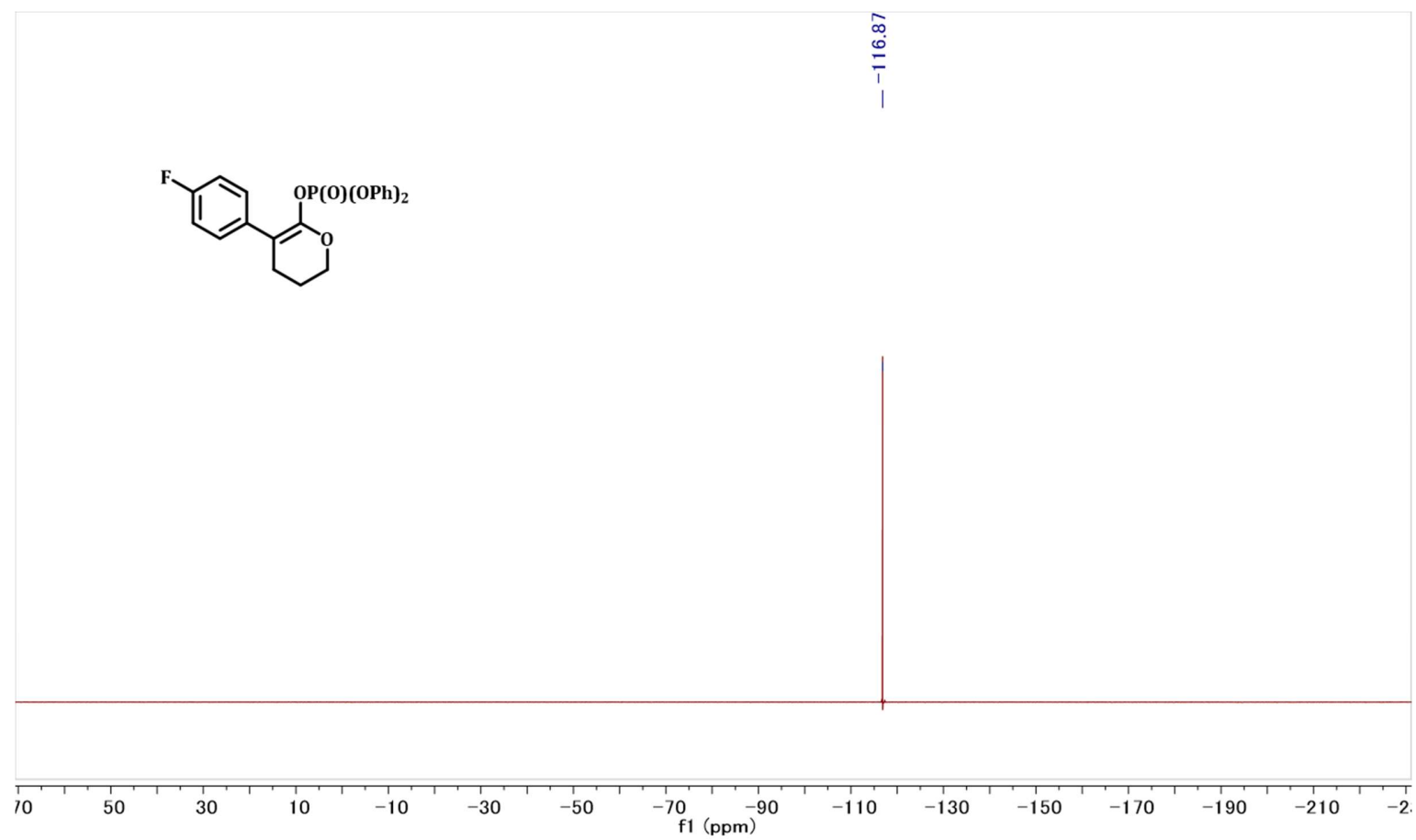
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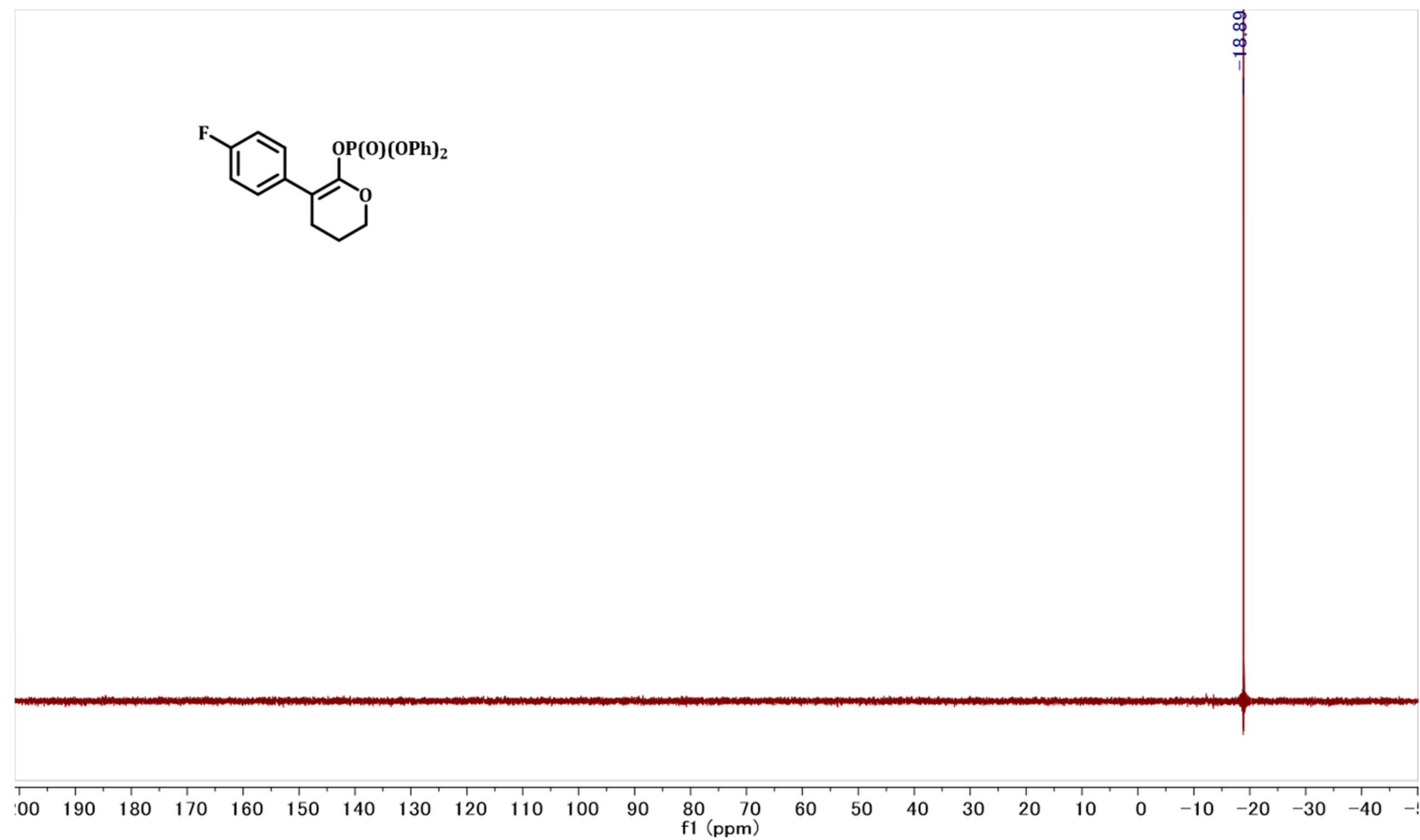
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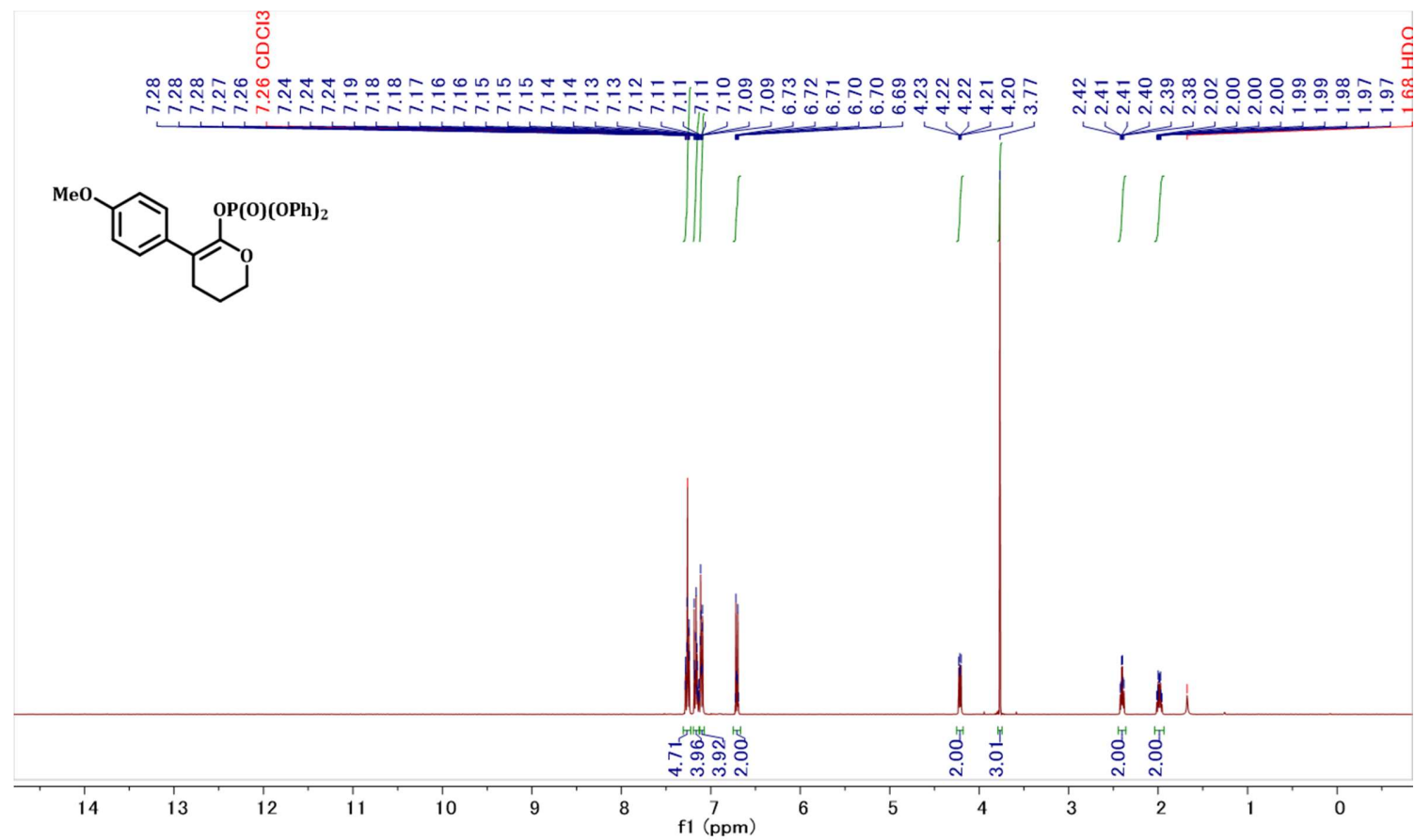
^{19}F NMR (376 MHz, CDCl_3) of compound **S35**



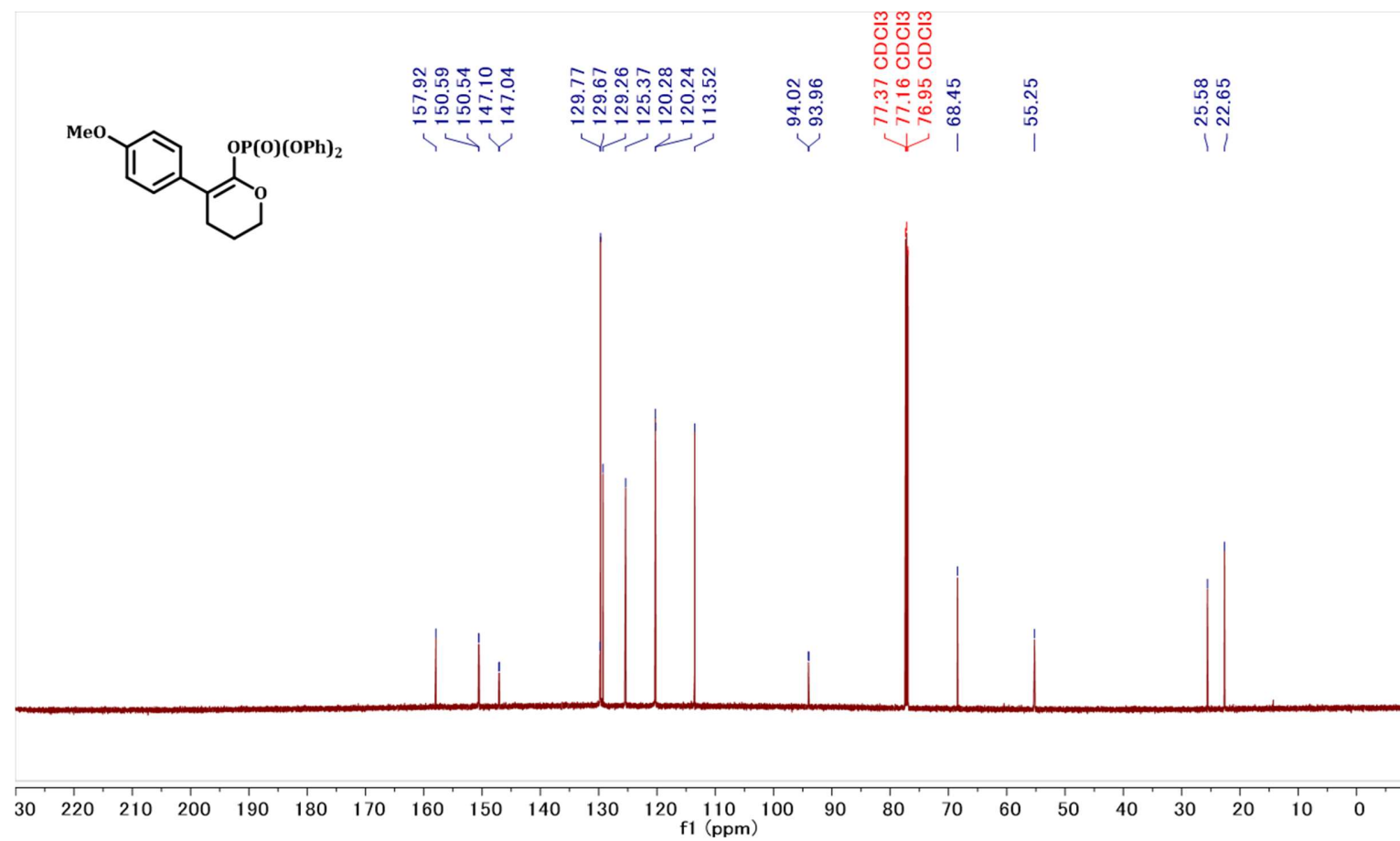
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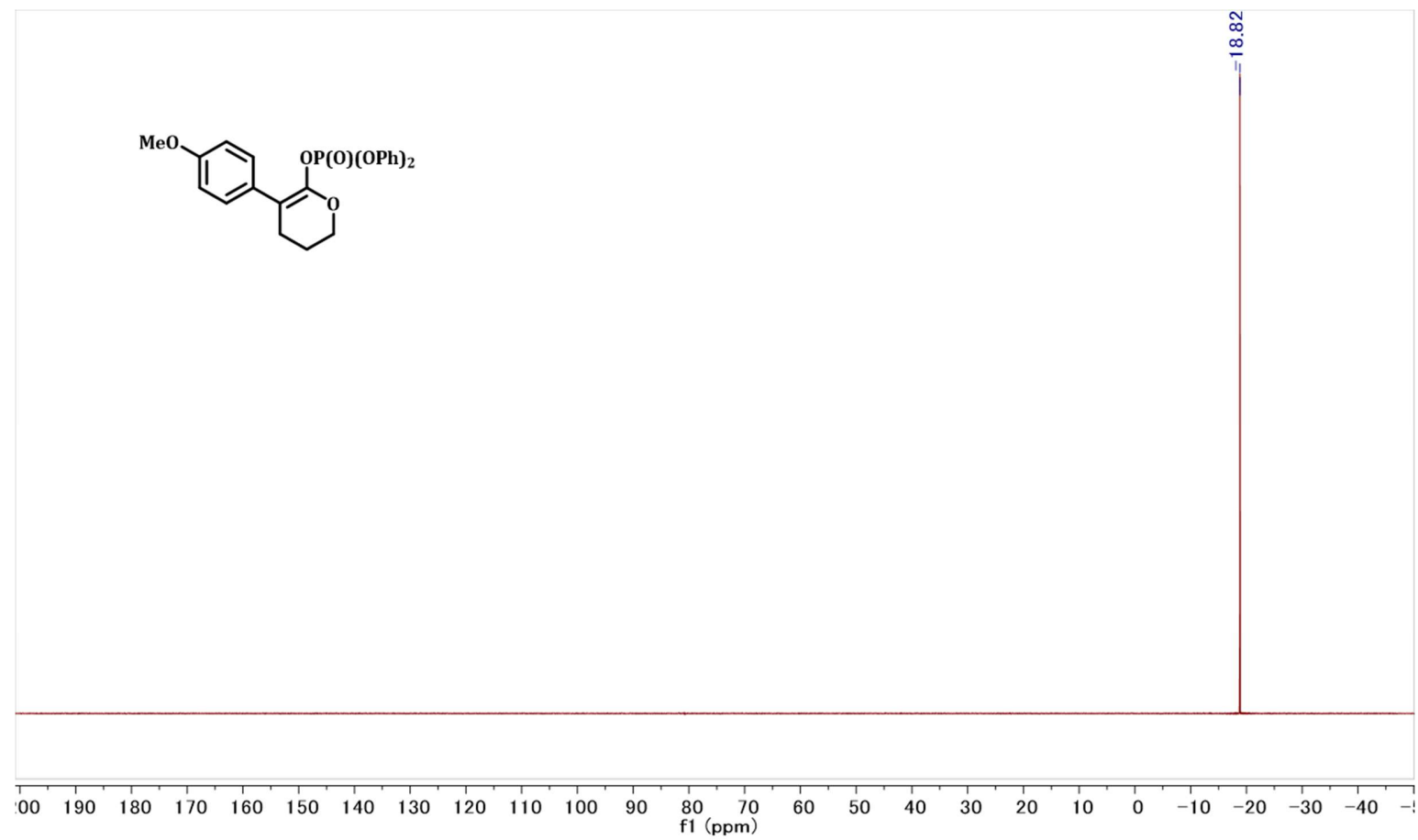
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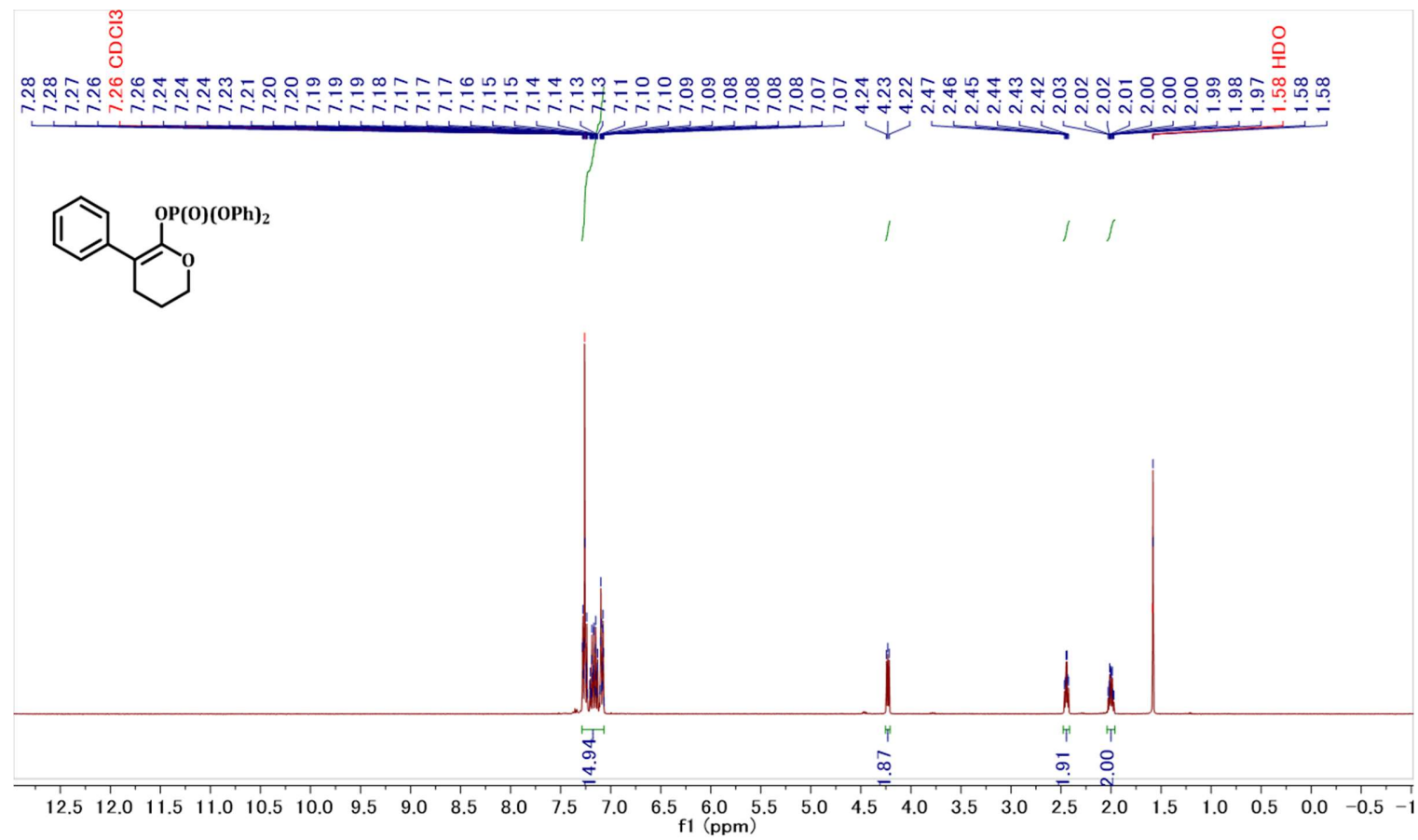
^{13}C NMR (151 MHz, CDCl_3) of compound **S36**



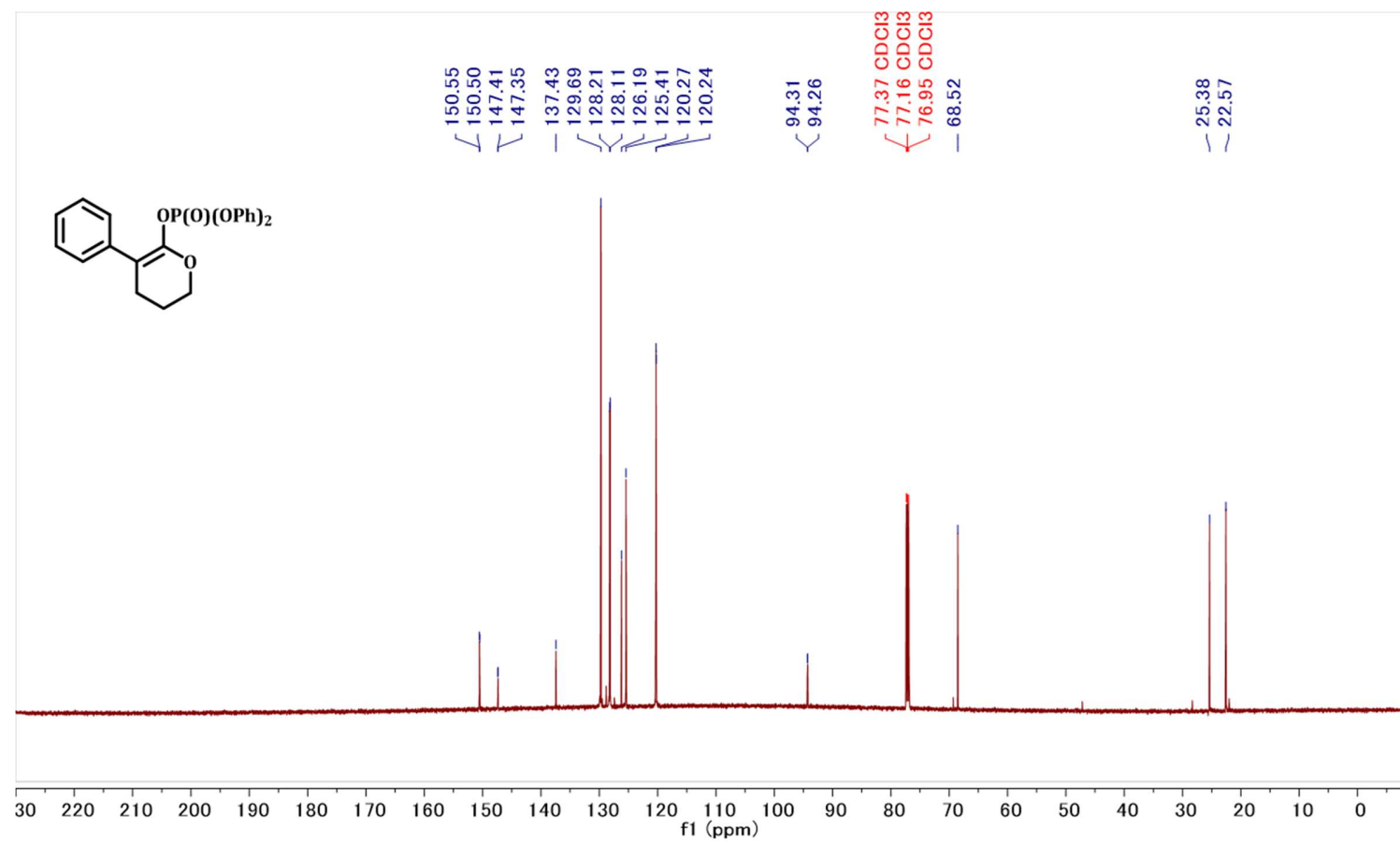
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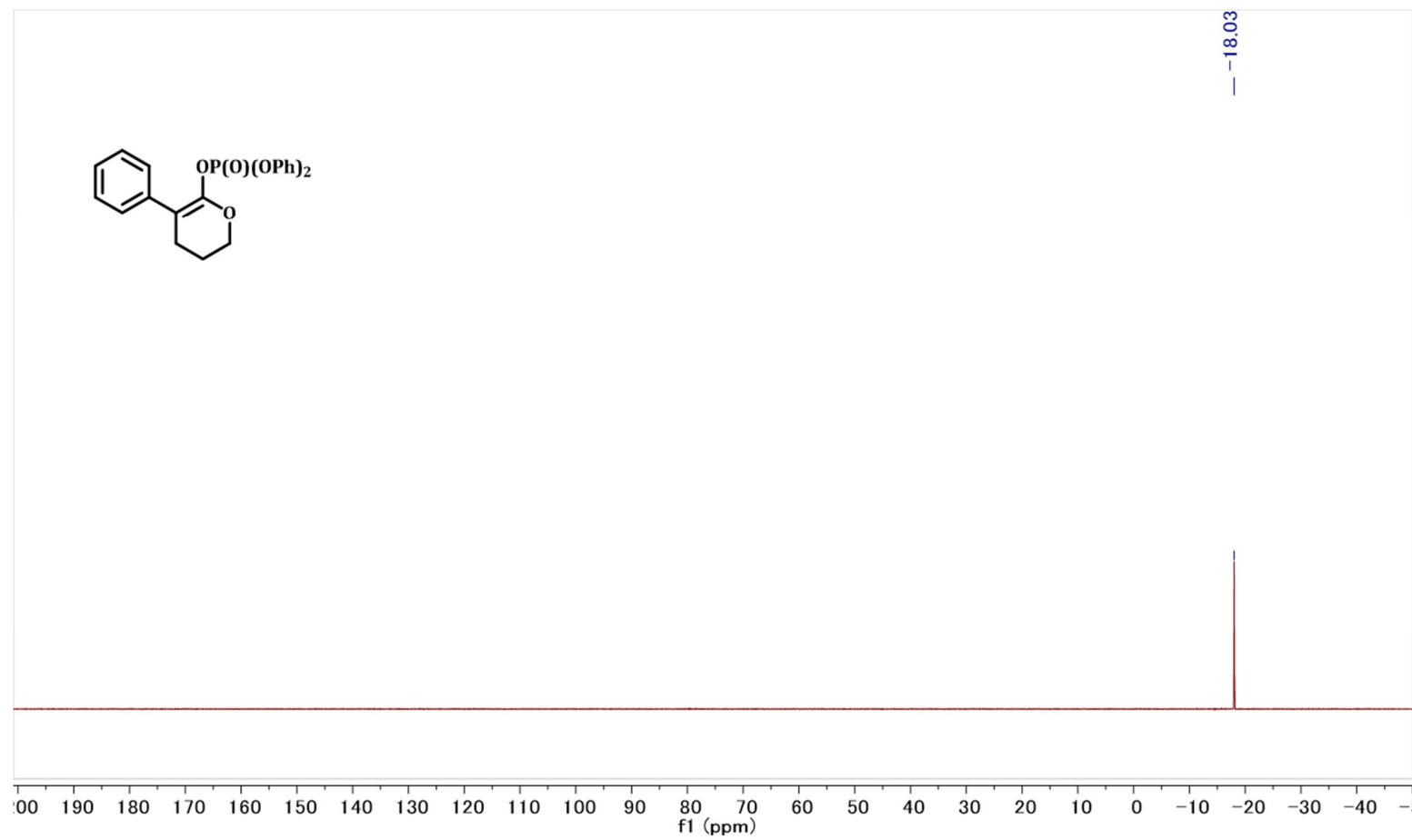
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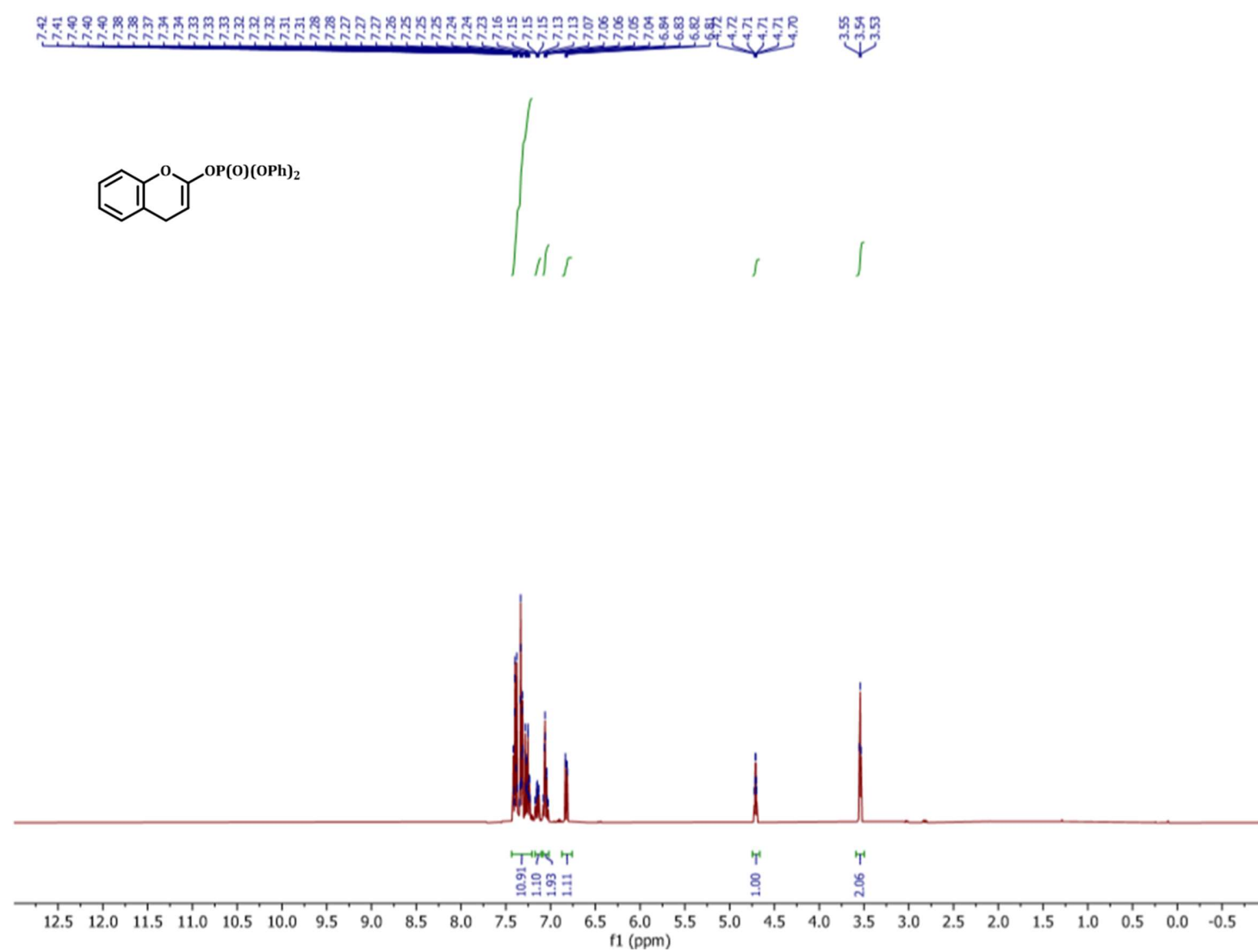
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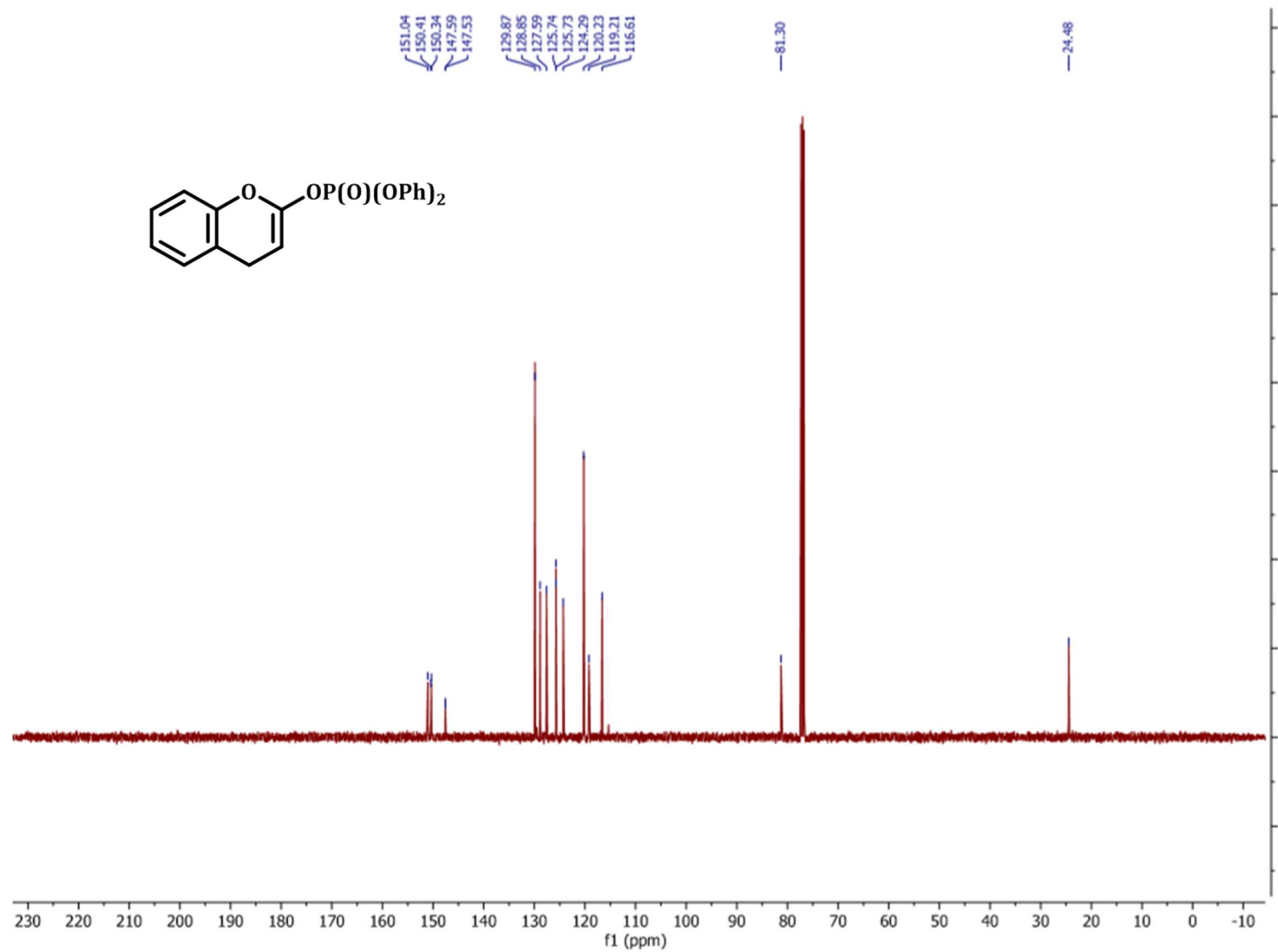
^{31}P NMR (162 MHz, CDCl_3) of compound **S37**



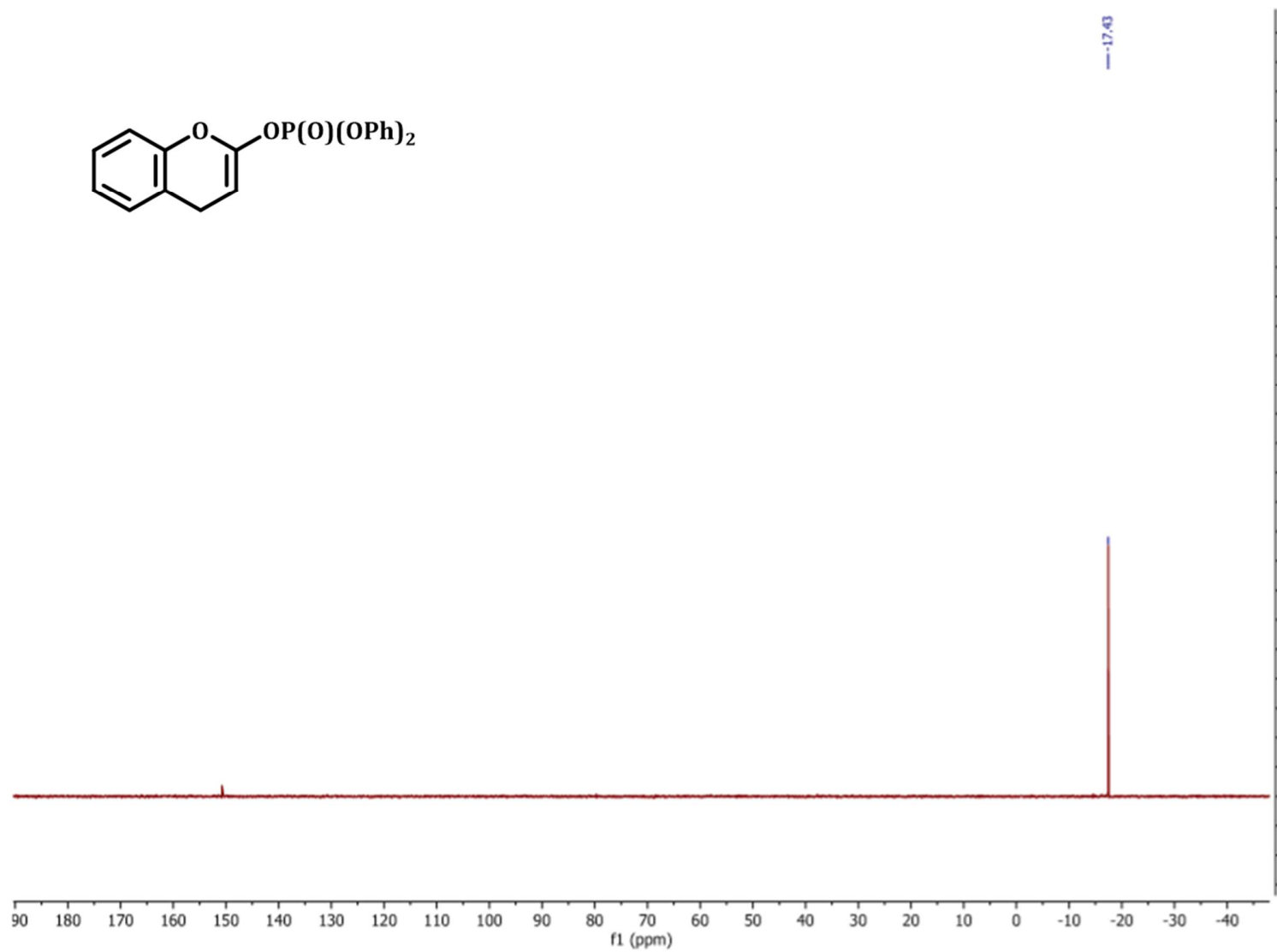
^1H NMR (400 MHz, CDCl_3) of compound **S38**



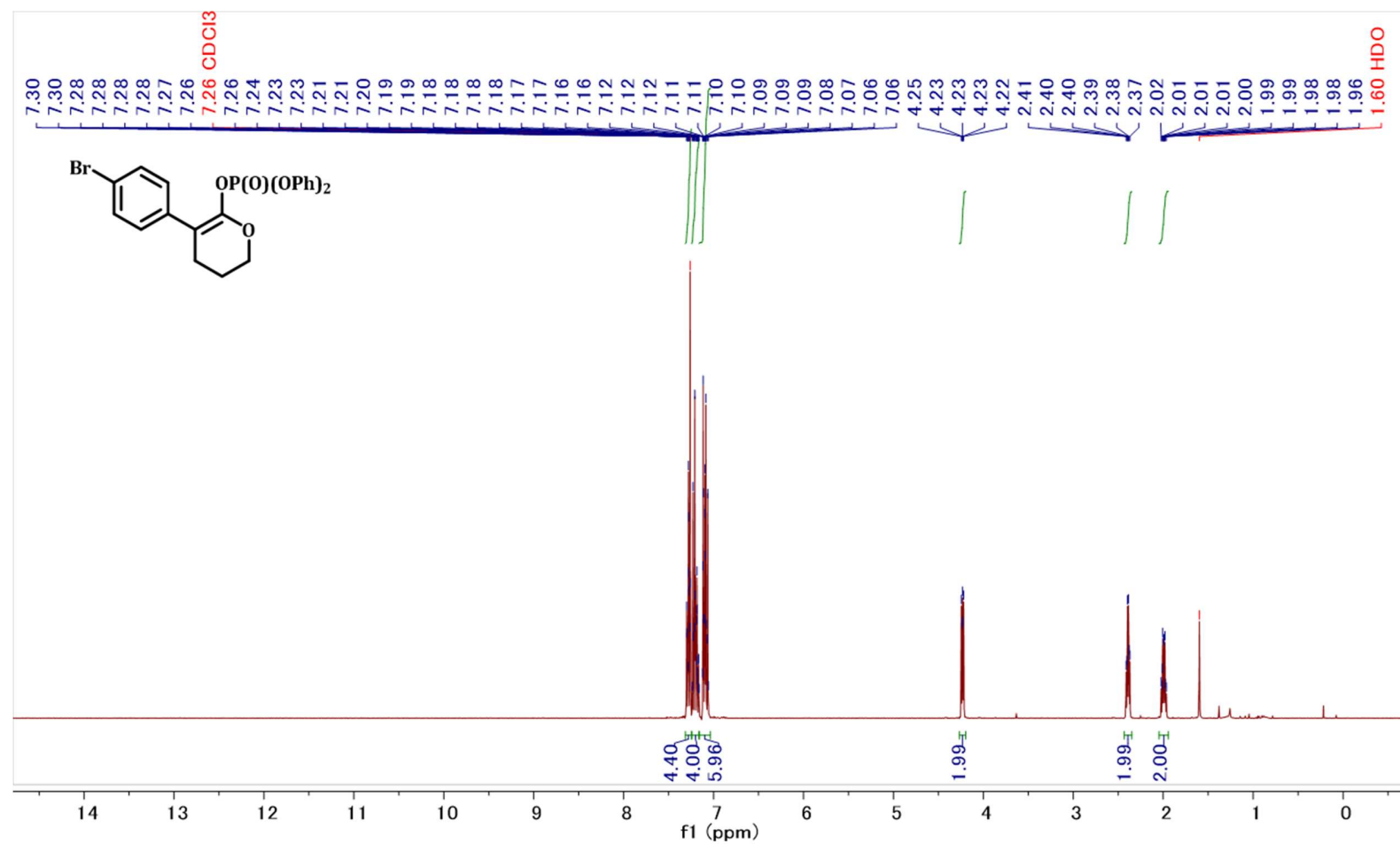
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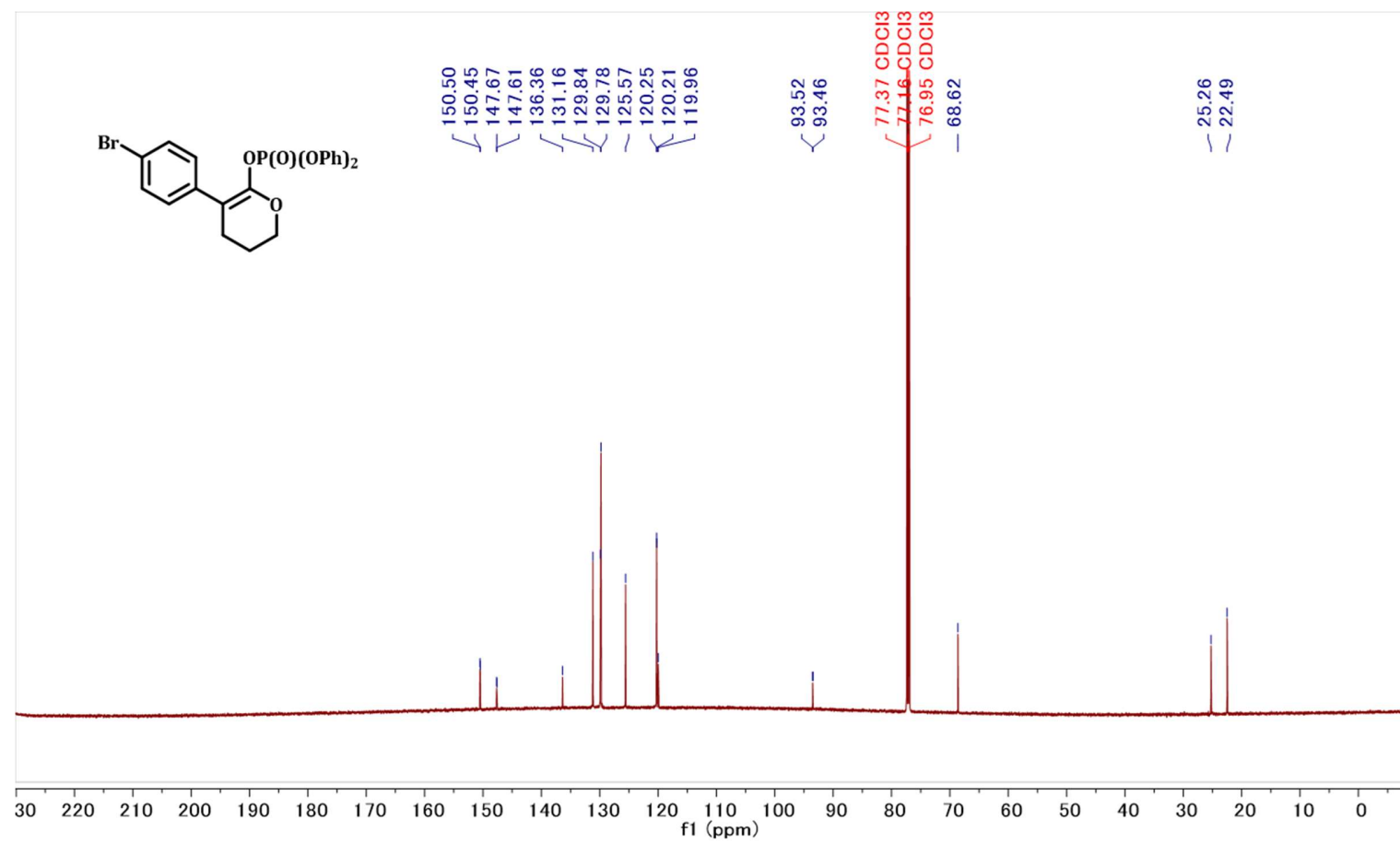
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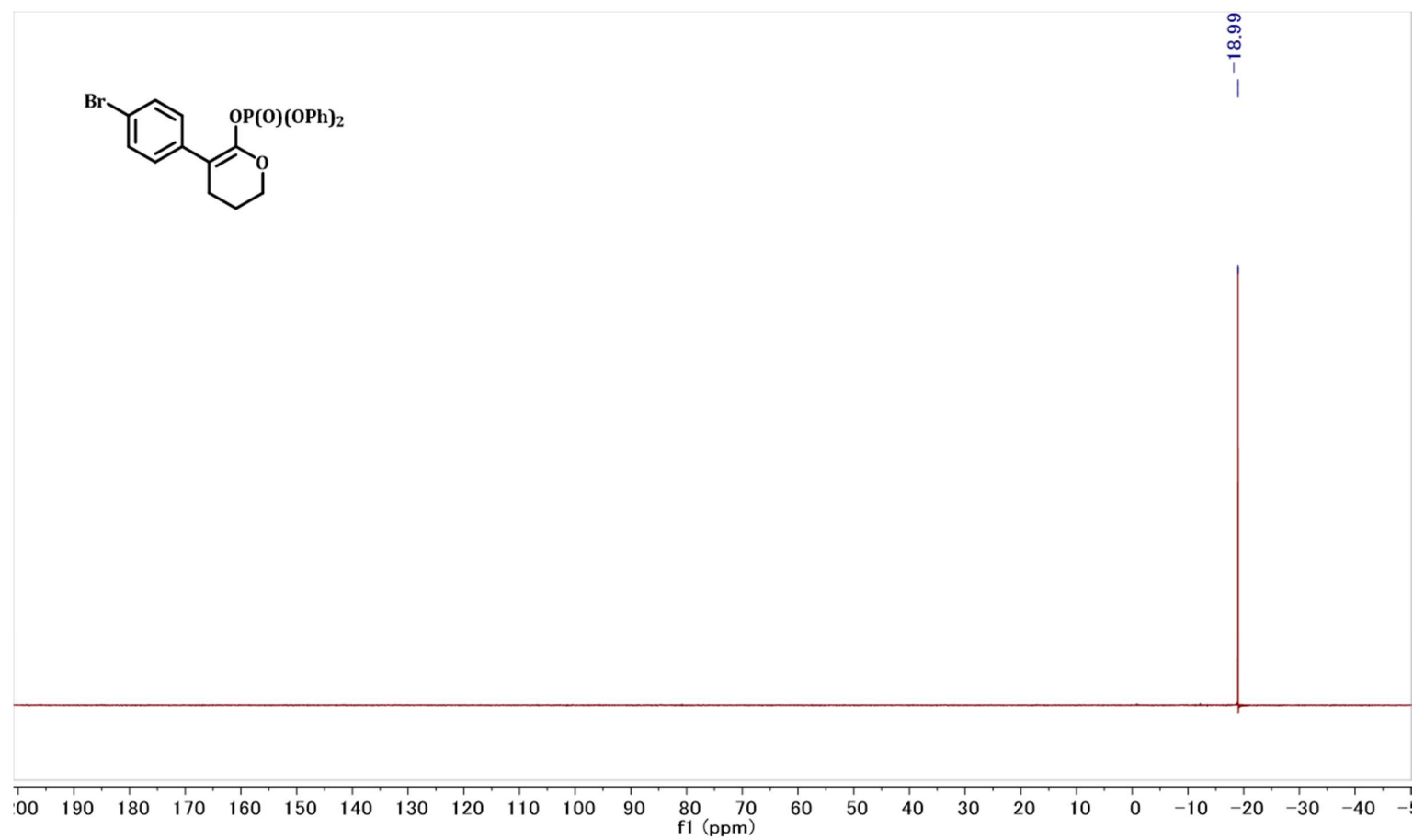
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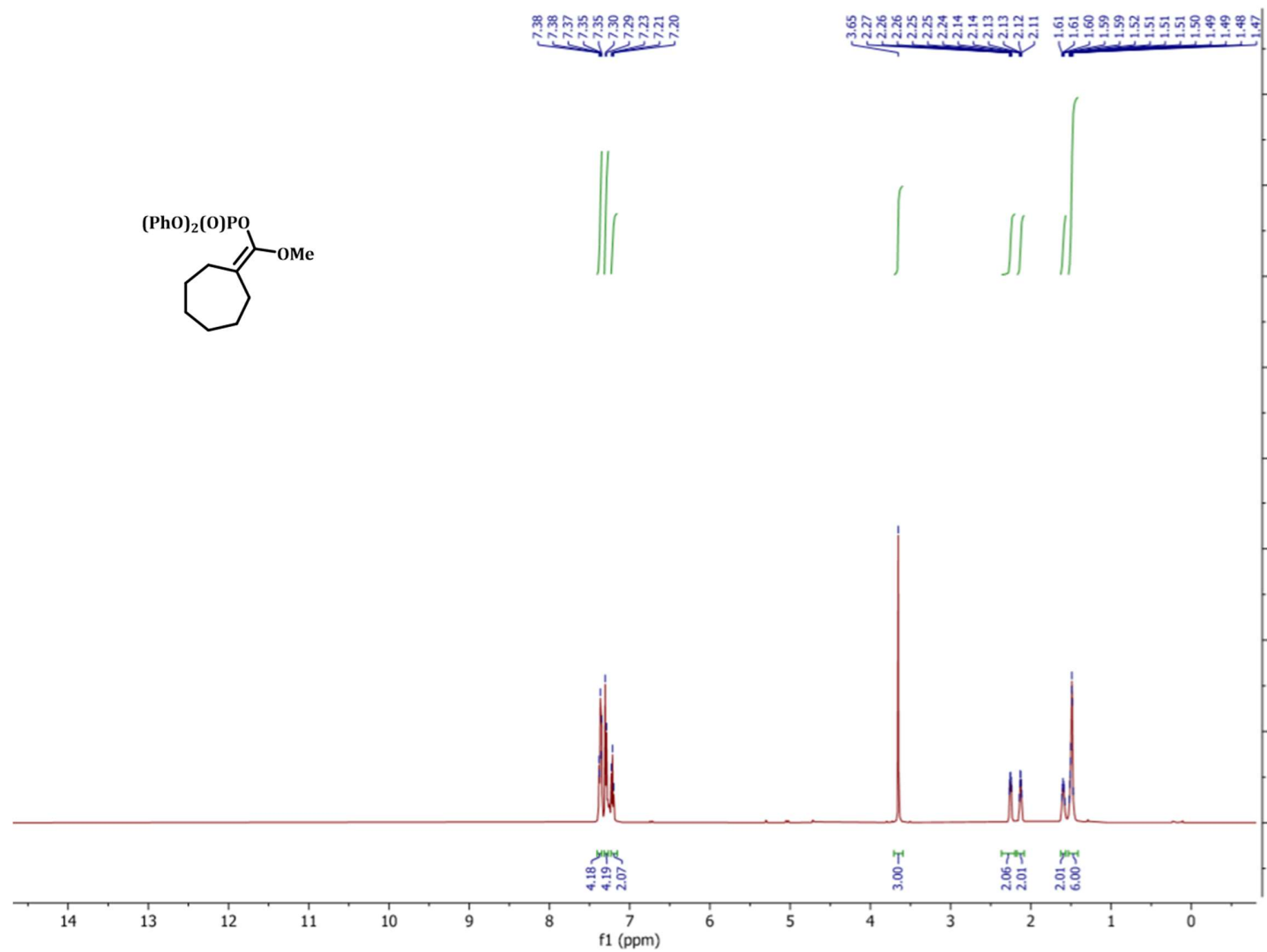
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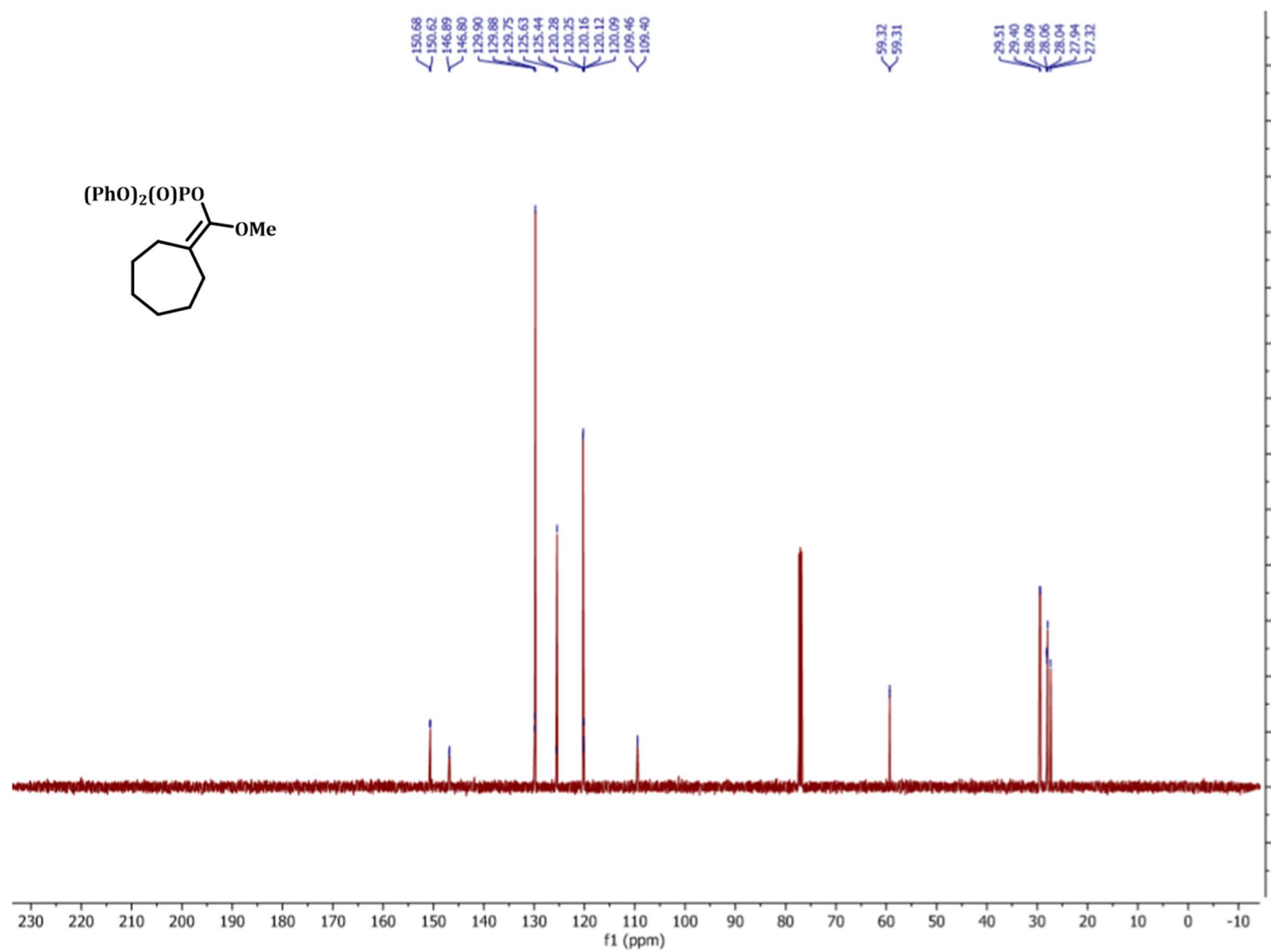
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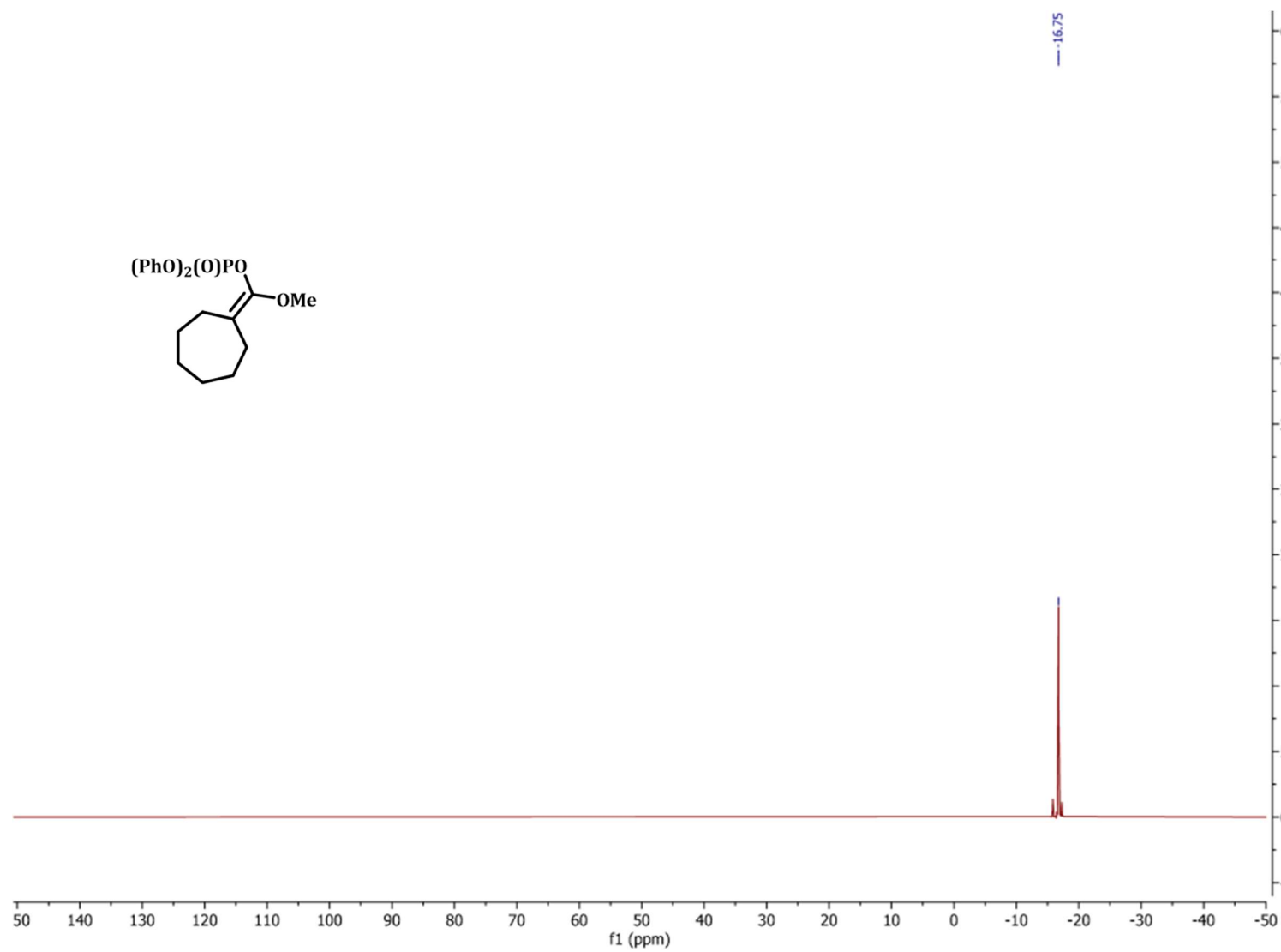
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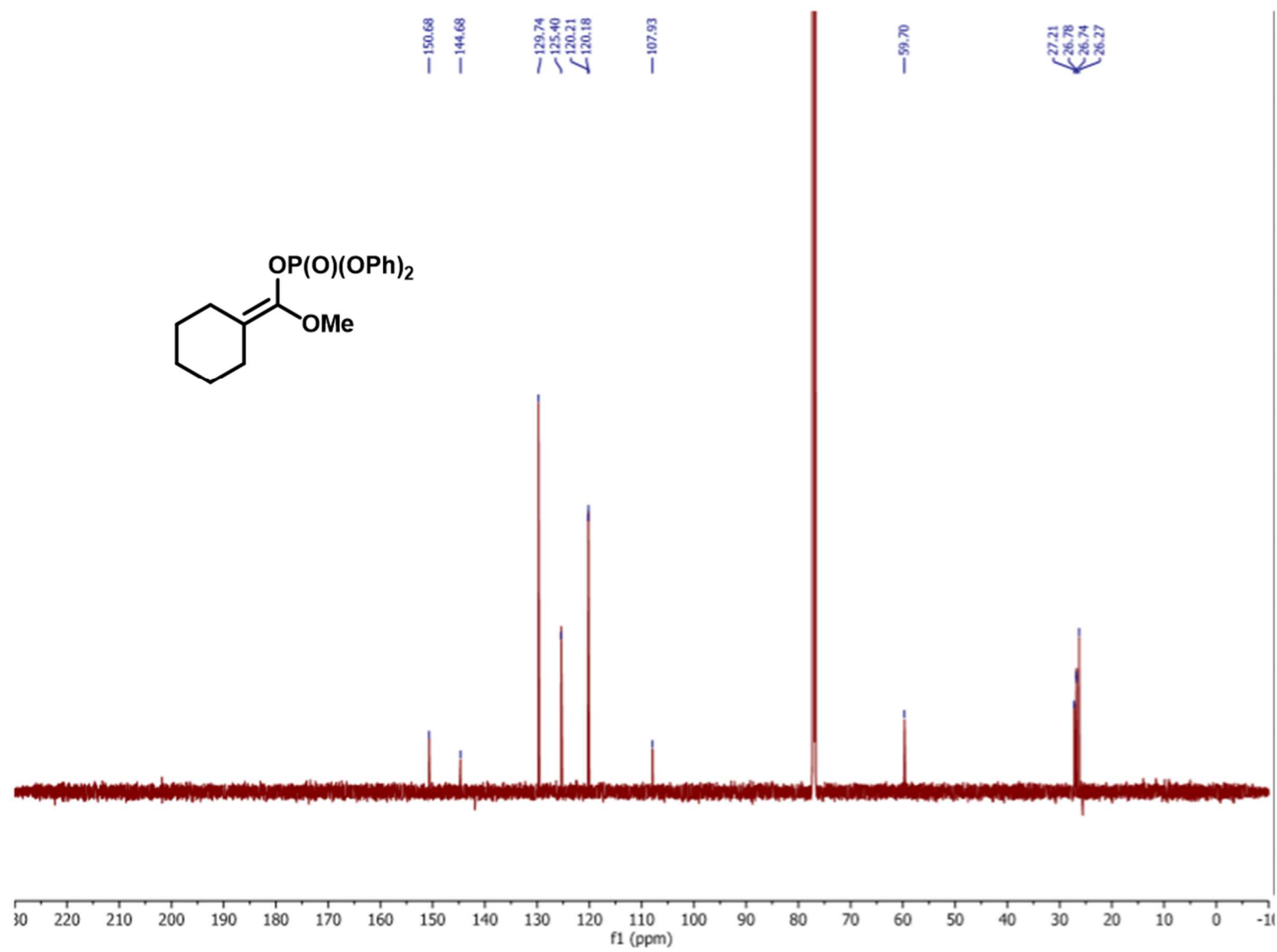
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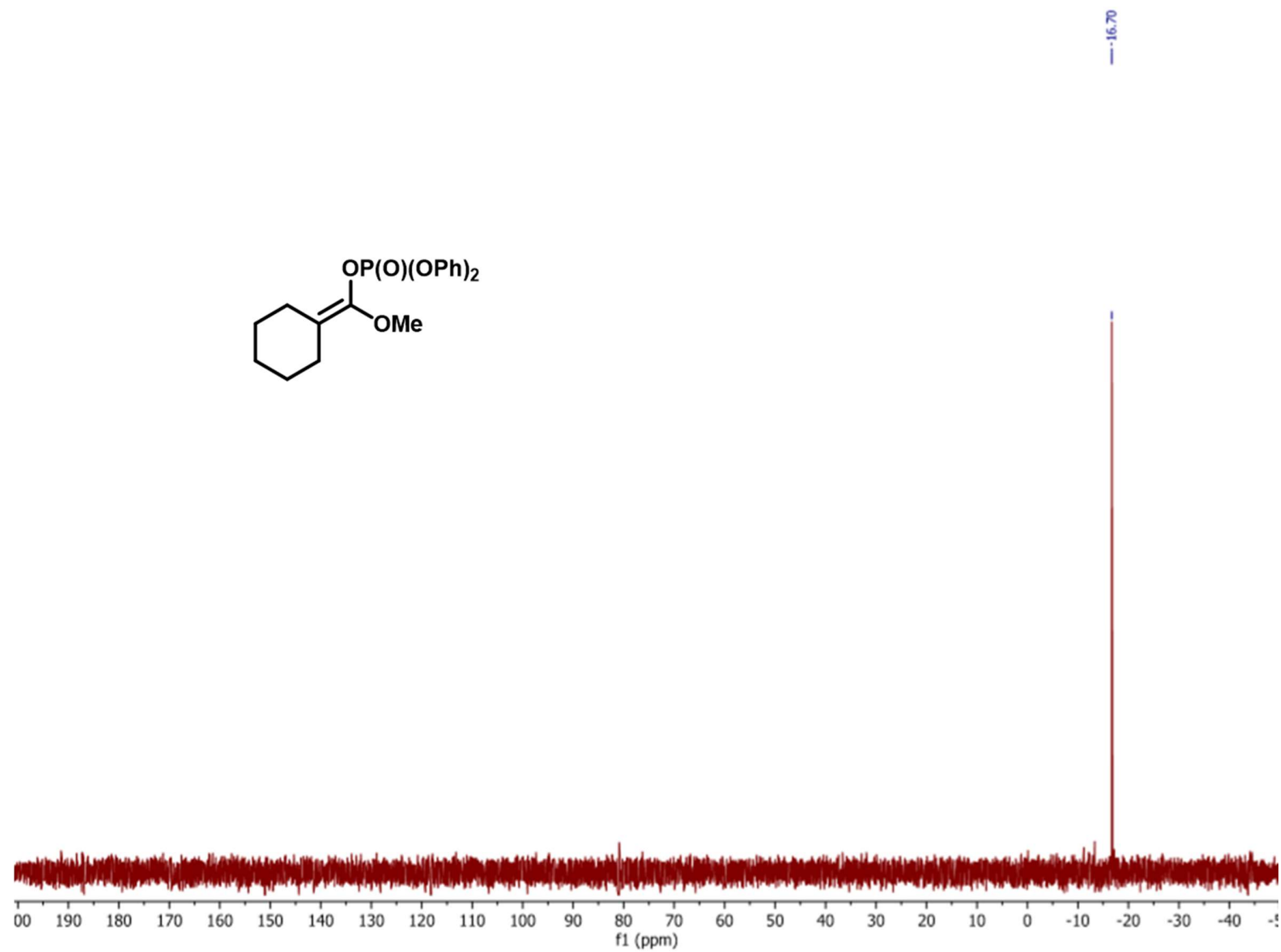
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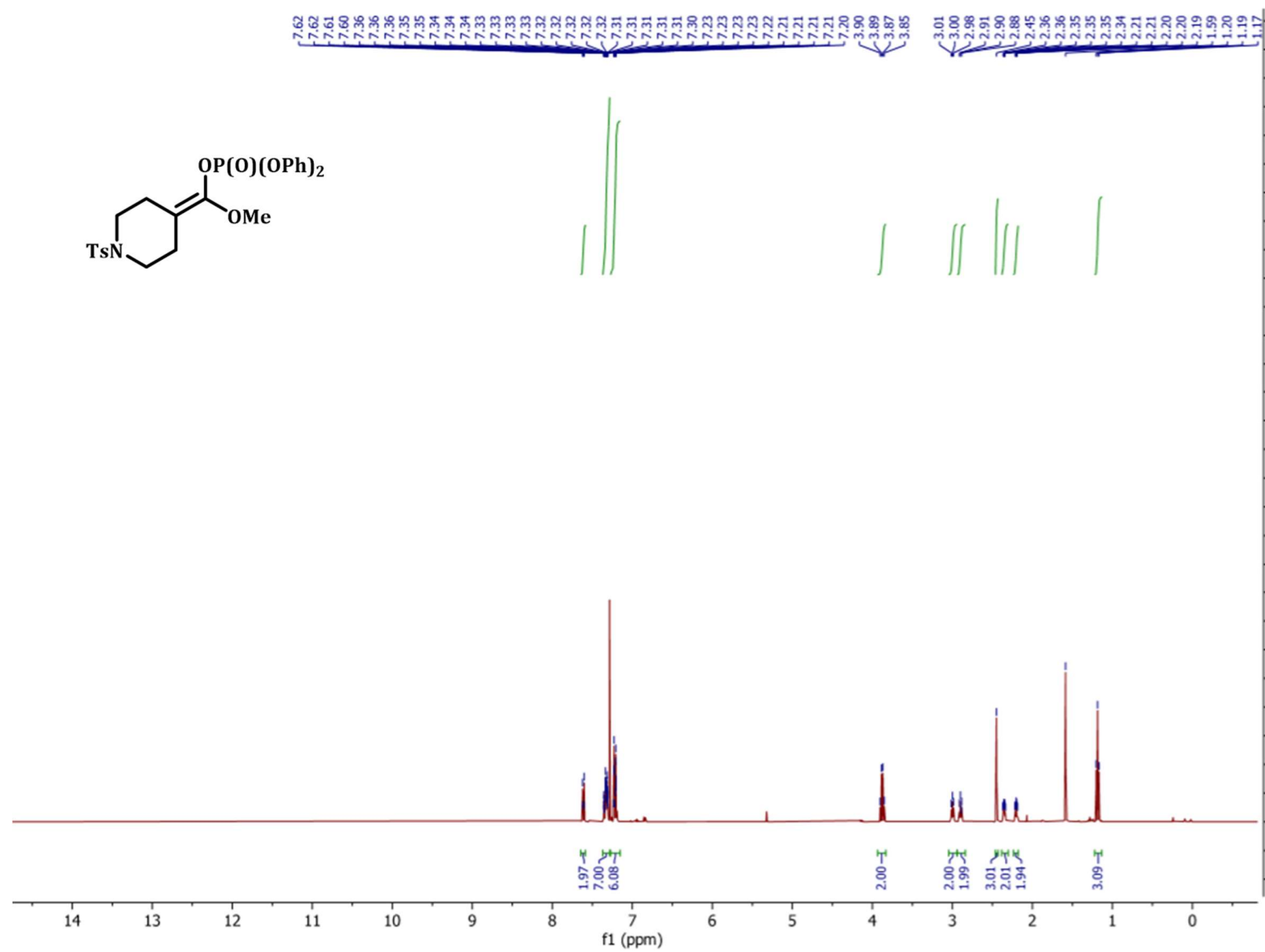
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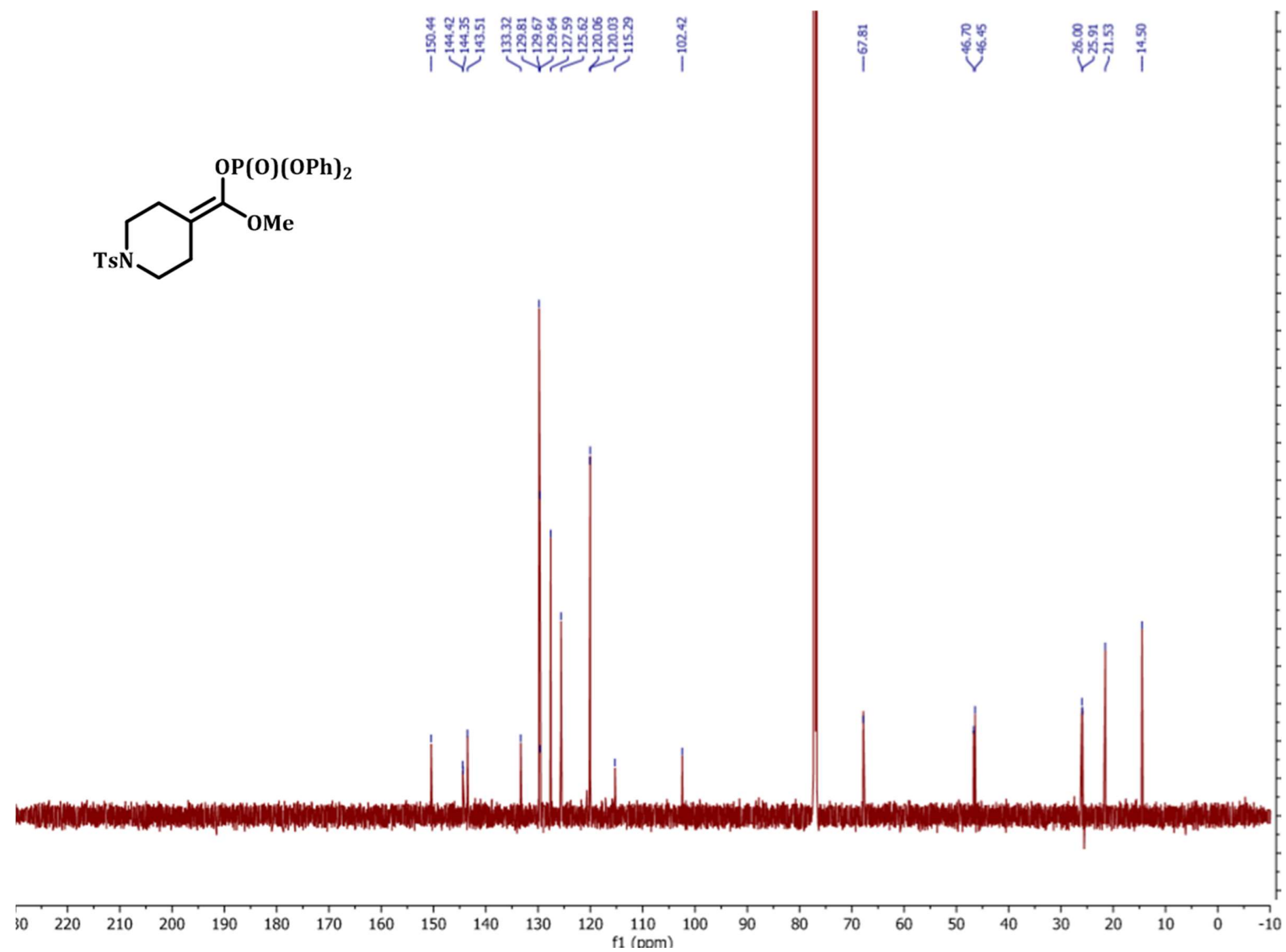
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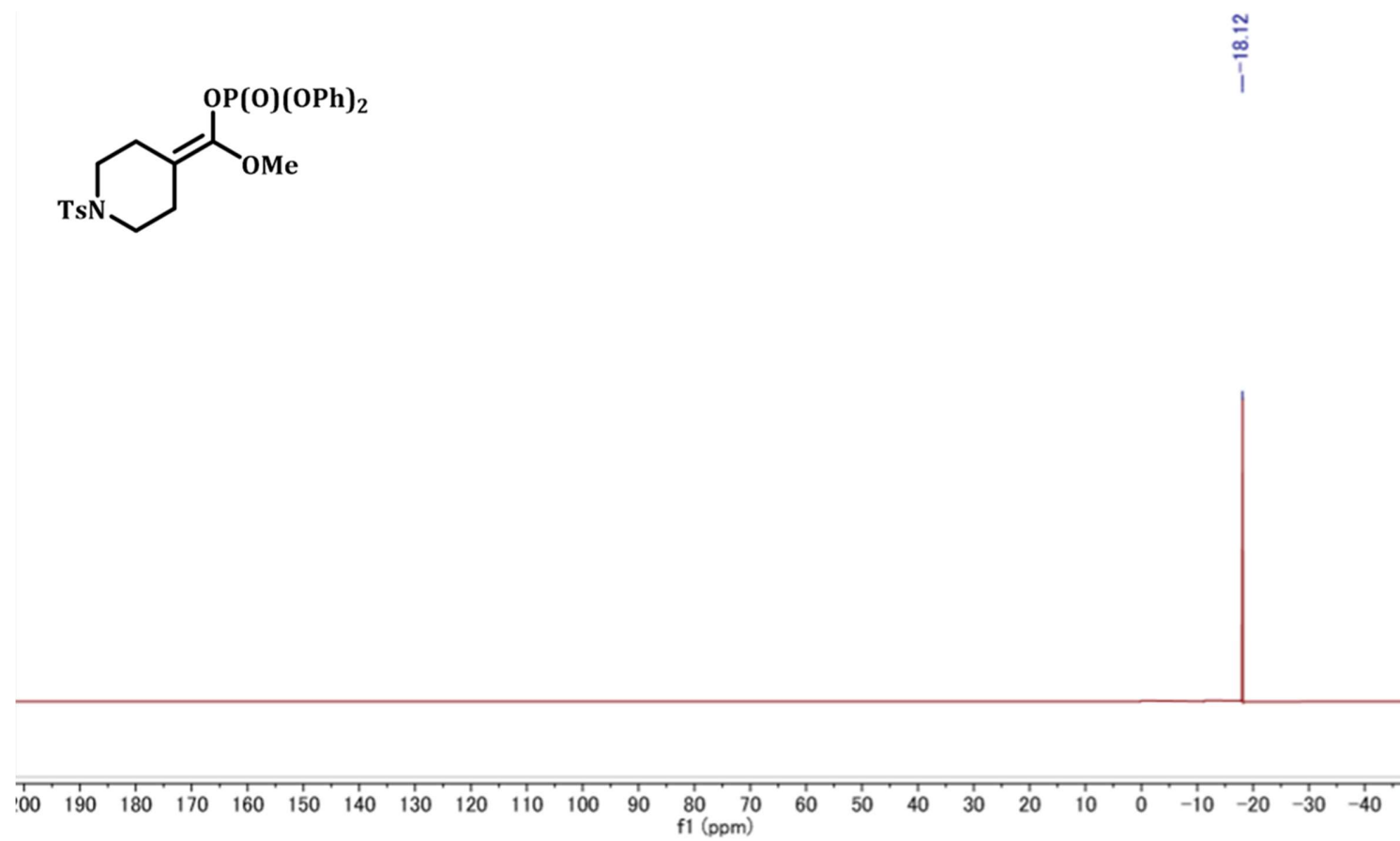
^1H NMR (400 MHz, CDCl_3) of compound **S42**



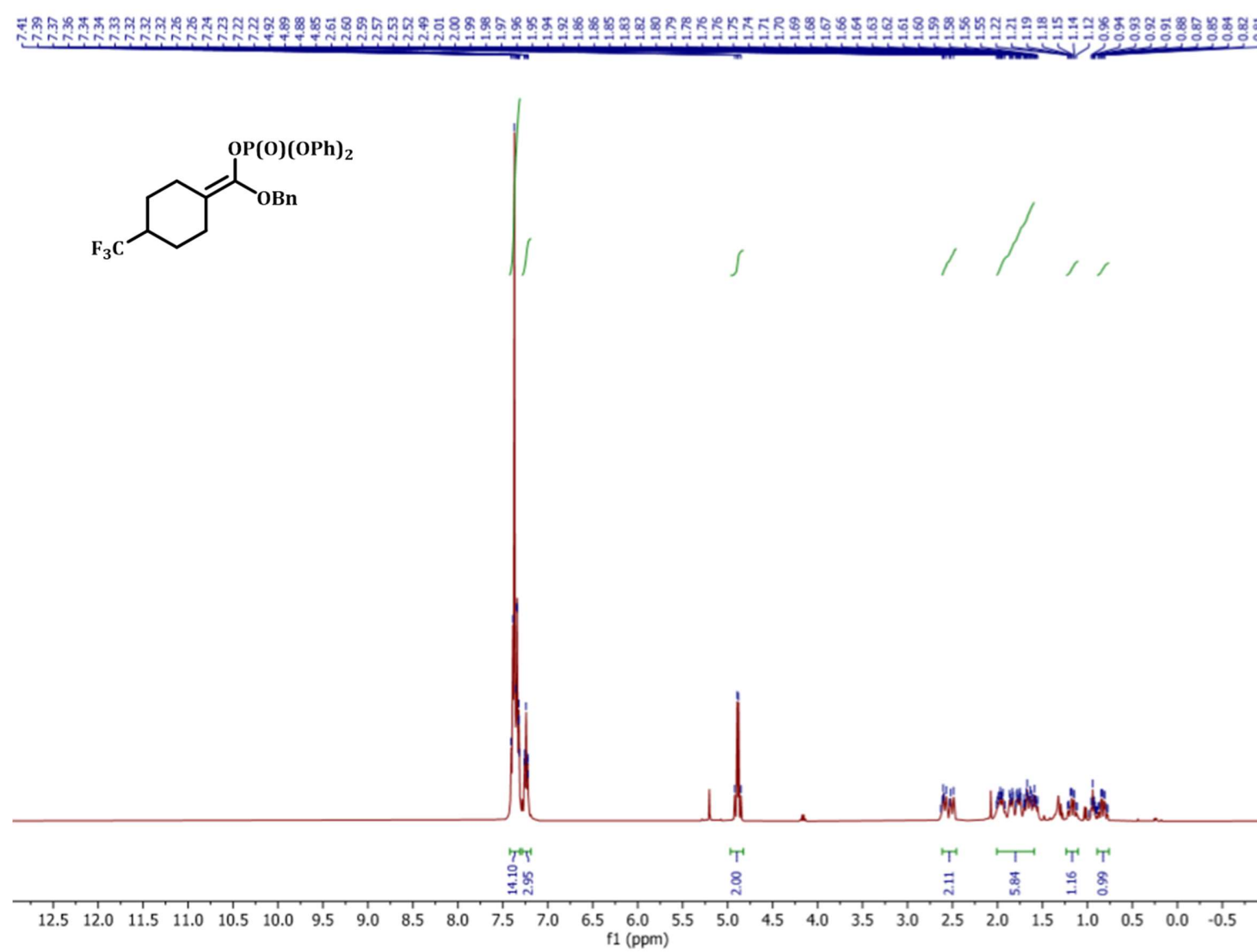
¹³CNMR (126 MHz, CDCl₃) of compound **S42**



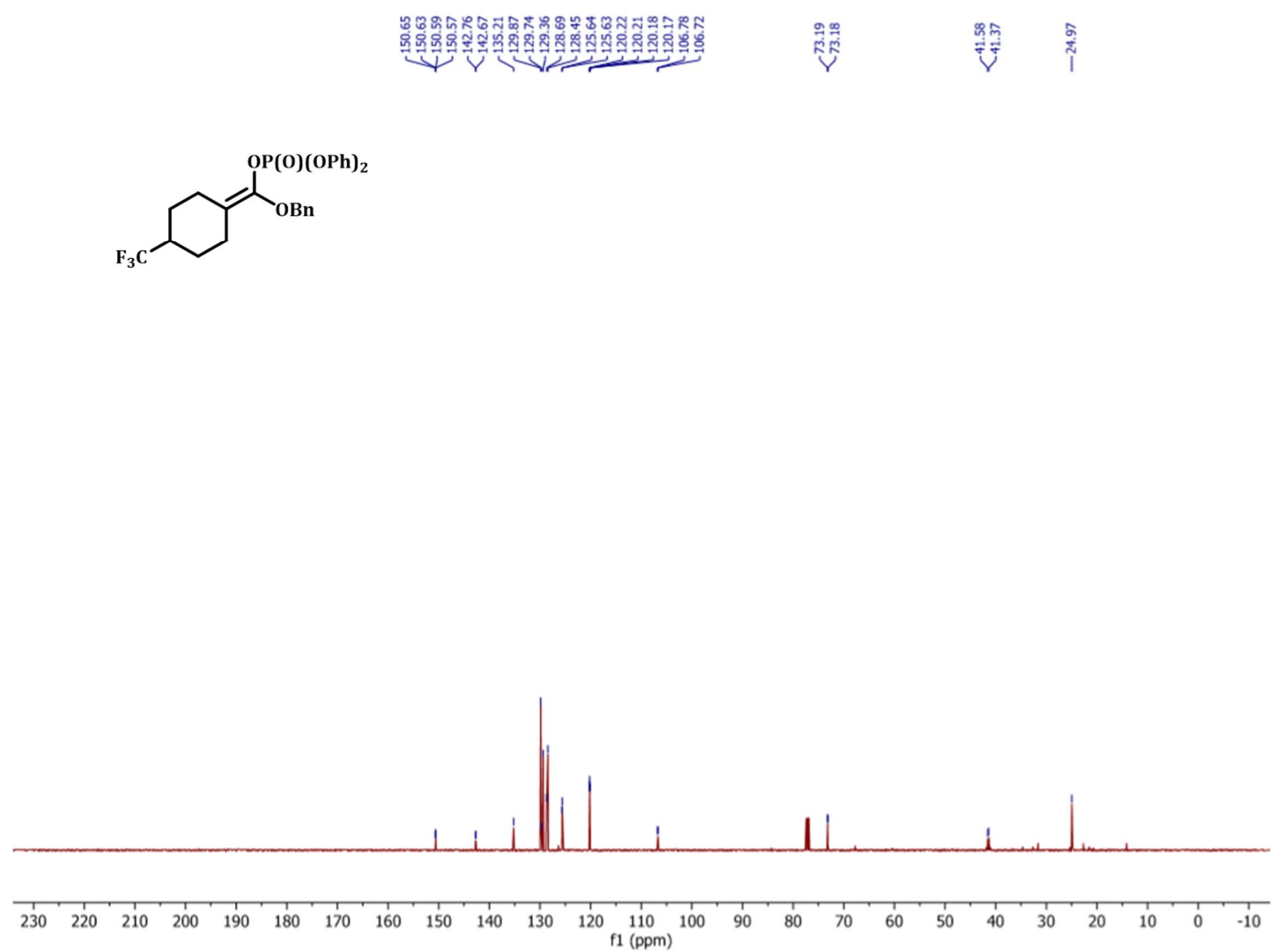
^{31}P NMR (162 MHz, CDCl_3) of compound **S42**



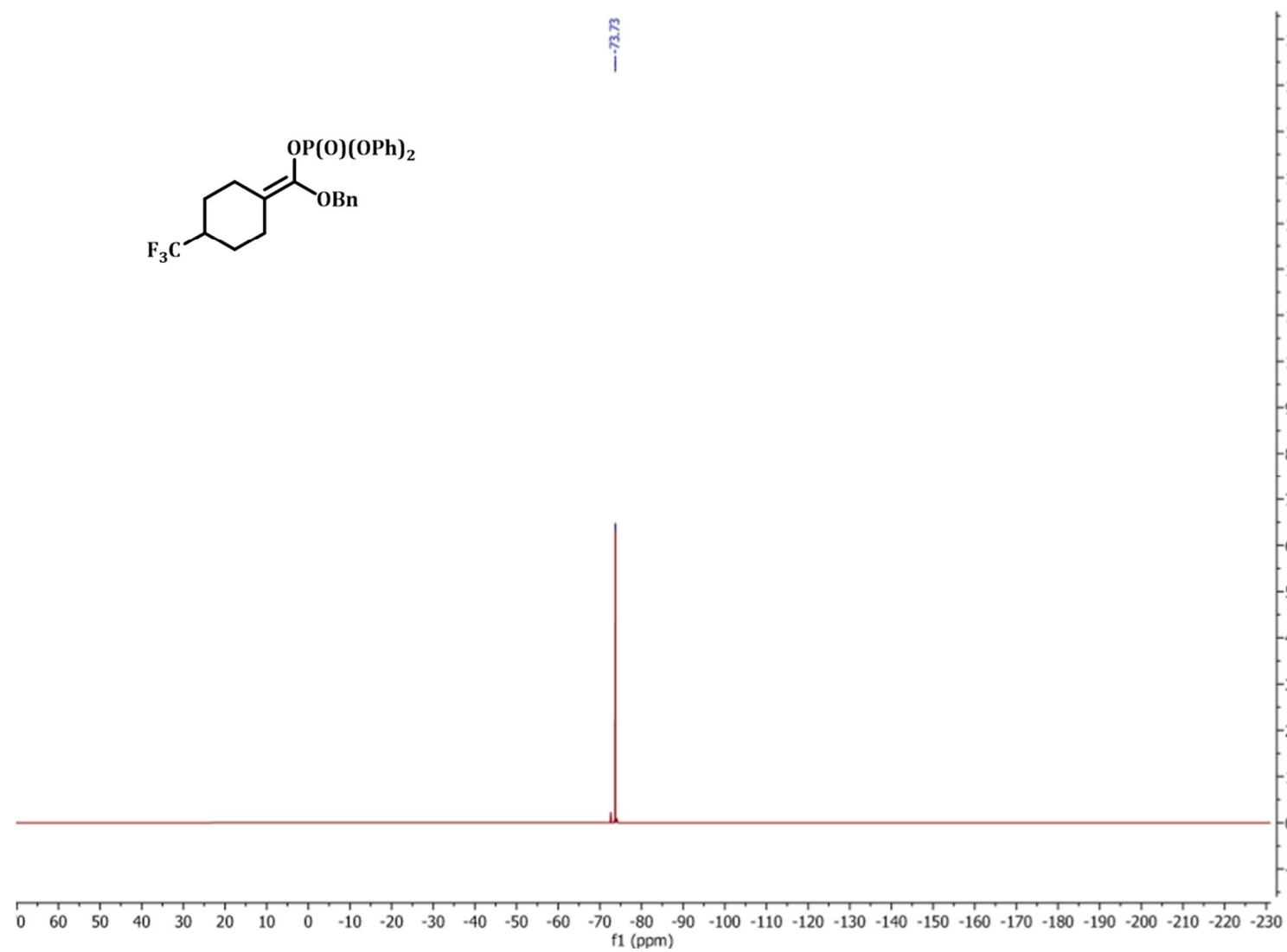
^1H NMR (400 MHz, CDCl_3) of compound **S43**



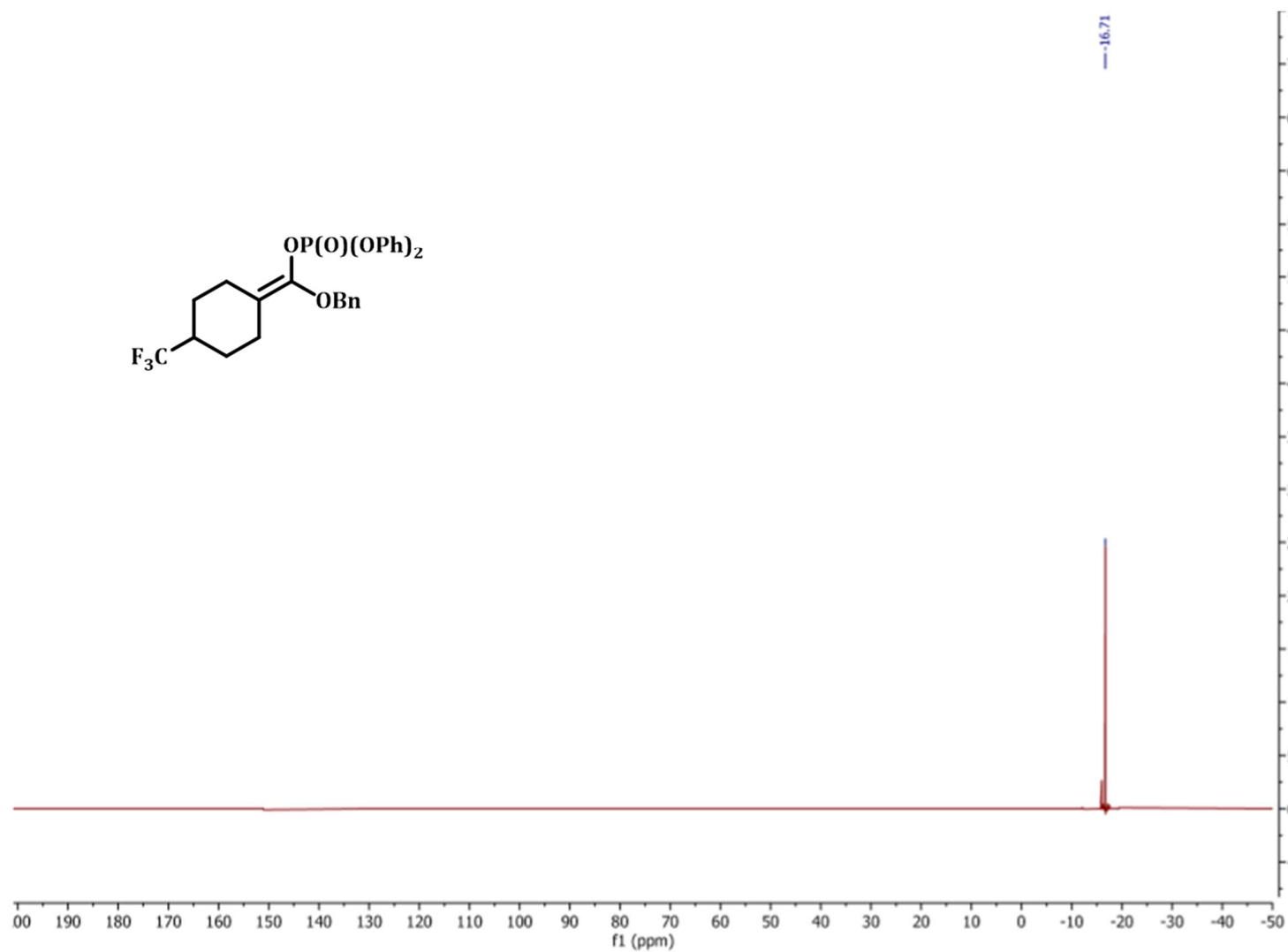
^{13}C NMR (126 MHz, CDCl_3) of compound **S43**



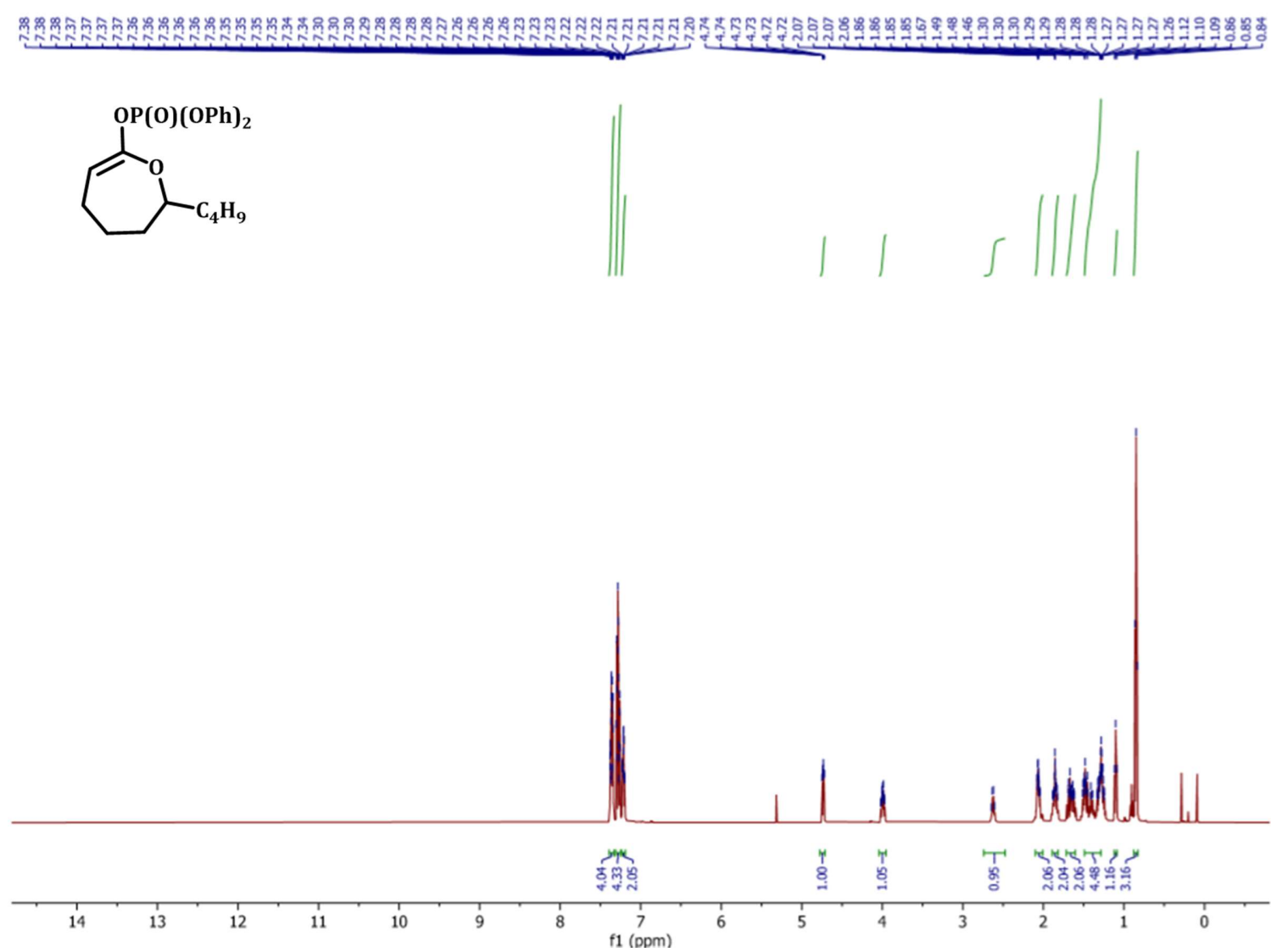
^{19}F NMR (376 MHz, CDCl_3) of compound **S43**



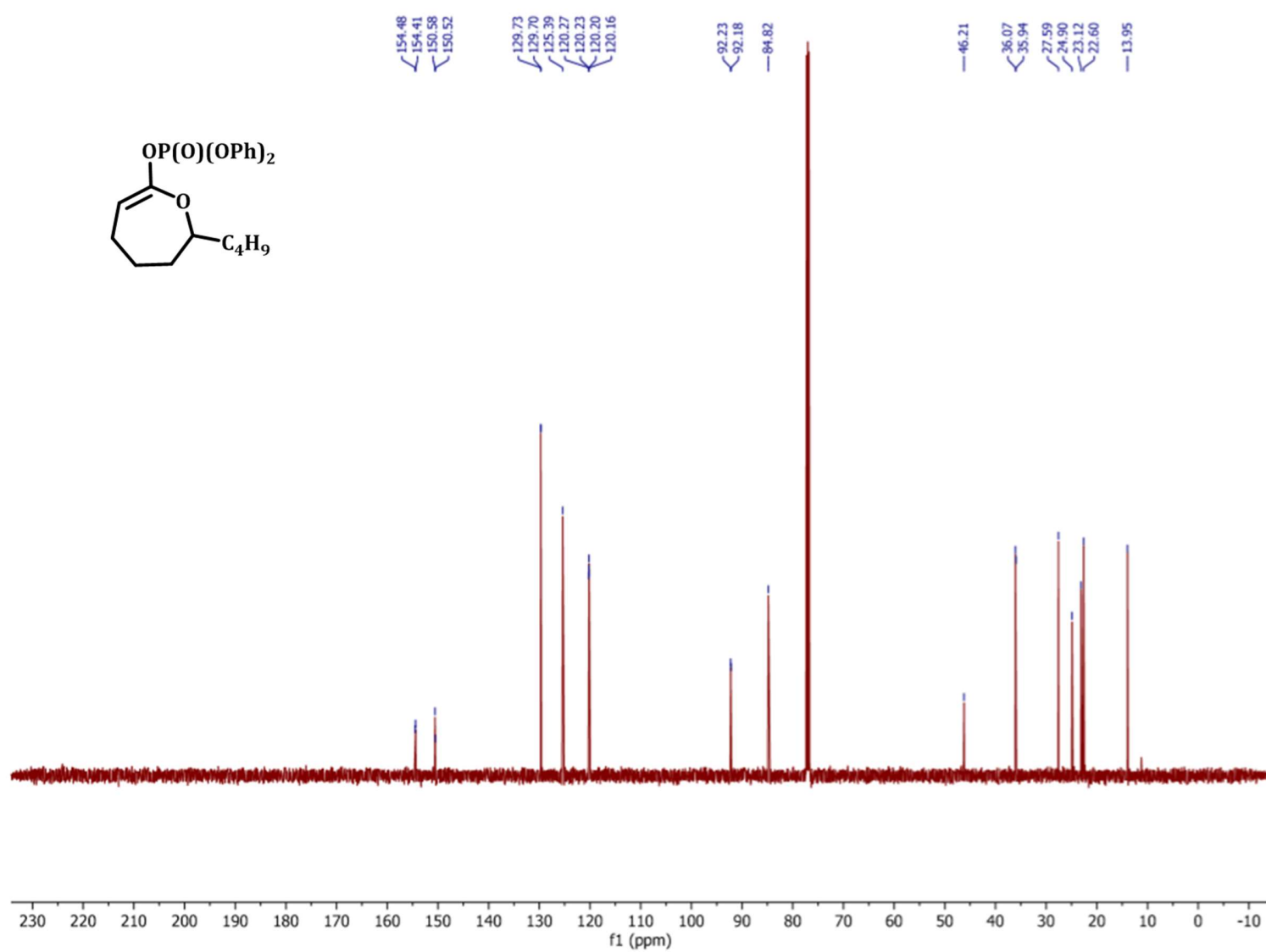
^{31}P NMR (162 MHz, CDCl_3) of compound **S43**



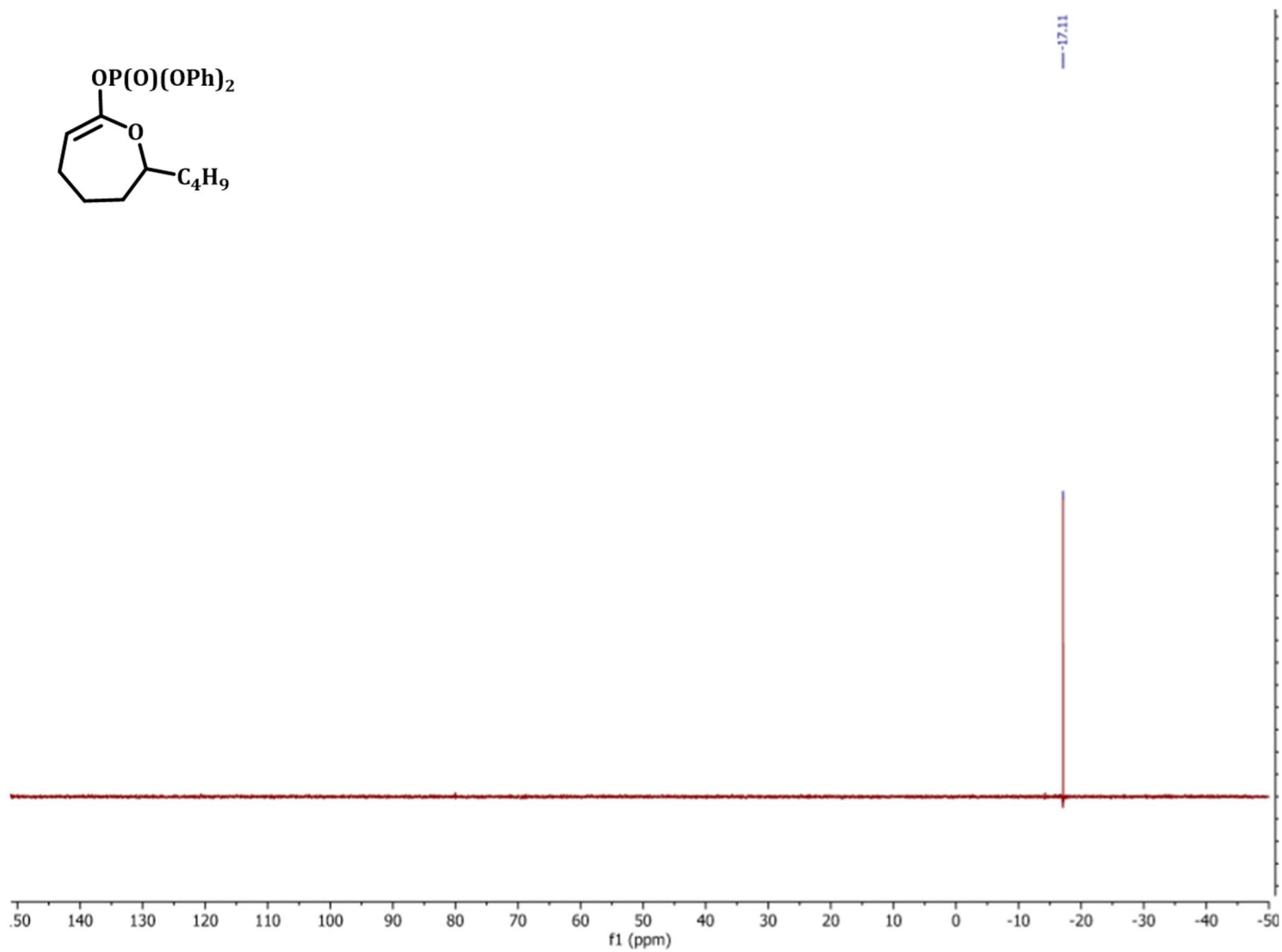
^1H NMR (500 MHz, CDCl_3) of compound **S44**



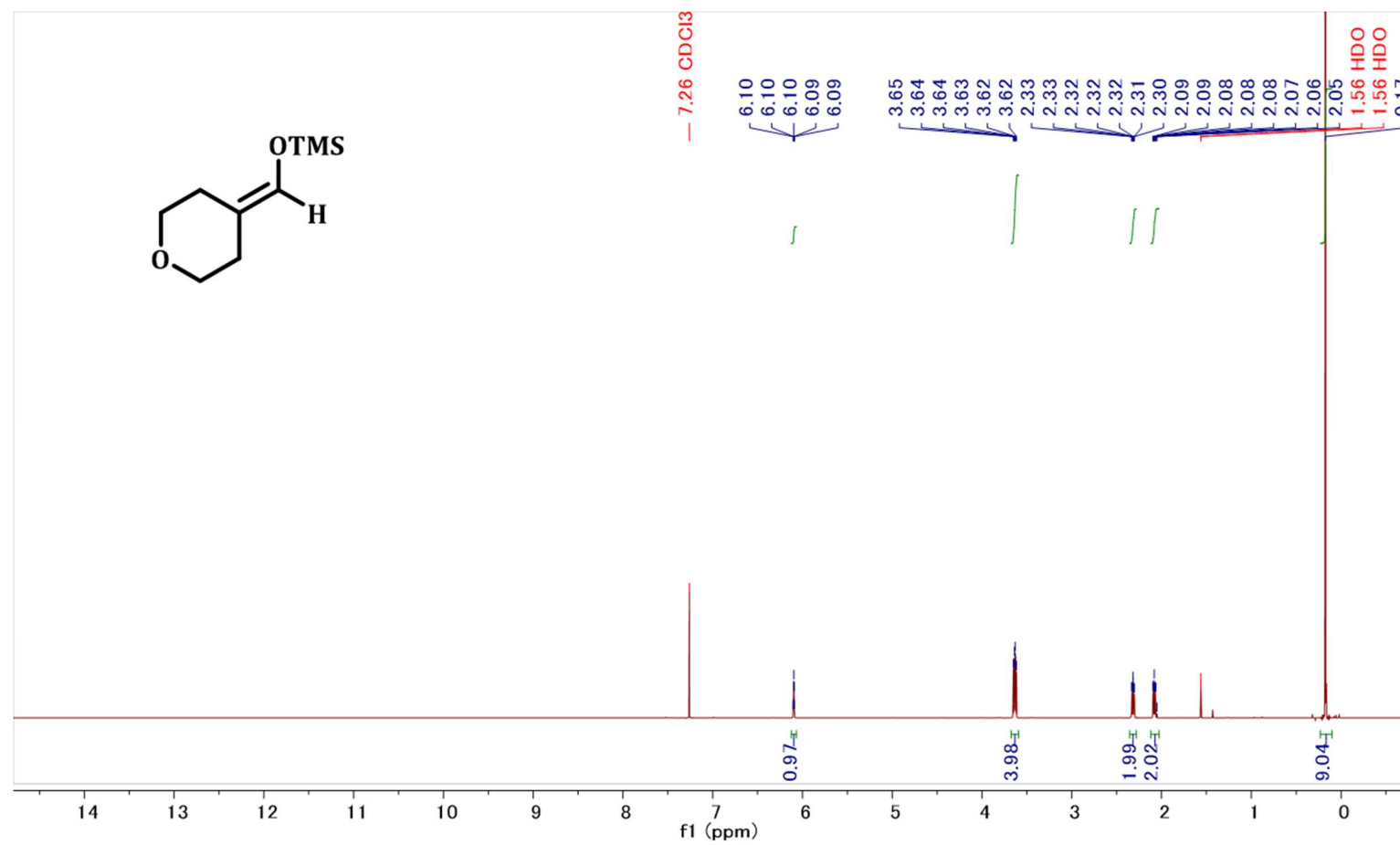
^{13}C NMR (126 MHz, CDCl_3) of compound **S44**



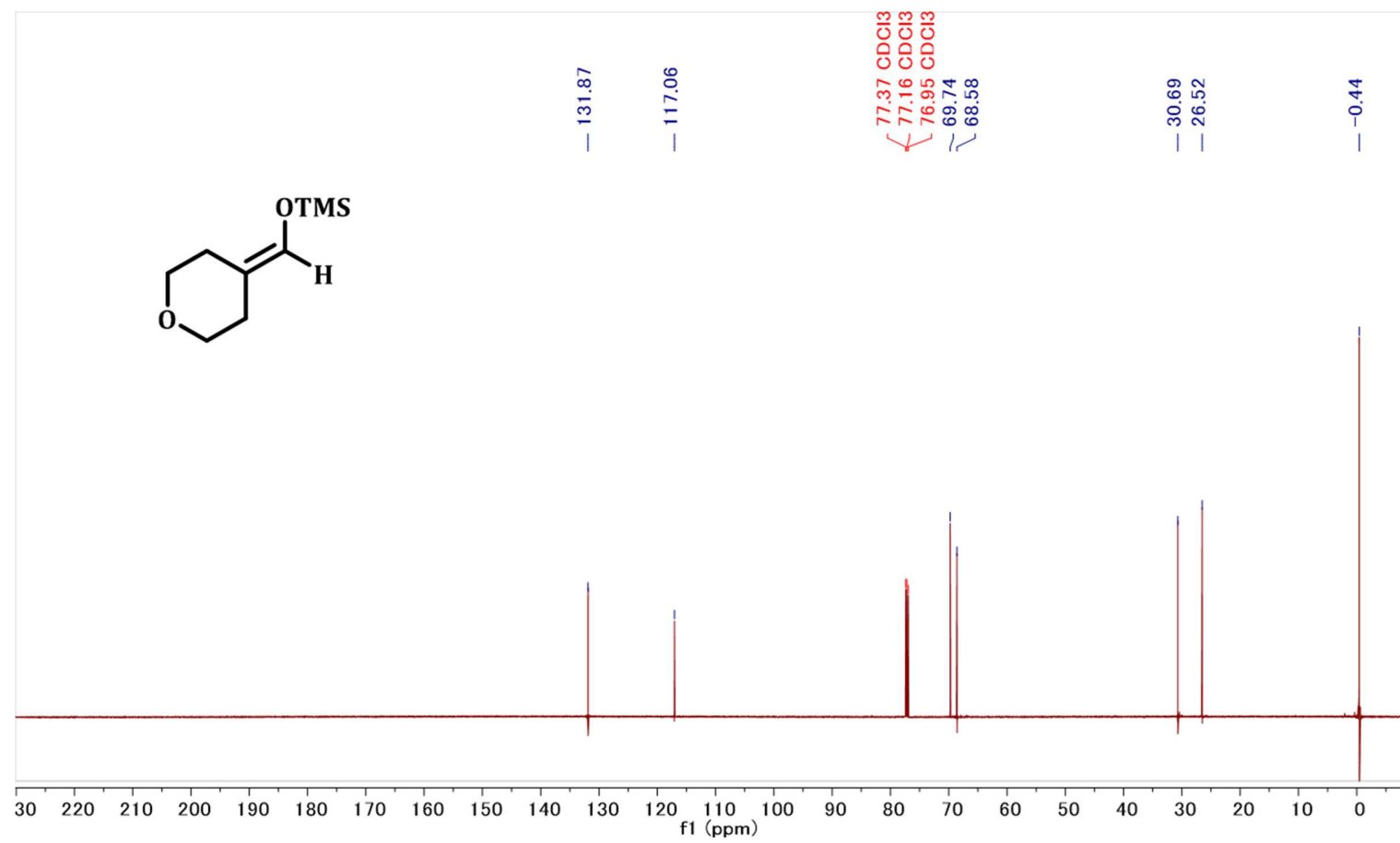
^{31}P NMR (162 MHz, CDCl_3) of compound **S44**



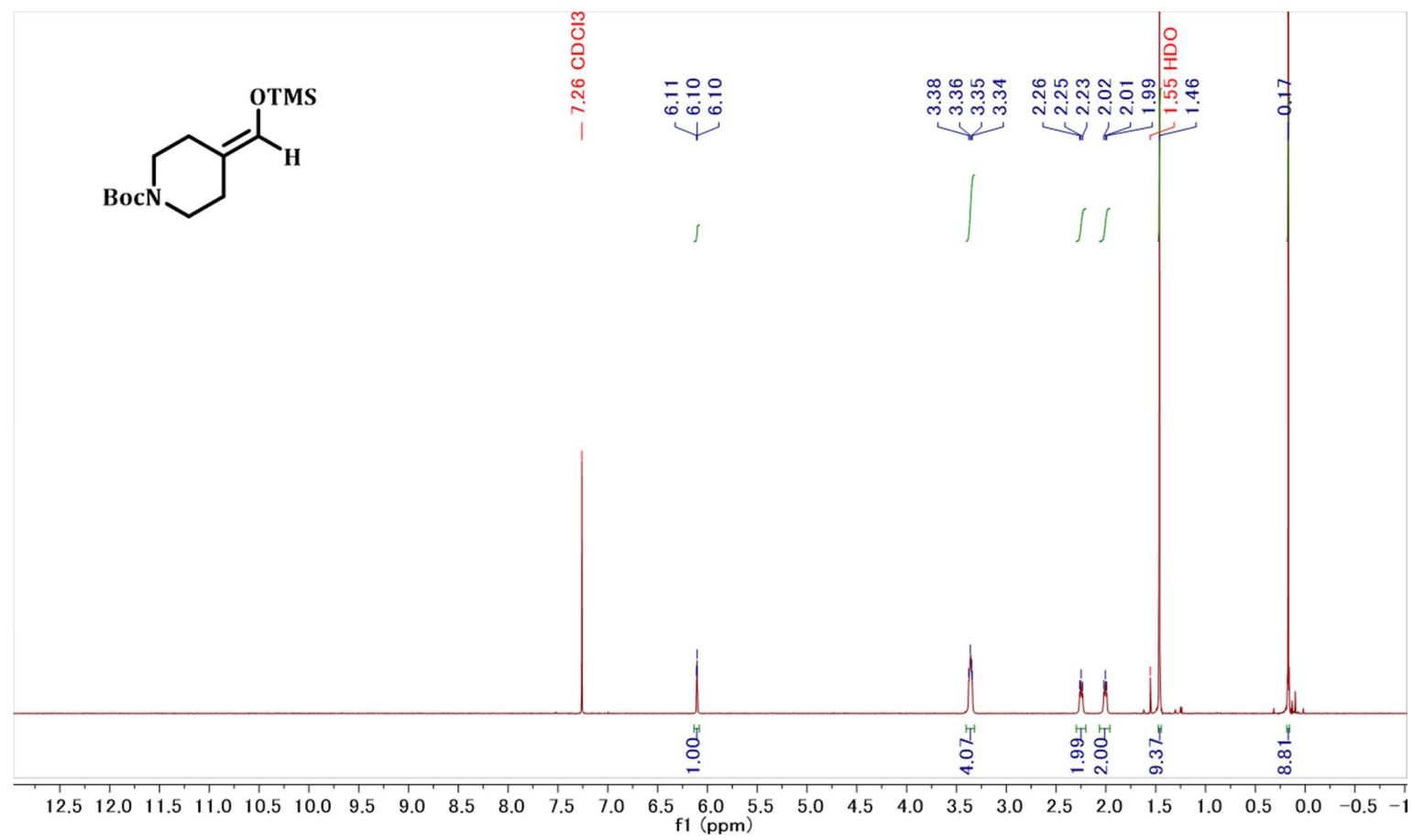
^1H NMR (400 MHz, CDCl_3) of compound **S45**



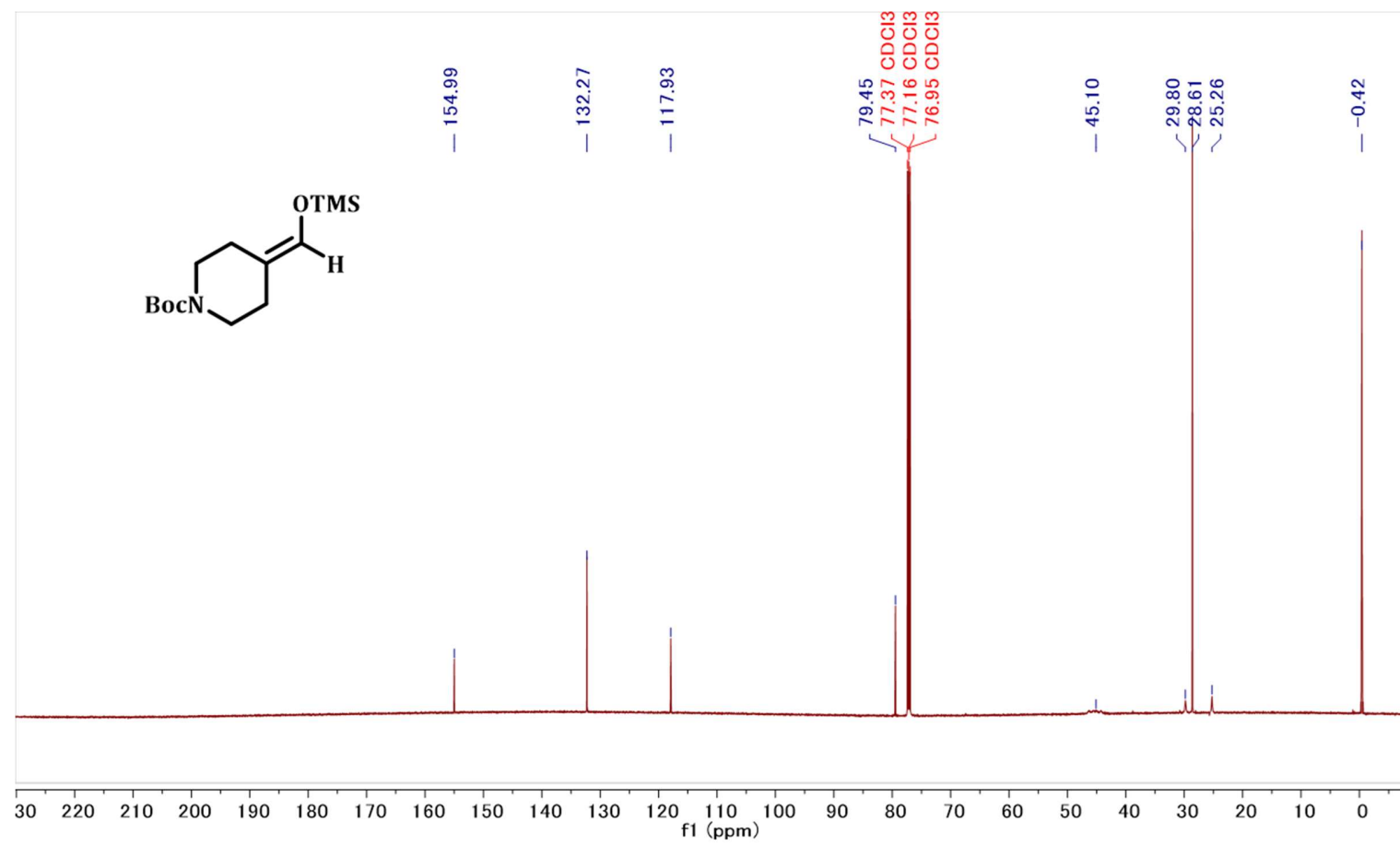
^{13}C NMR (151 MHz, CDCl_3) of compound **S45**



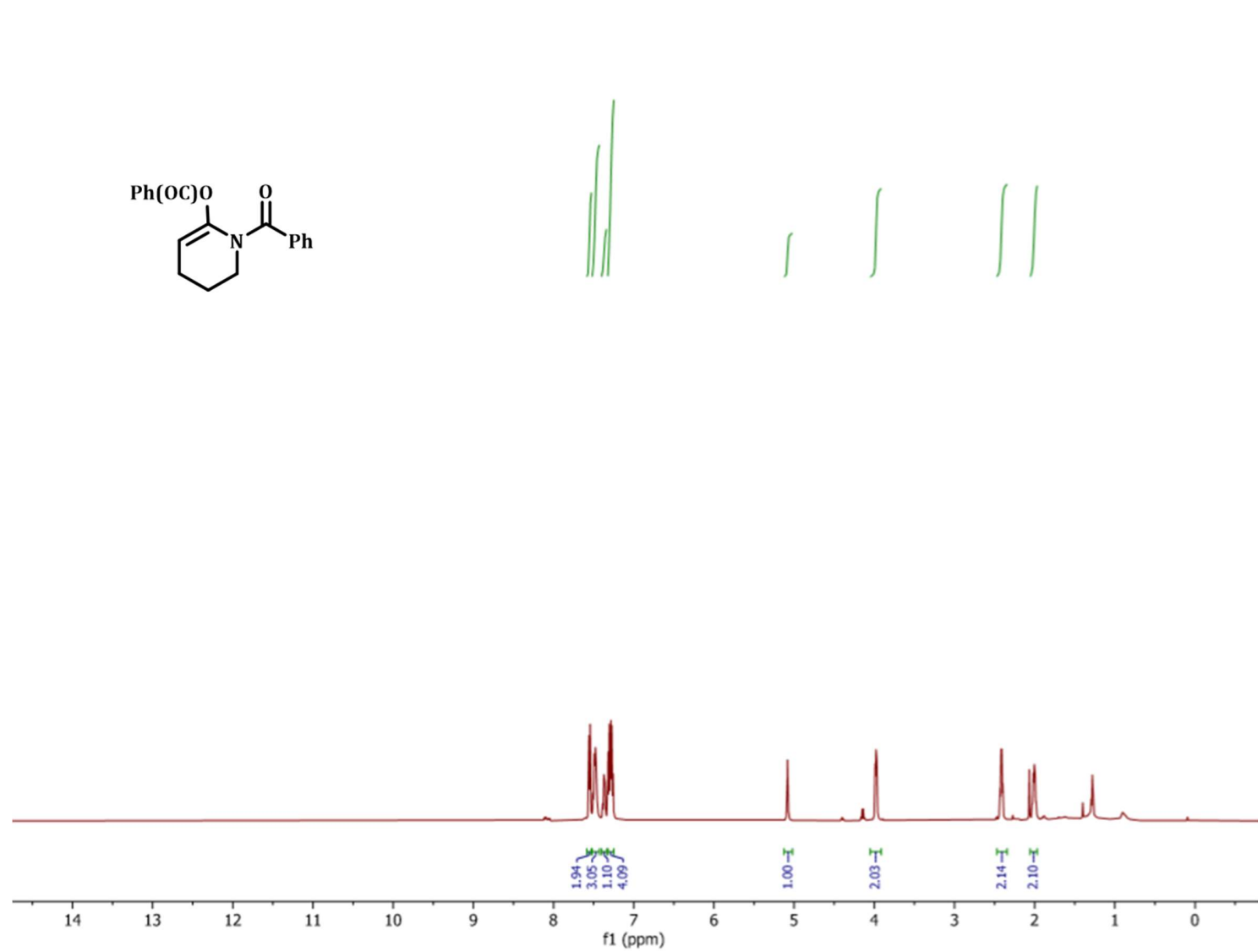
¹H NMR (400 MHz, CDCl₃) of compound **S46**



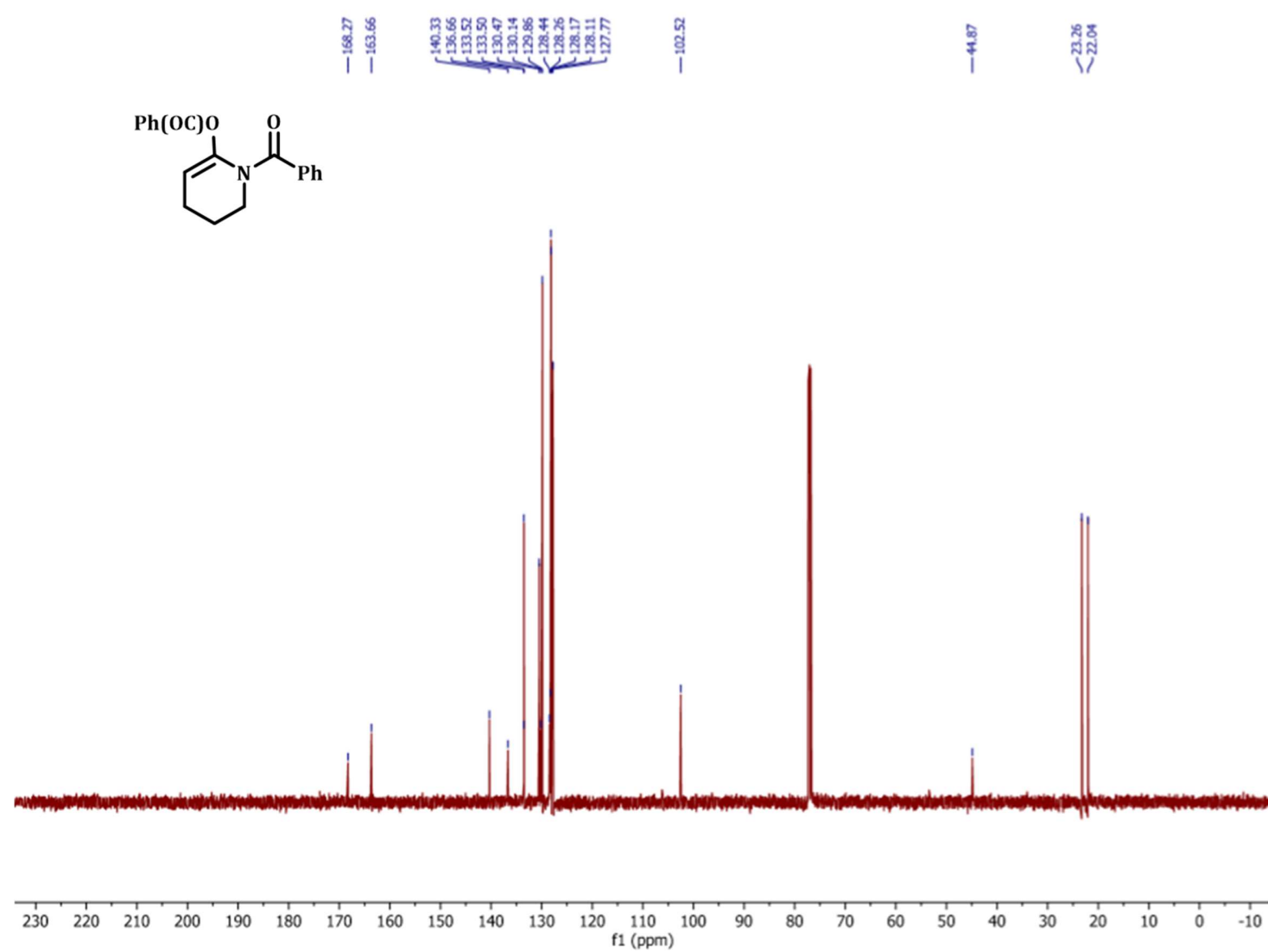
^{13}C NMR (151 MHz, CDCl_3) of compound **S46**



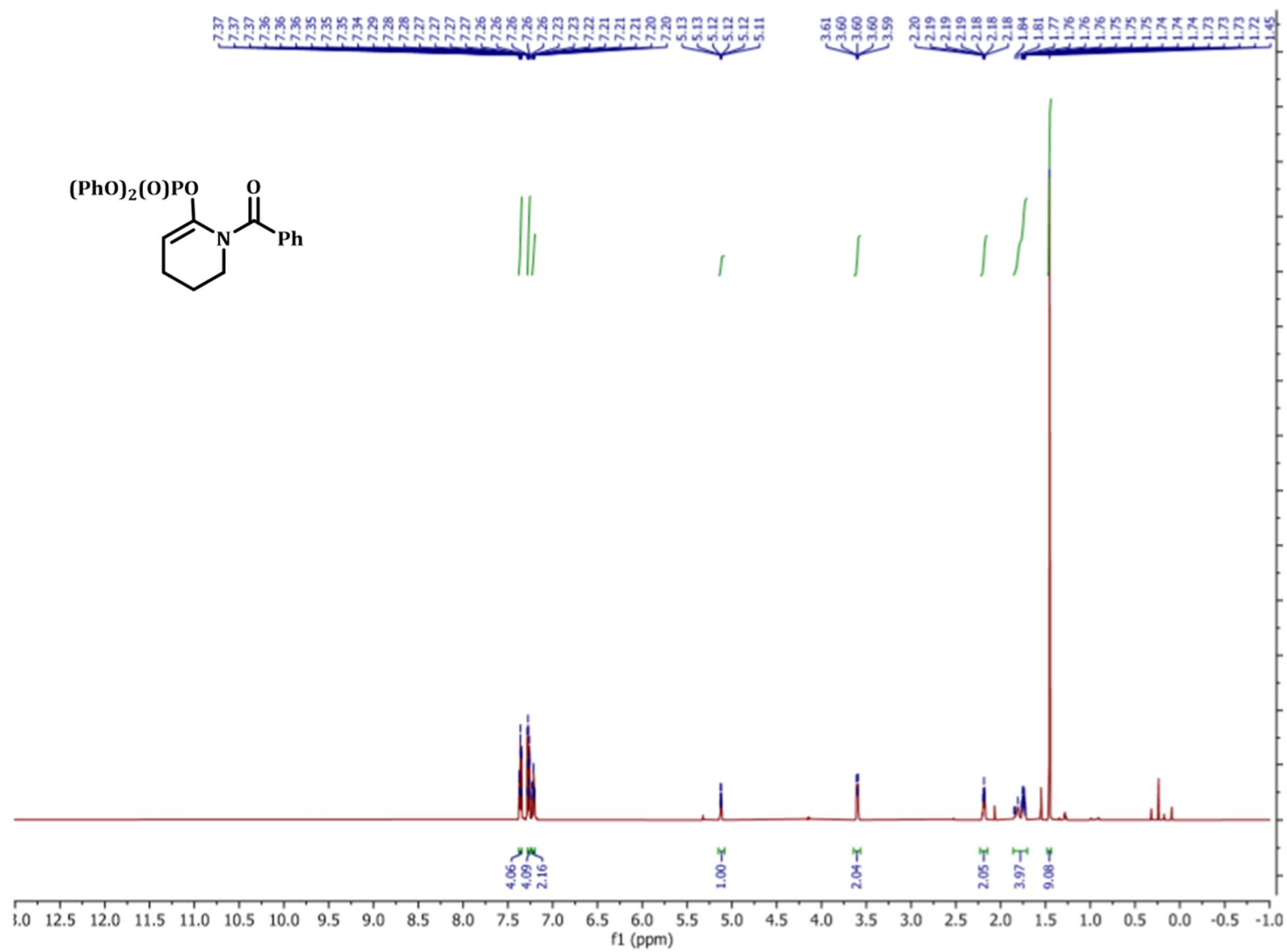
^1H NMR (500 MHz, CDCl_3) of compound **S47**



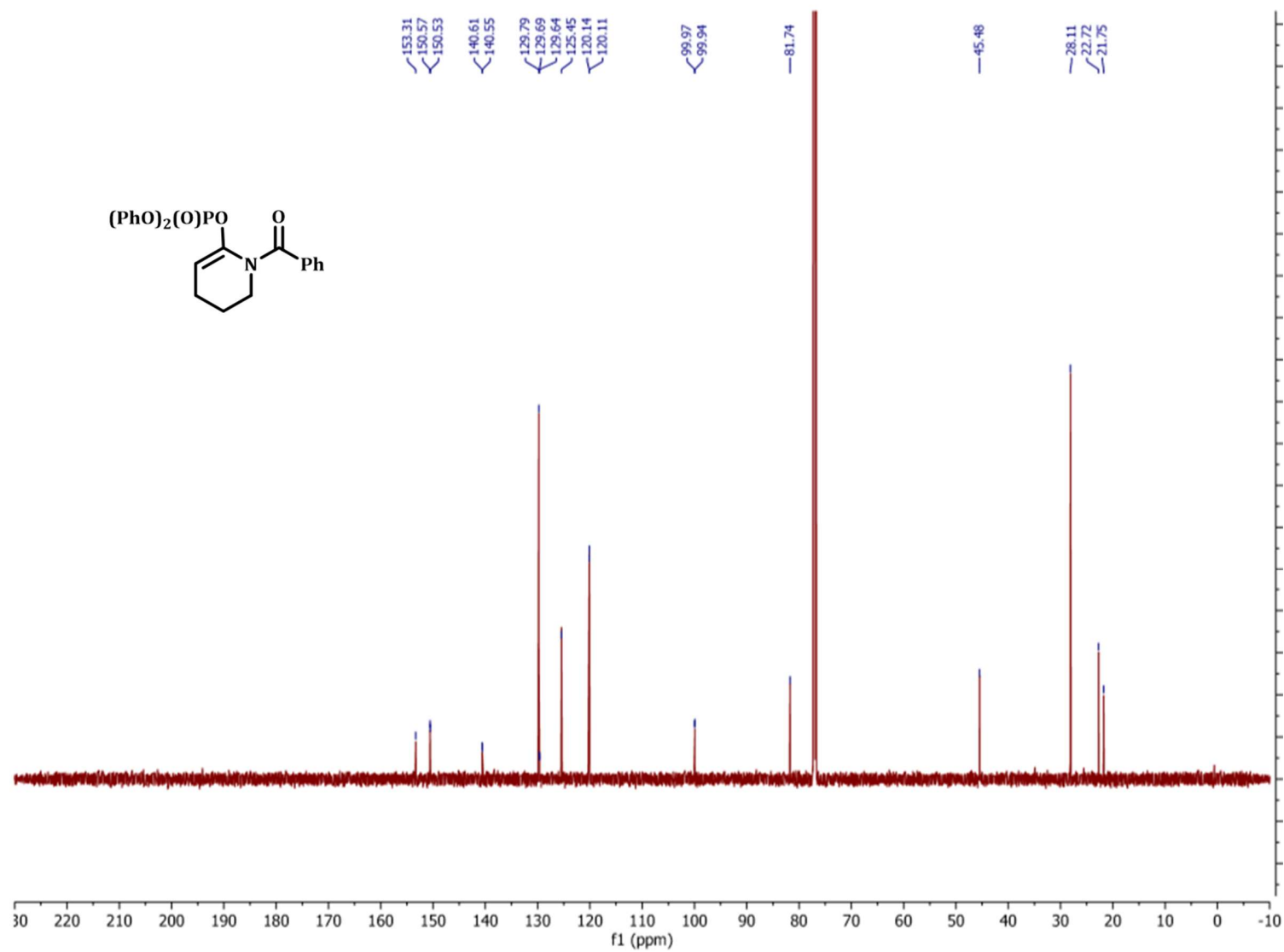
^{13}C NMR (126 MHz, CDCl_3) of compound **S47**



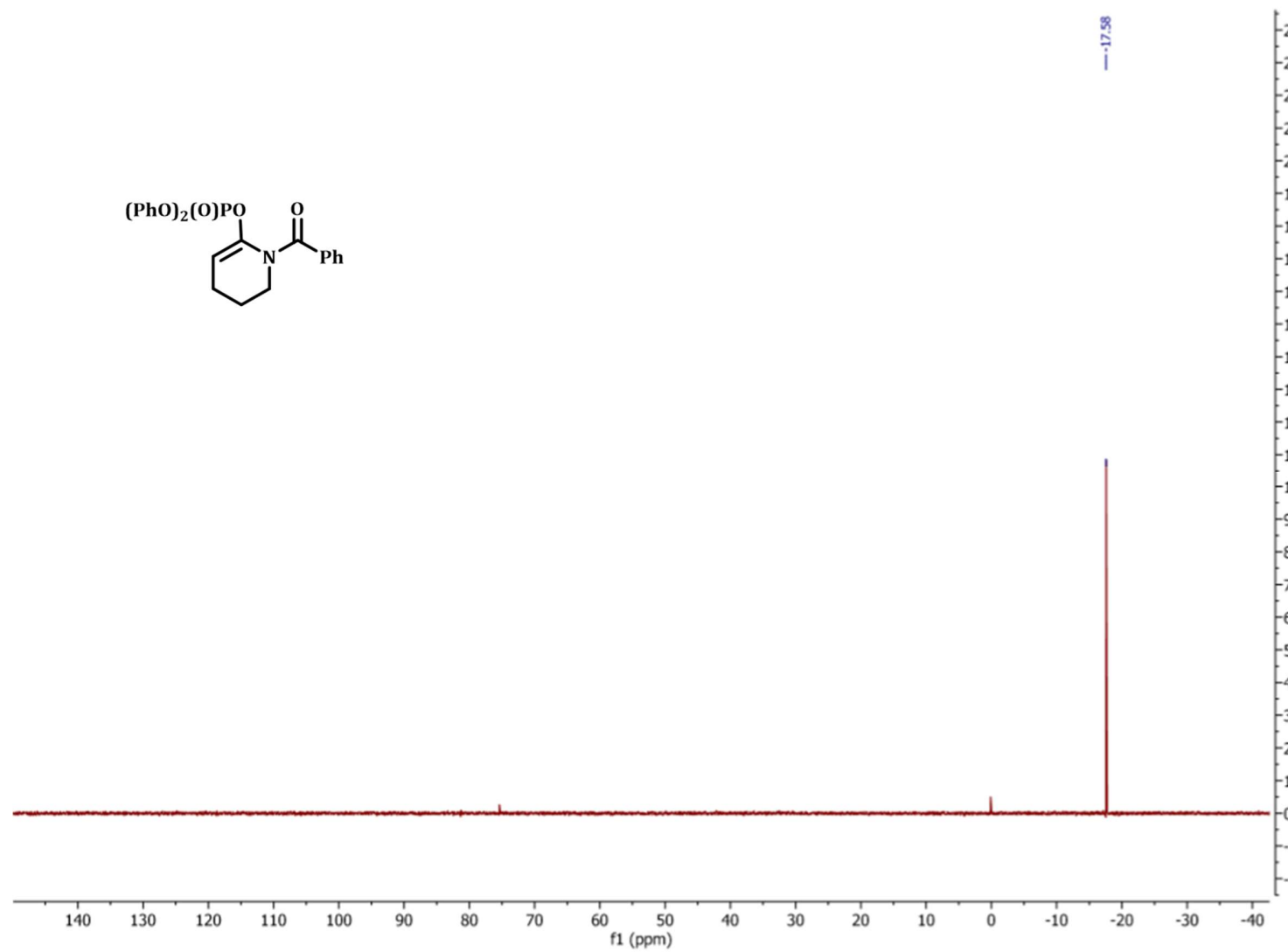
^1H NMR (600 MHz, CDCl_3) of compound **58**



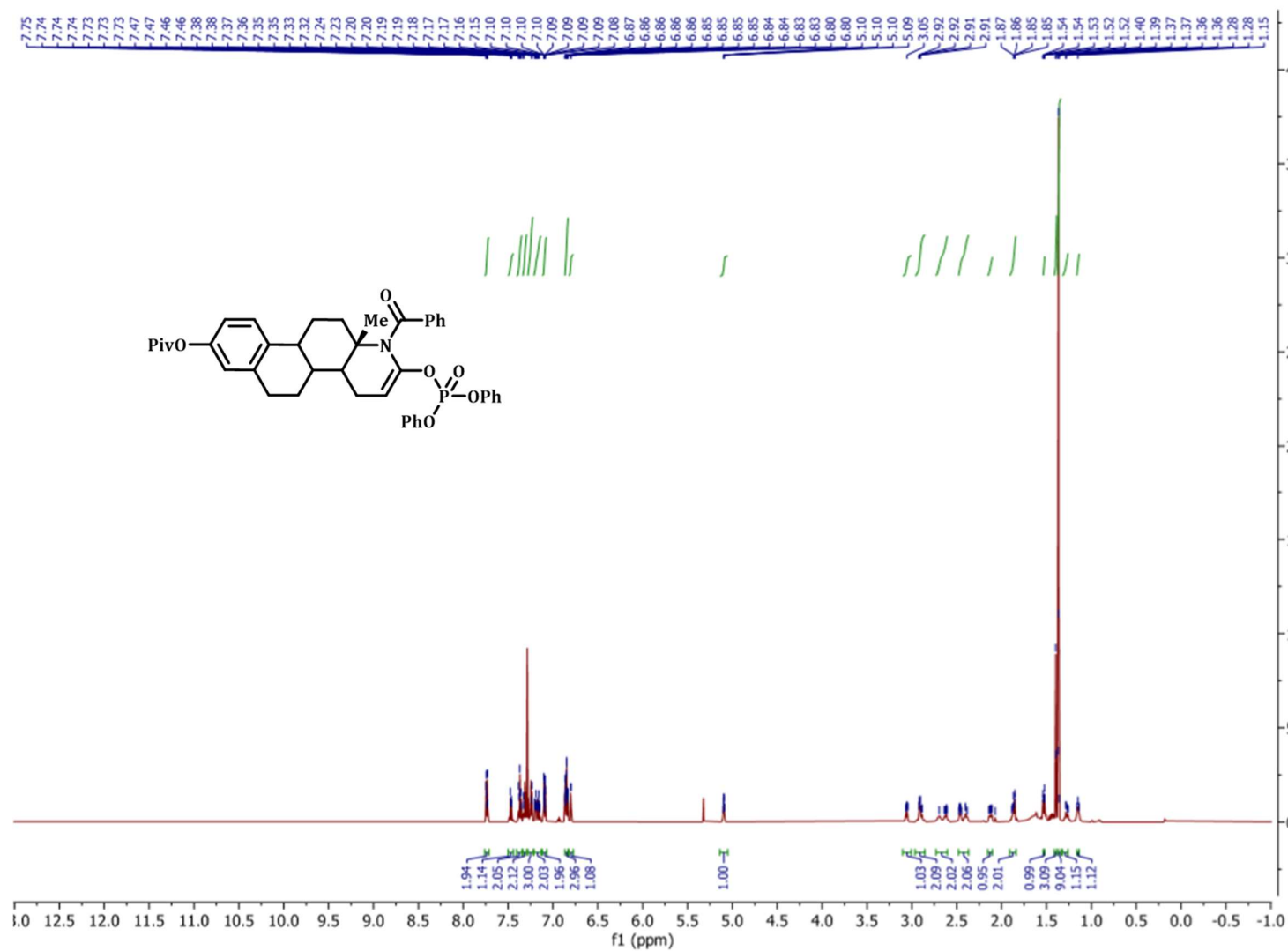
^{13}C NMR (151 MHz, CDCl_3) of compound **58**



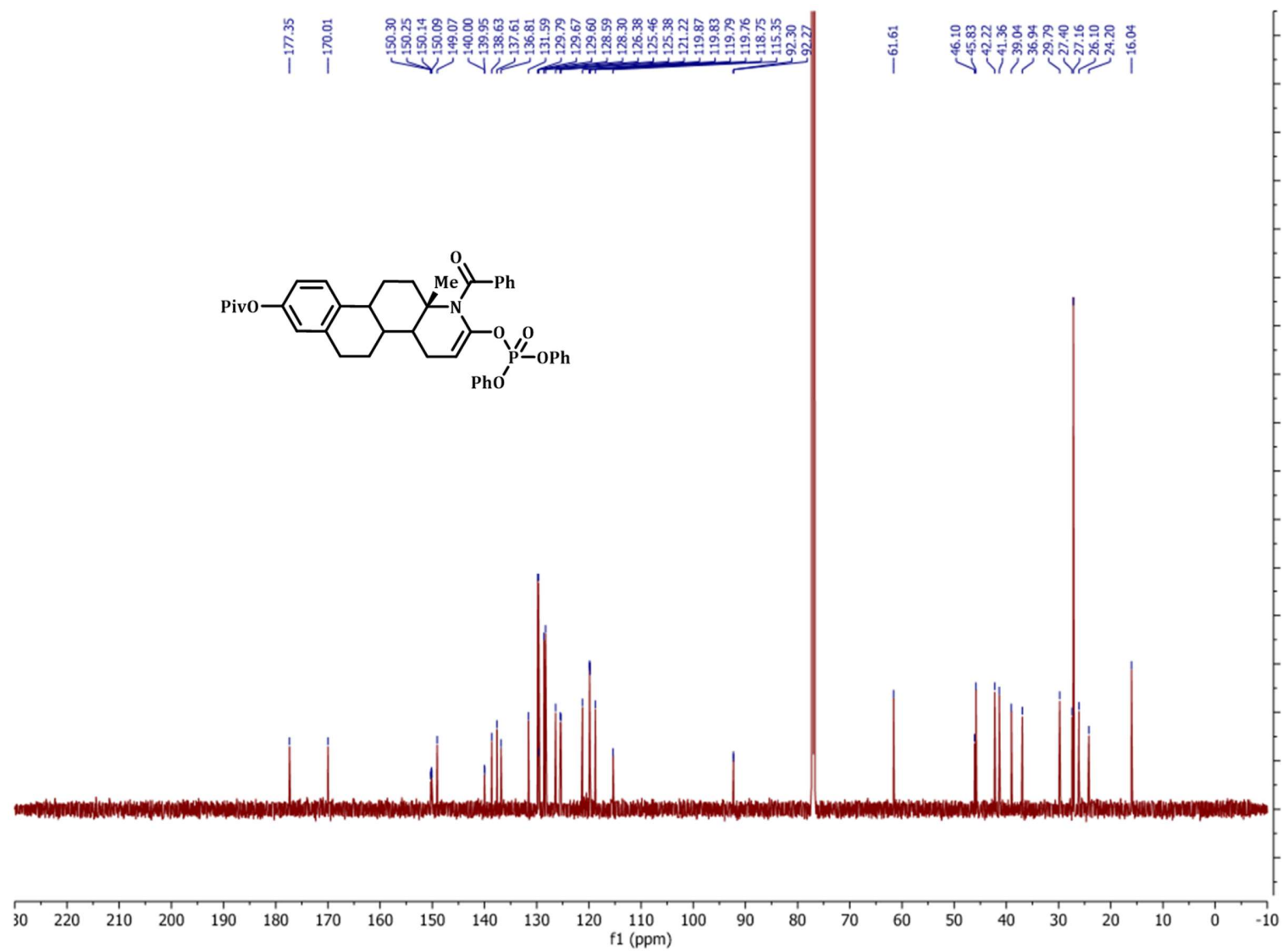
^{31}P NMR (162 MHz, CDCl_3) of compound **58**



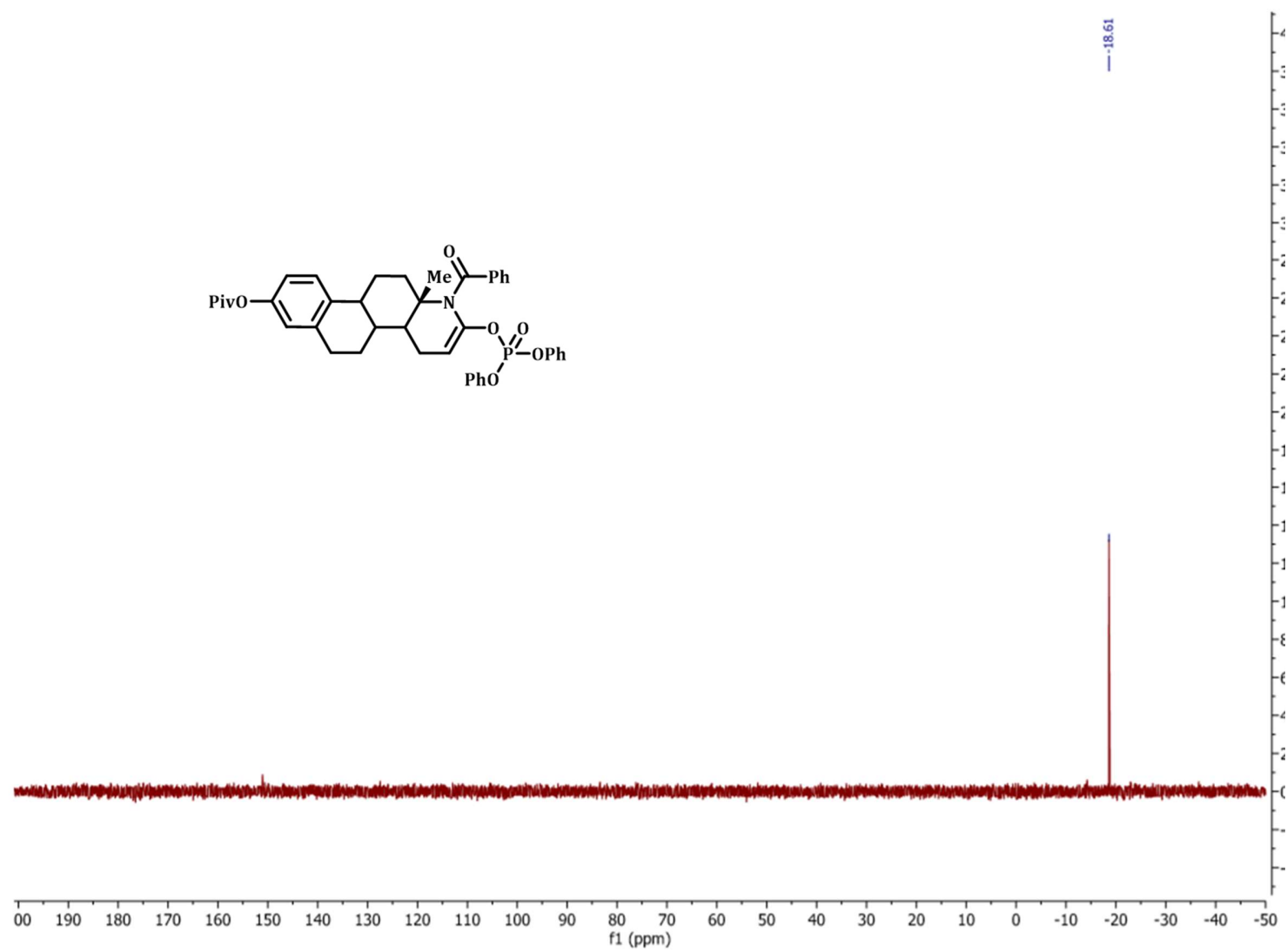
^1H NMR (600 MHz, CDCl_3) of compound **S48**



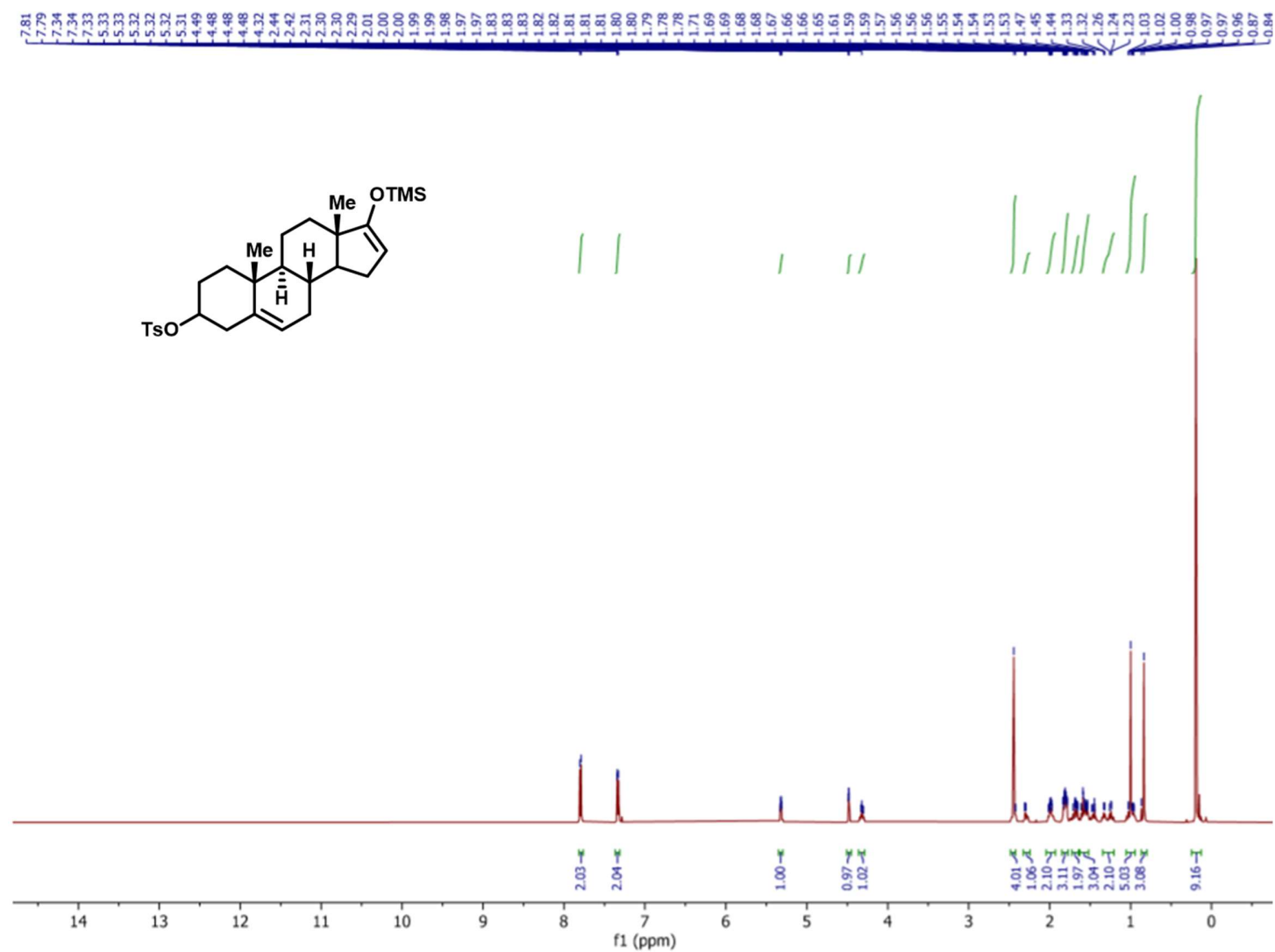
^{13}C NMR (151 MHz, CDCl_3) of compound **S48**



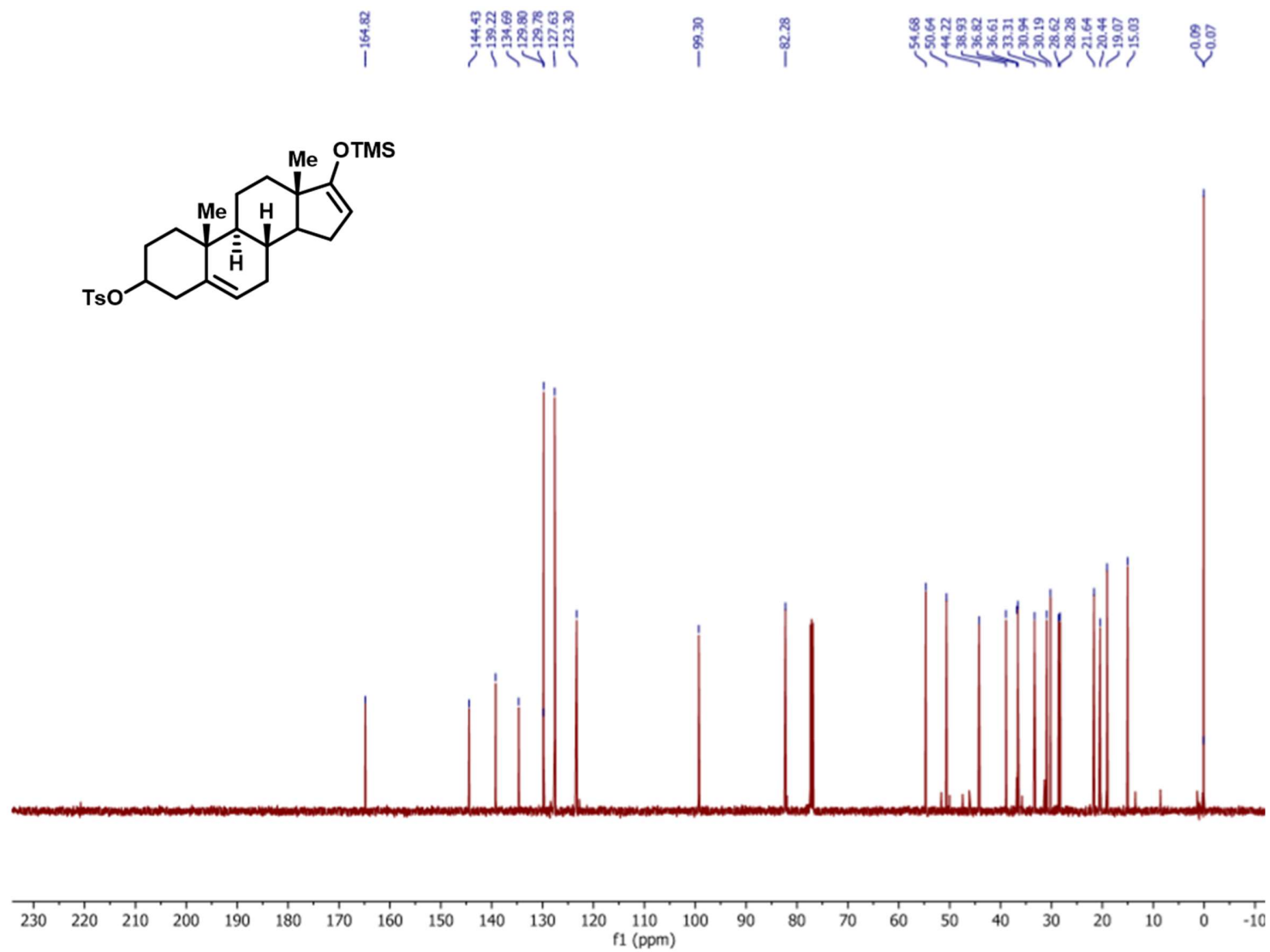
^{31}P NMR (162 MHz, CDCl_3) of compound **S48**



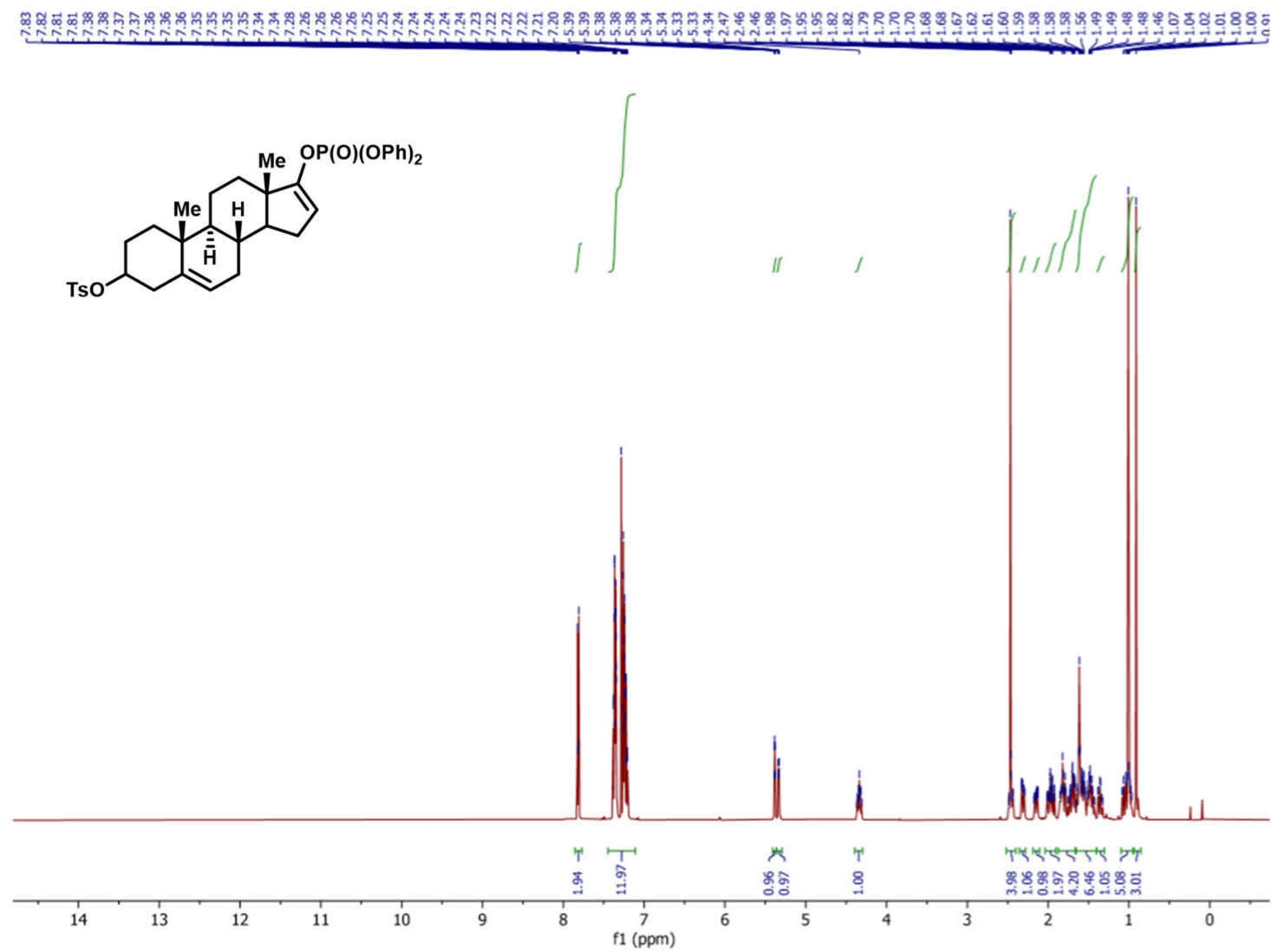
^1H NMR (500 MHz, CDCl_3) of compound **54**



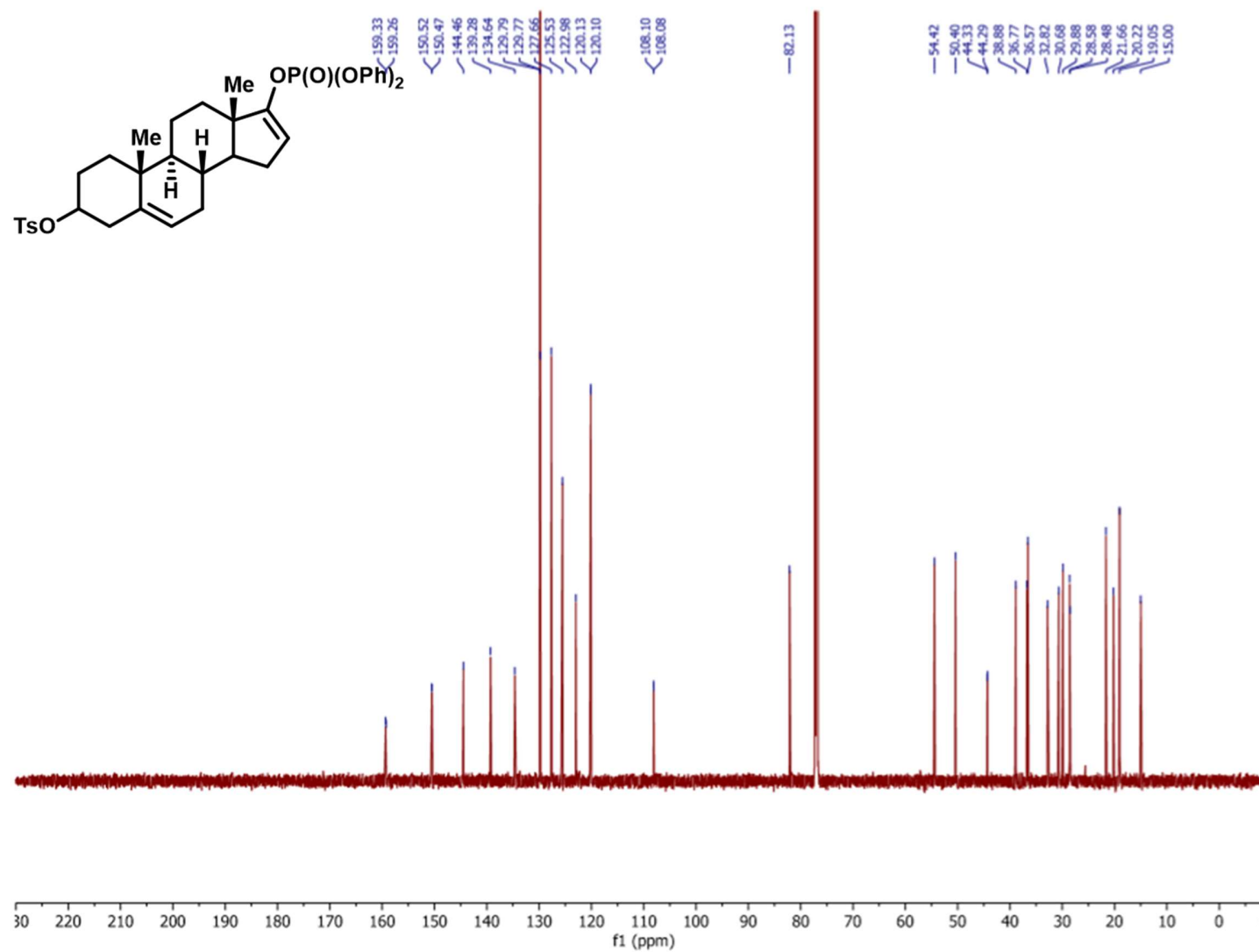
^{13}C NMR (126 MHz, CDCl_3) of compound **54**



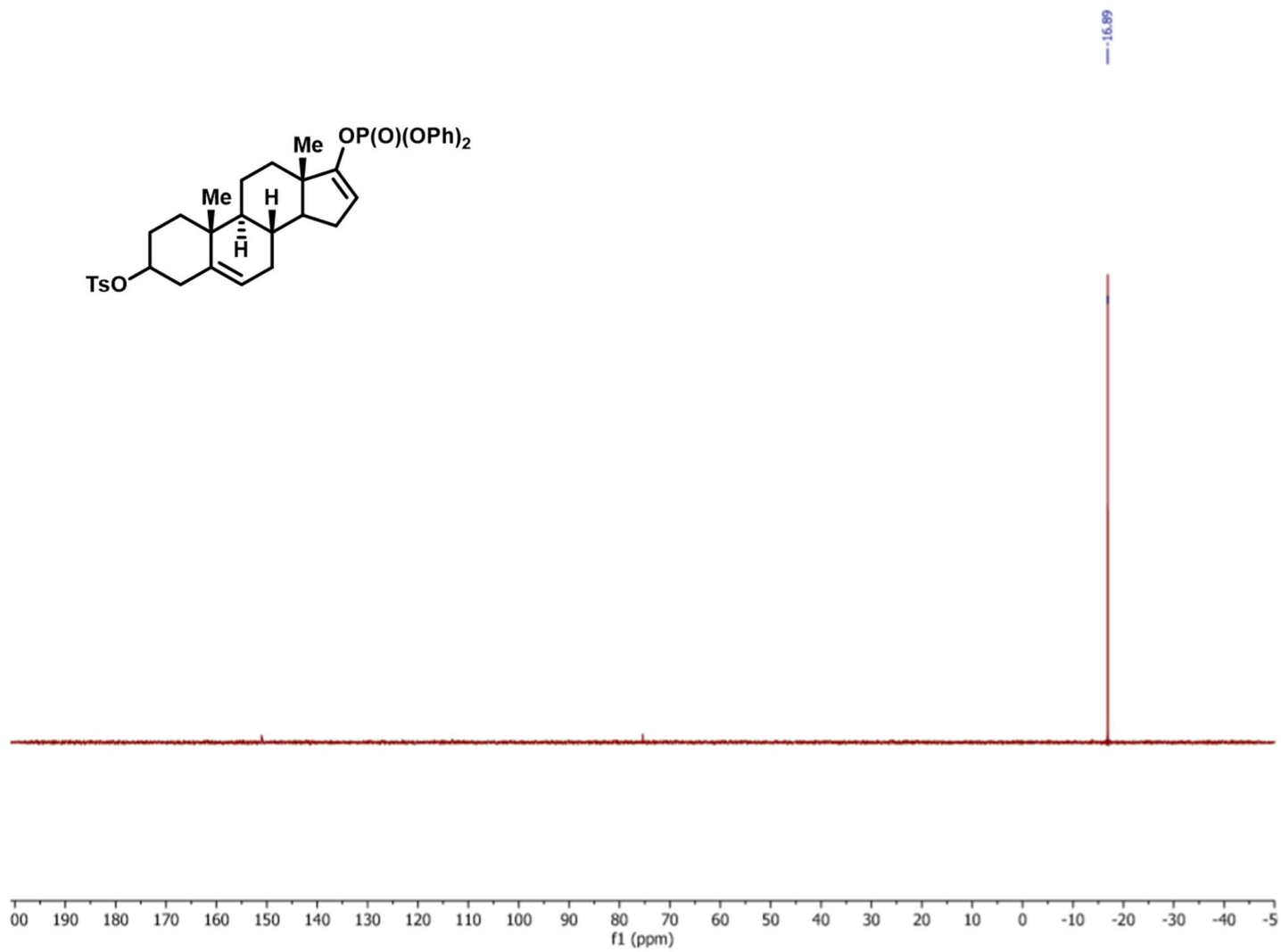
^1H NMR (500 MHz, CDCl_3) of compound **51**



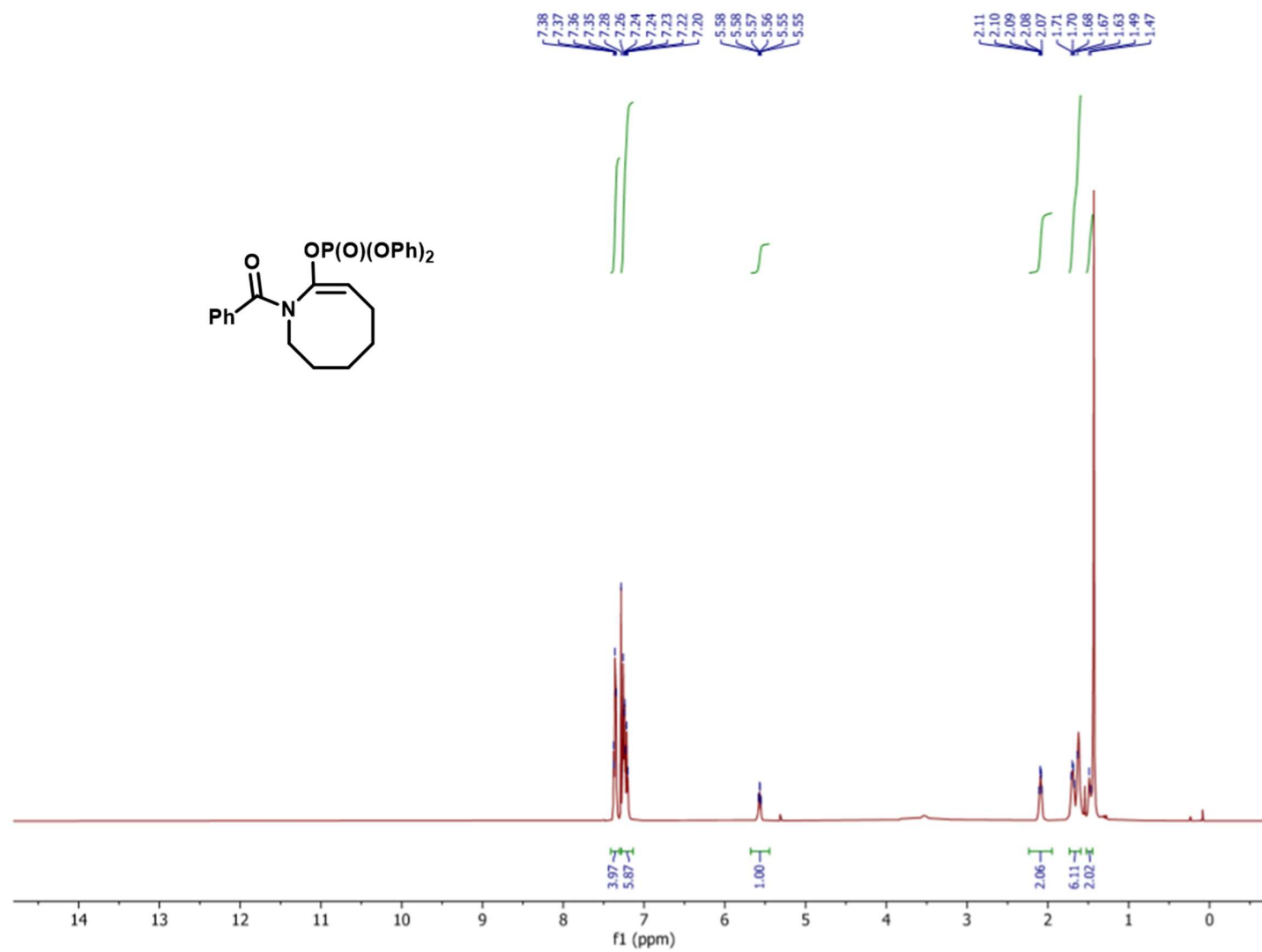
^{13}C NMR (151 MHz, CDCl_3) of compound **51**



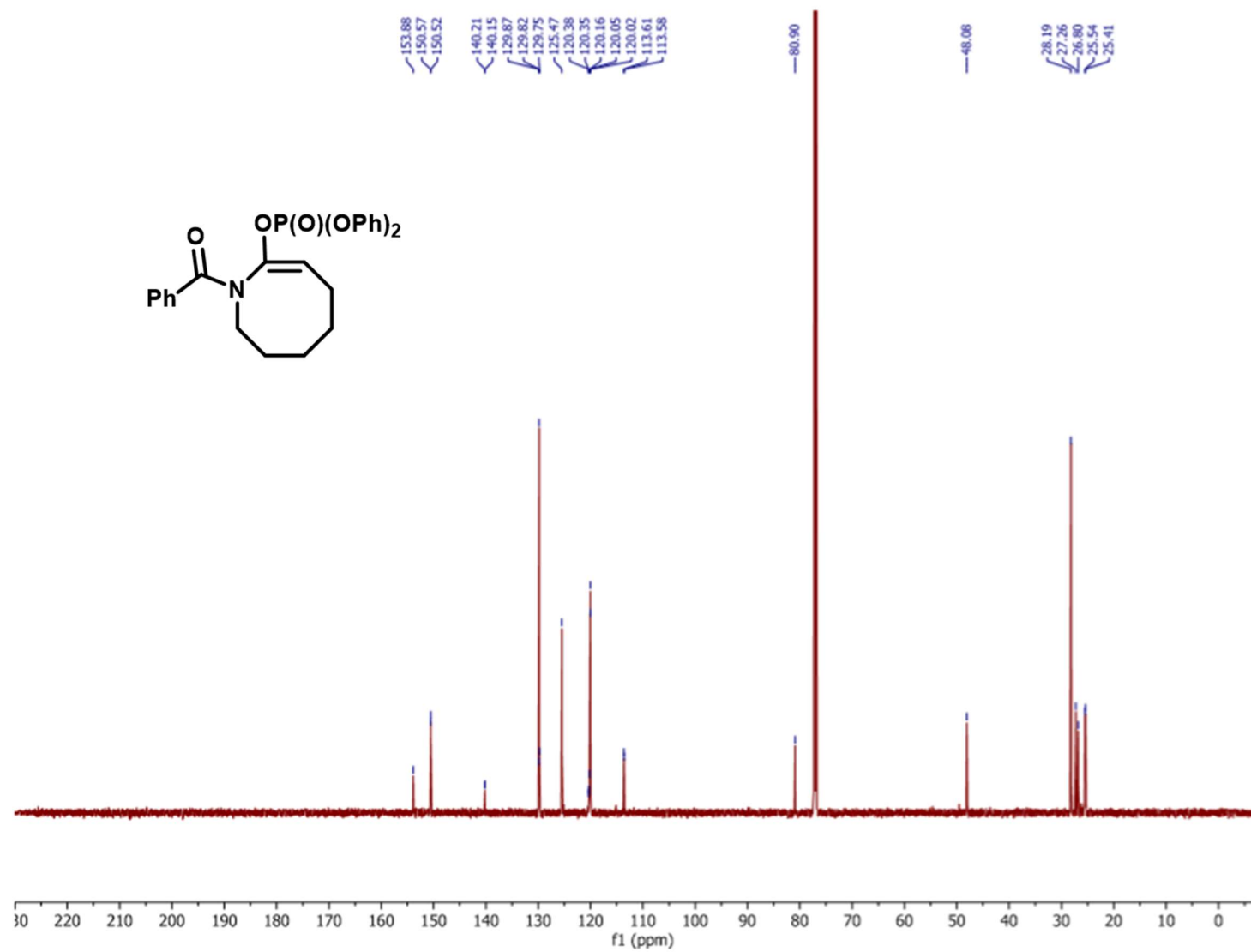
^{31}P NMR (162 MHz, CDCl_3) of compound **51**



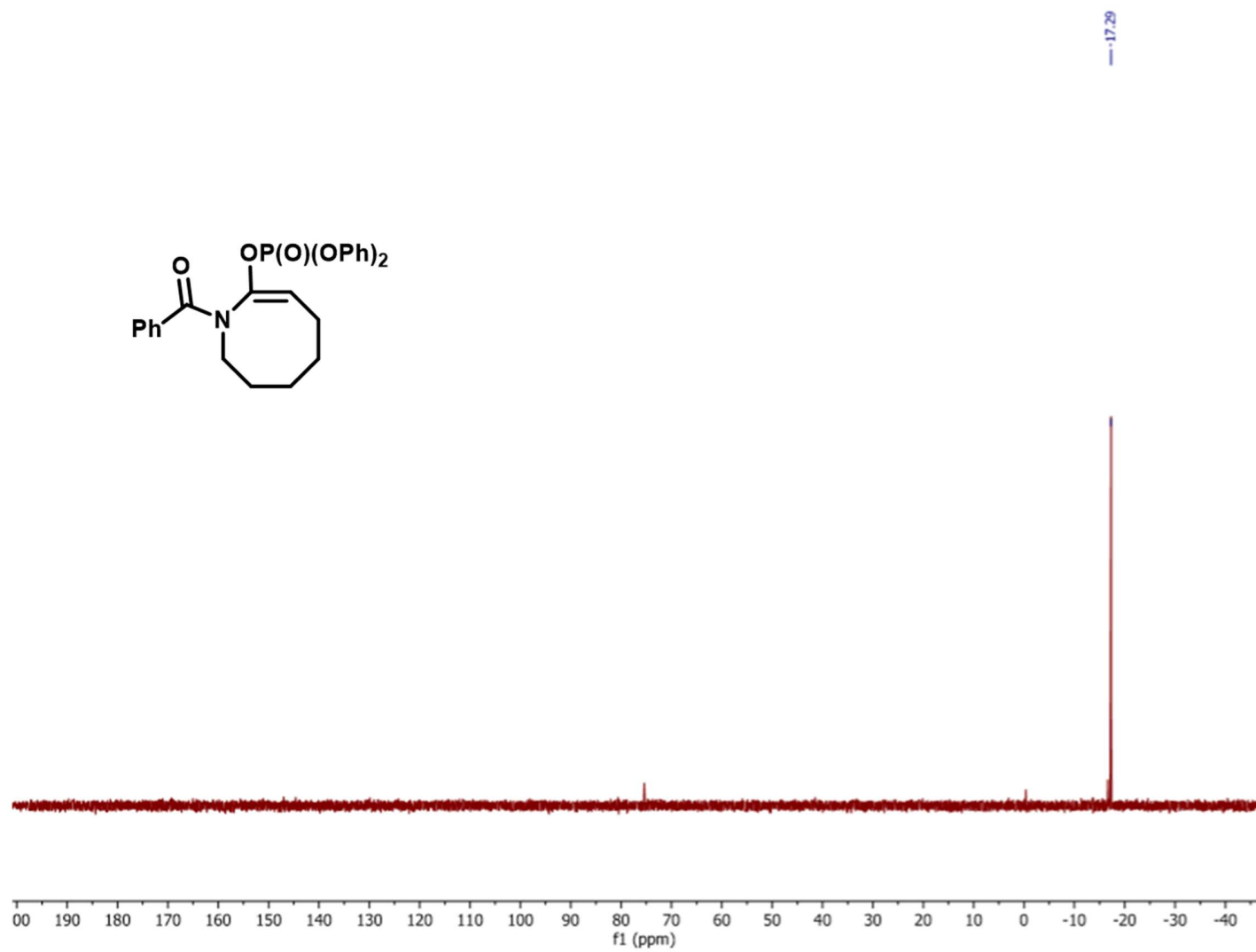
^1H NMR (500 MHz, CDCl_3) of compound **57**



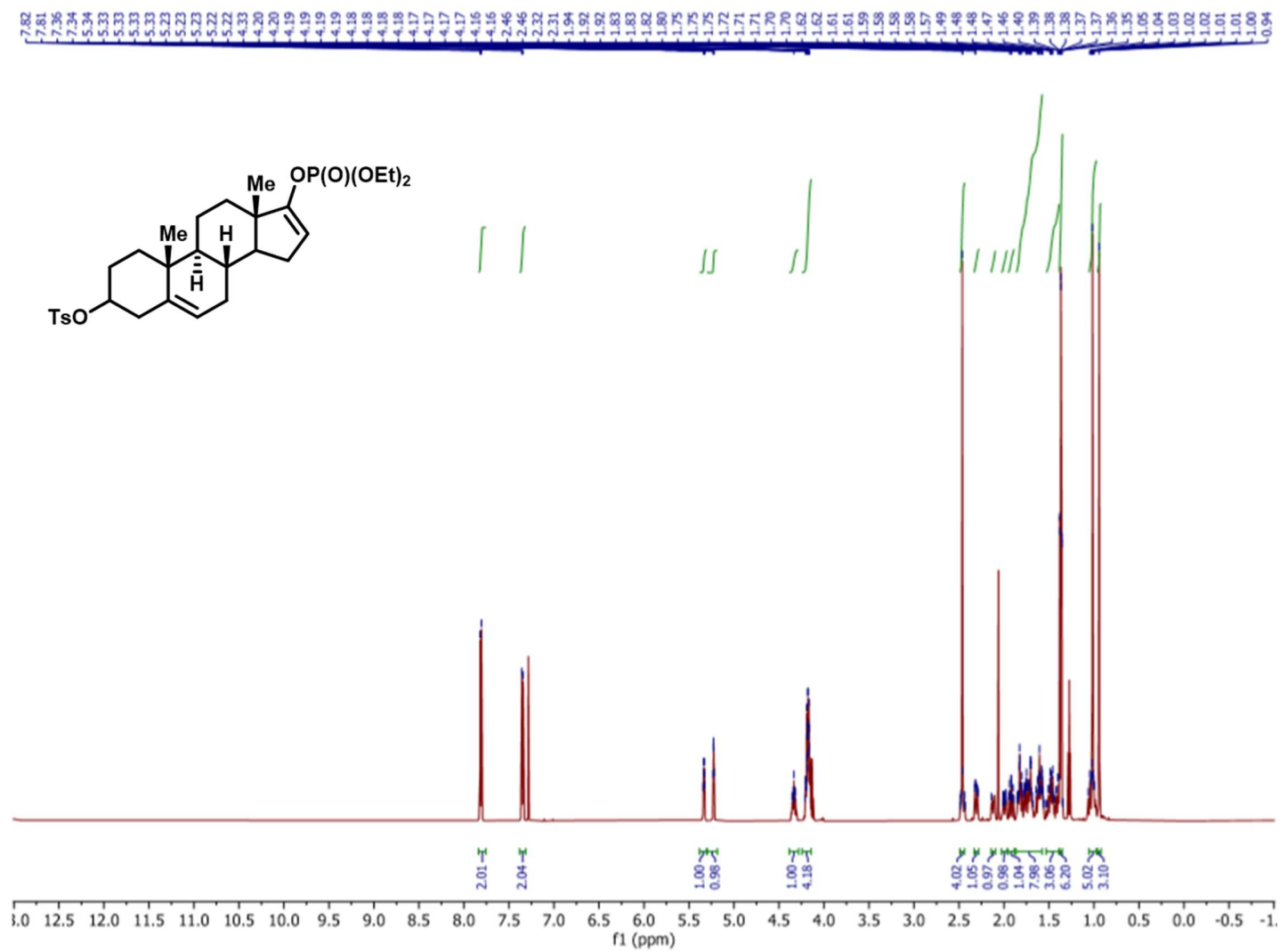
^{13}C NMR (151 MHz, CDCl_3) of compound **57**



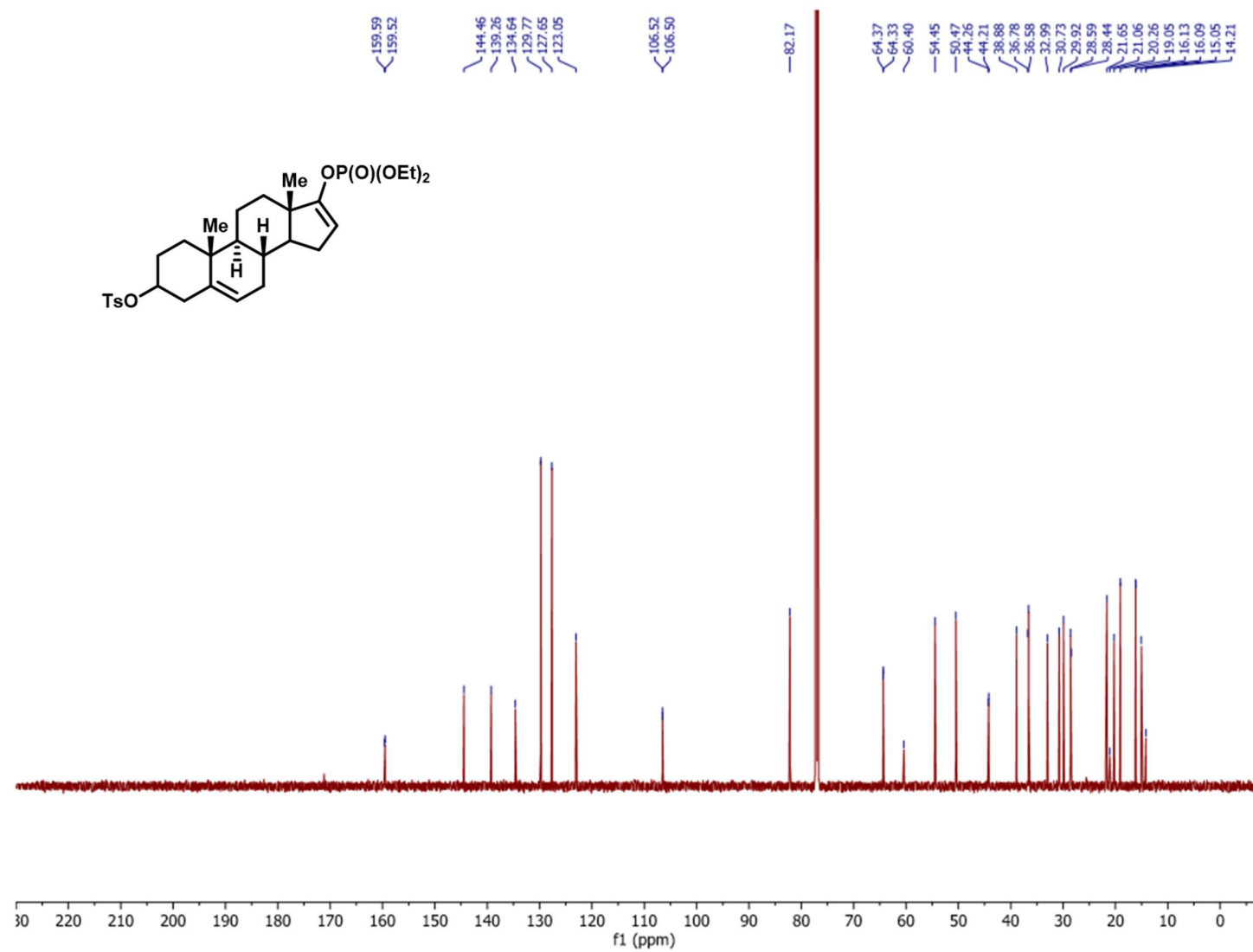
^{31}P NMR (162 MHz, CDCl_3) of compound **S57**

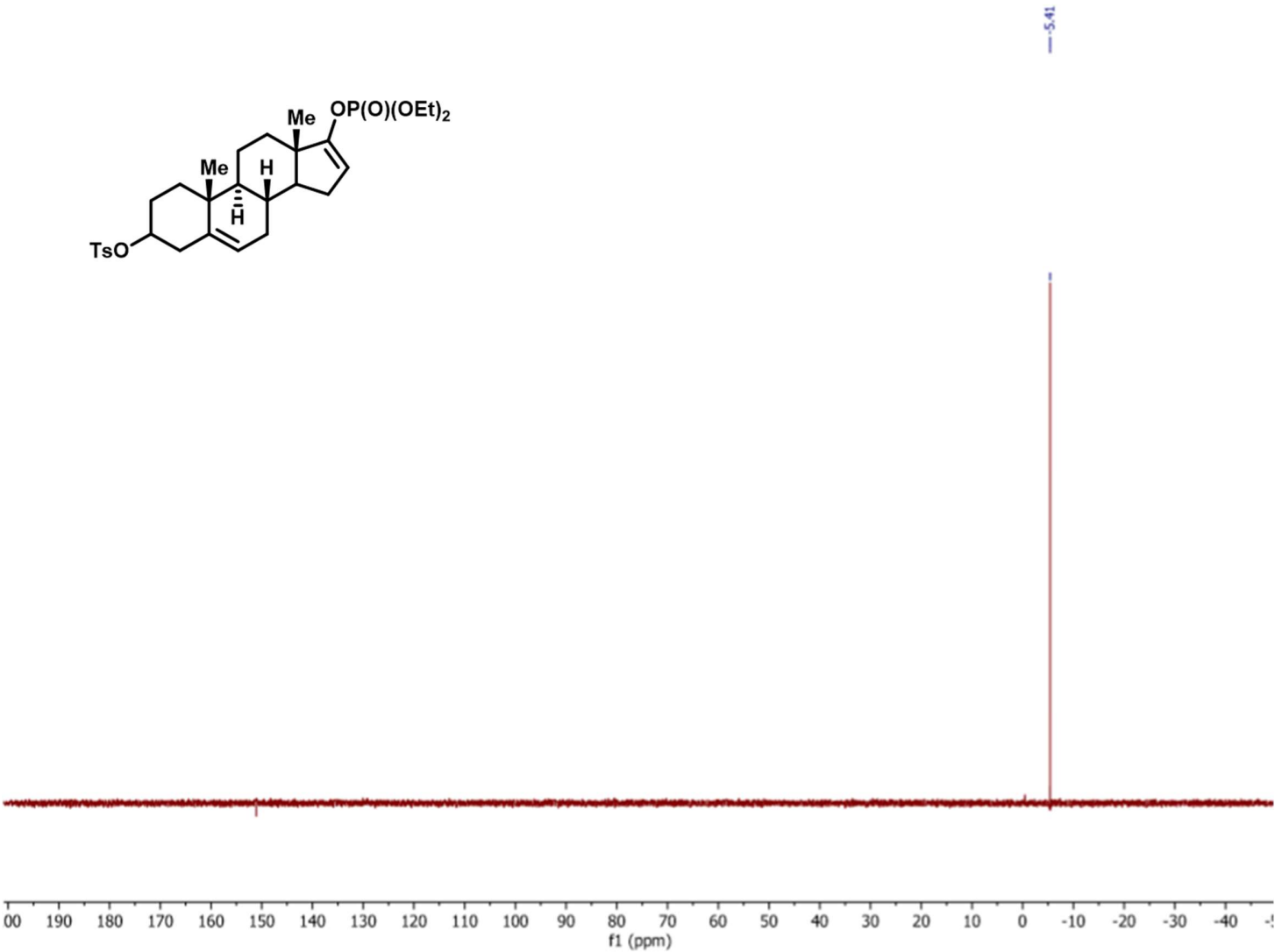
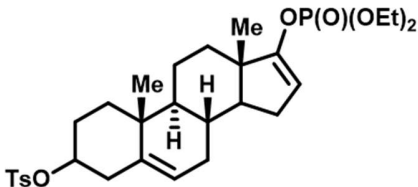


¹H NMR (600 MHz, CDCl₃) of compound **48**

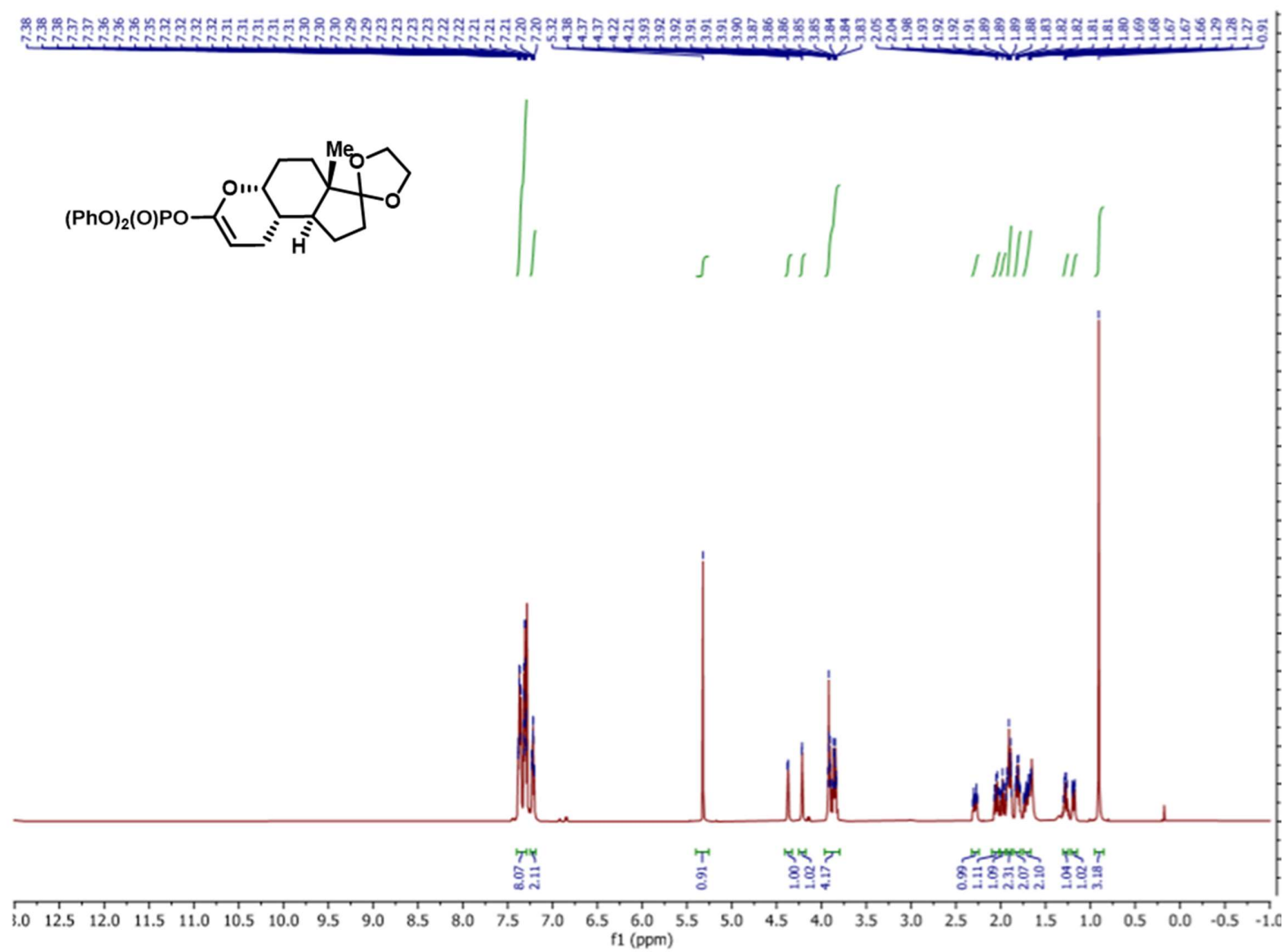


¹³C NMR (151 MHz, CDCl₃) of compound **48**

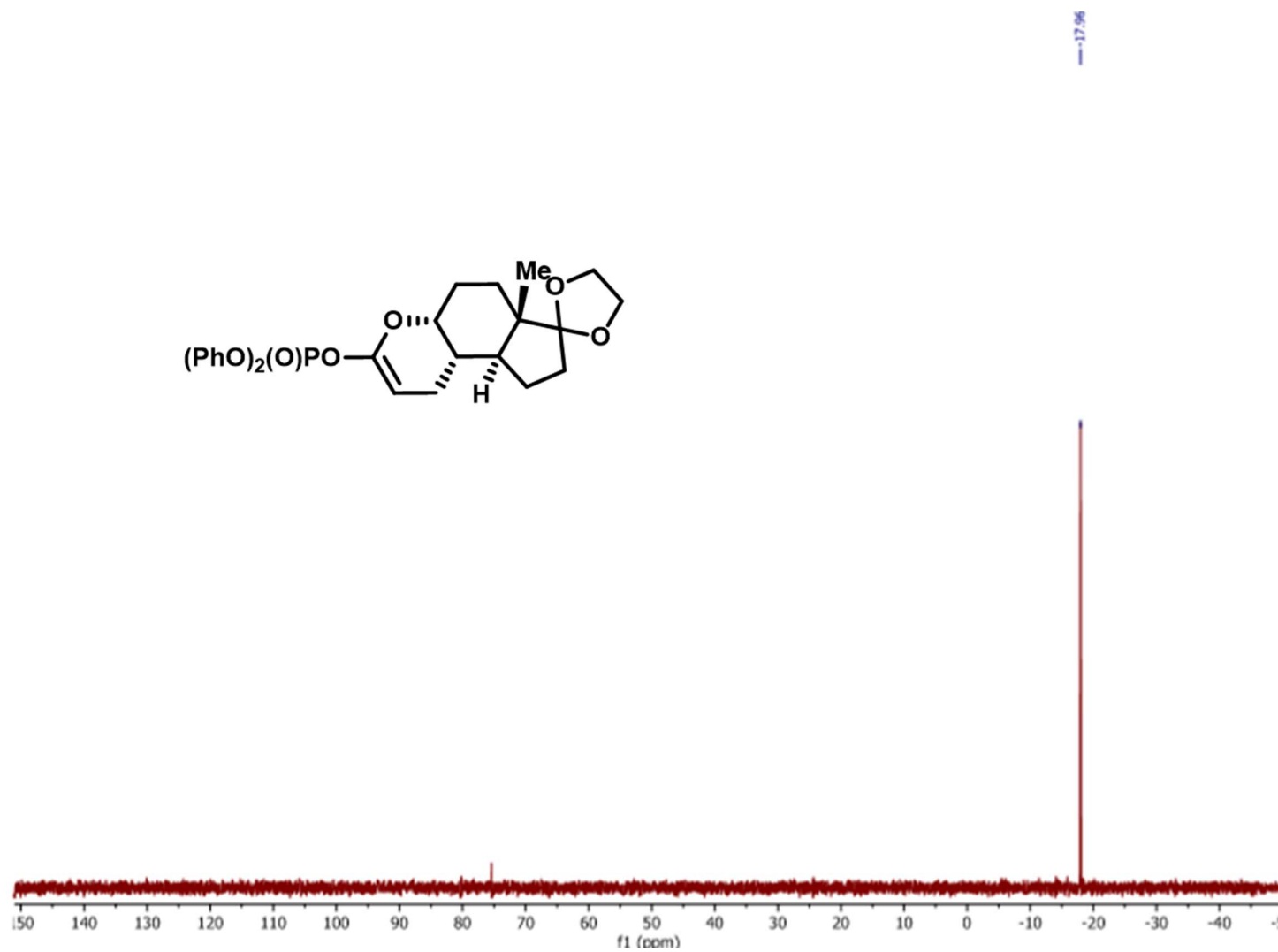


³¹P NMR (162 MHz, CDCl₃) of compound **48**

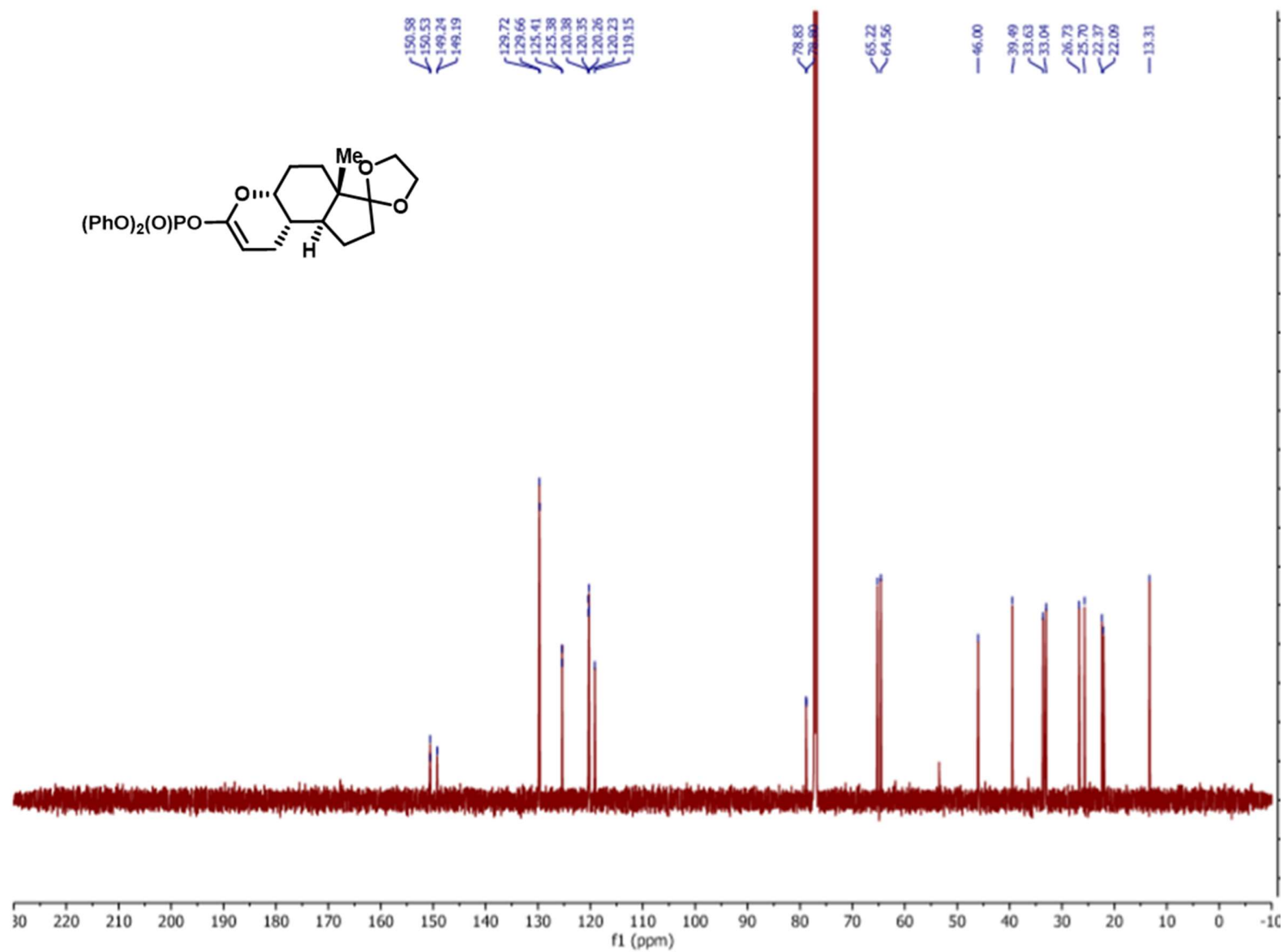
^1H NMR (600 MHz, CDCl_3) of compound **49**



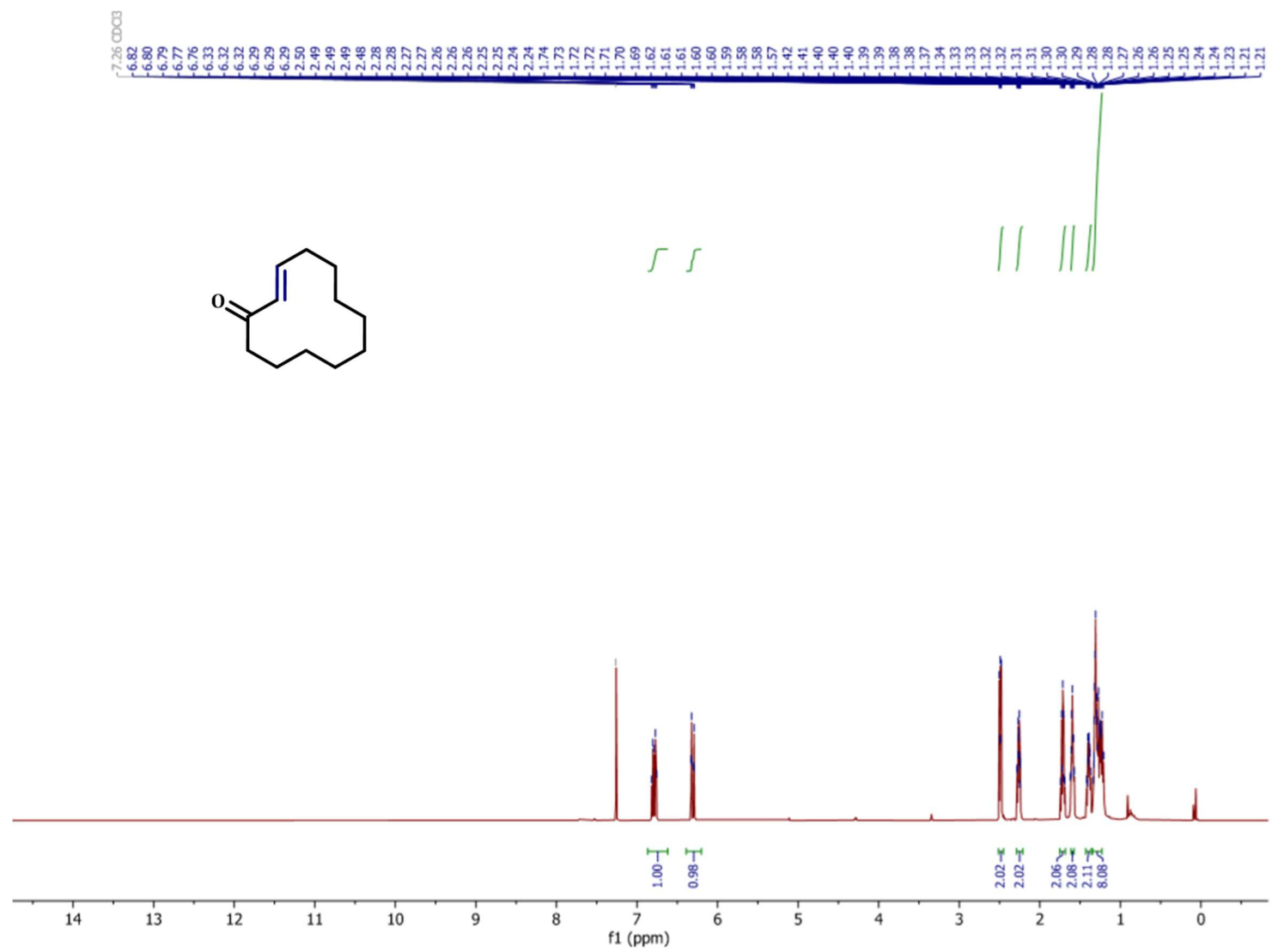
^{31}P NMR (162 MHz, CDCl_3) of compound **49**



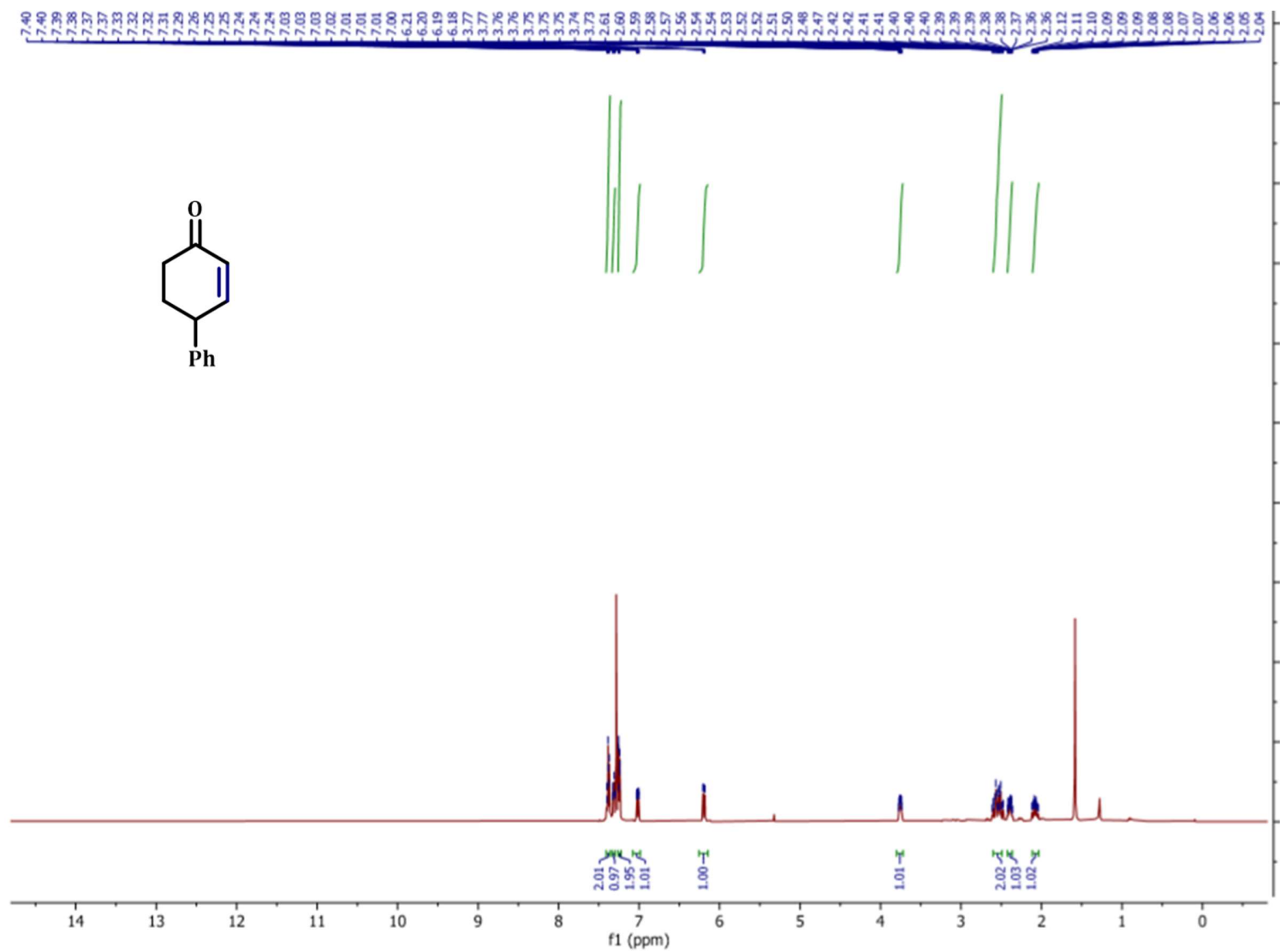
^{13}C NMR (151 MHz, CDCl_3) of compound **49**



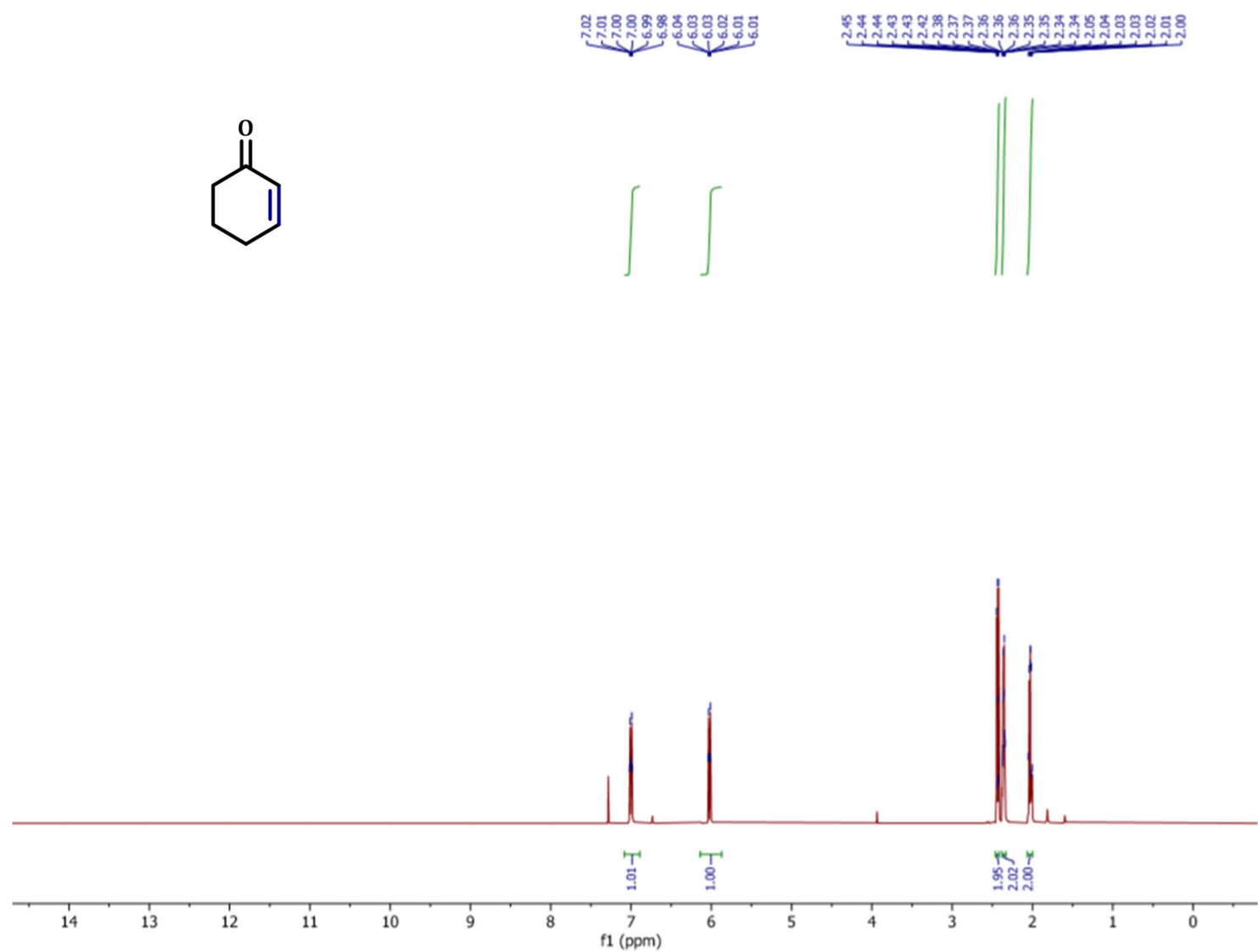
^1H NMR (500 MHz, CDCl_3) of compound **2**



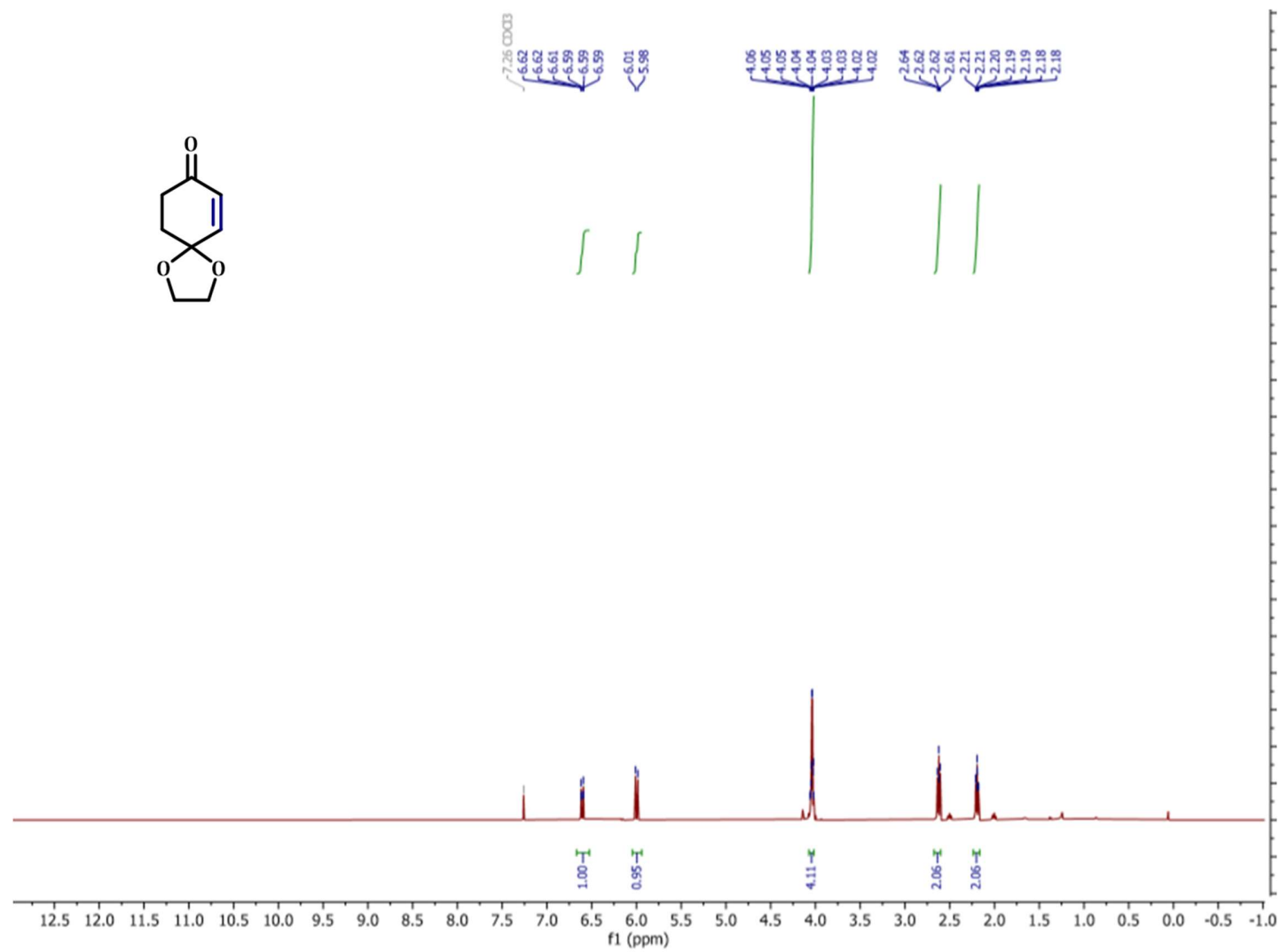
^1H NMR (500 MHz, CDCl_3) of compound **3**



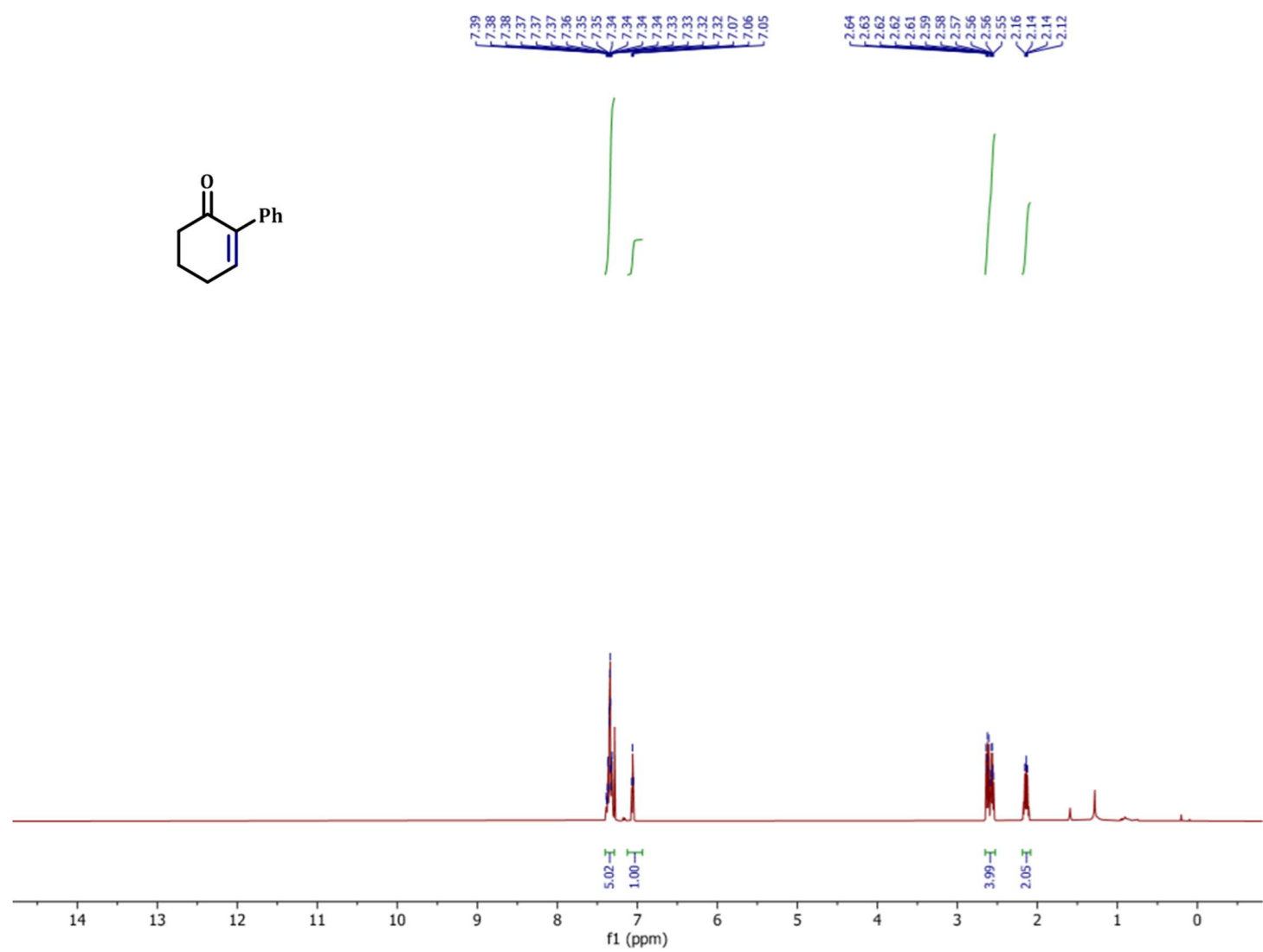
^1H NMR (500 MHz, CDCl_3) of compound **5**



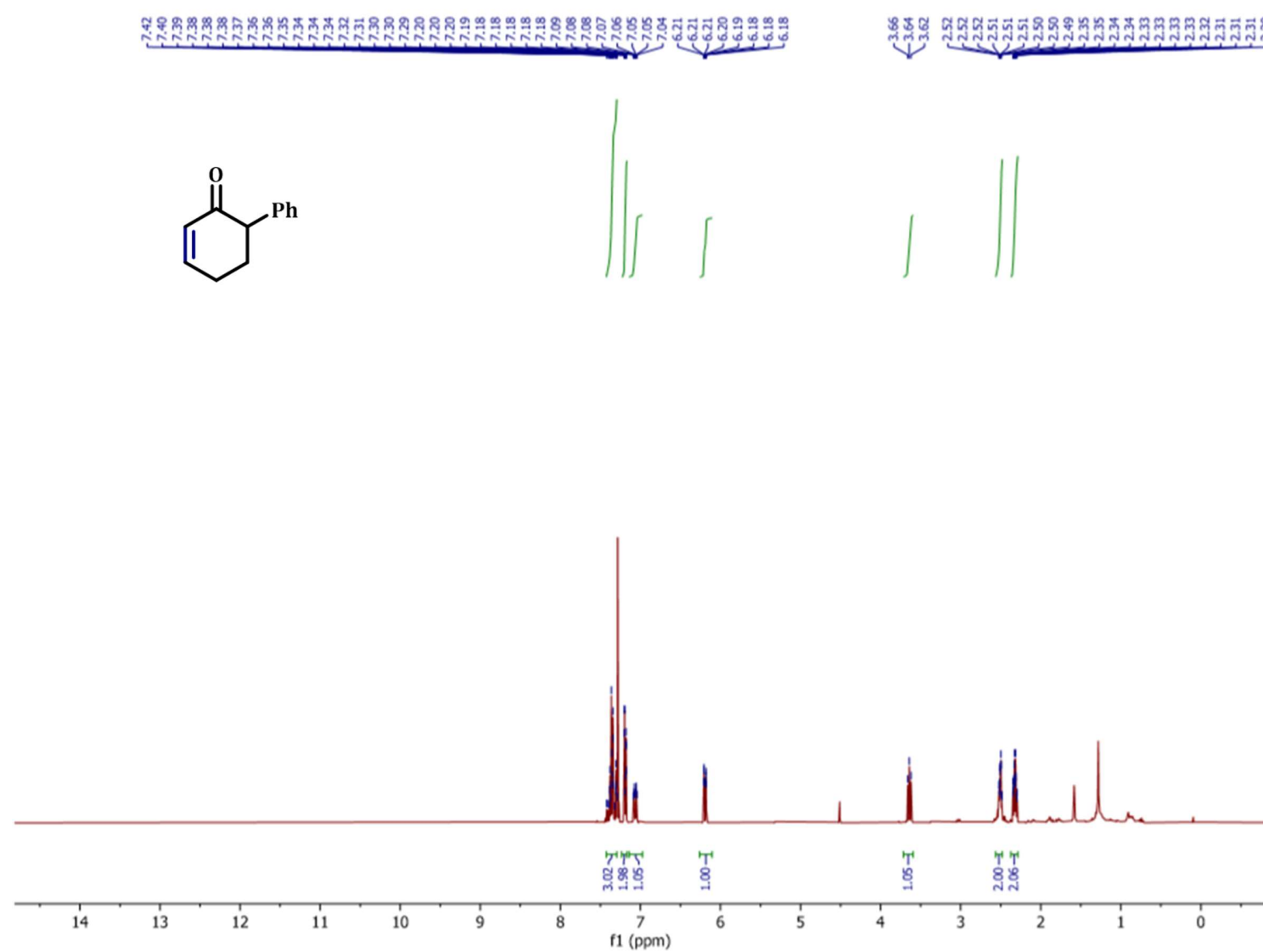
^1H NMR (400 MHz, CDCl_3) of compound **6**



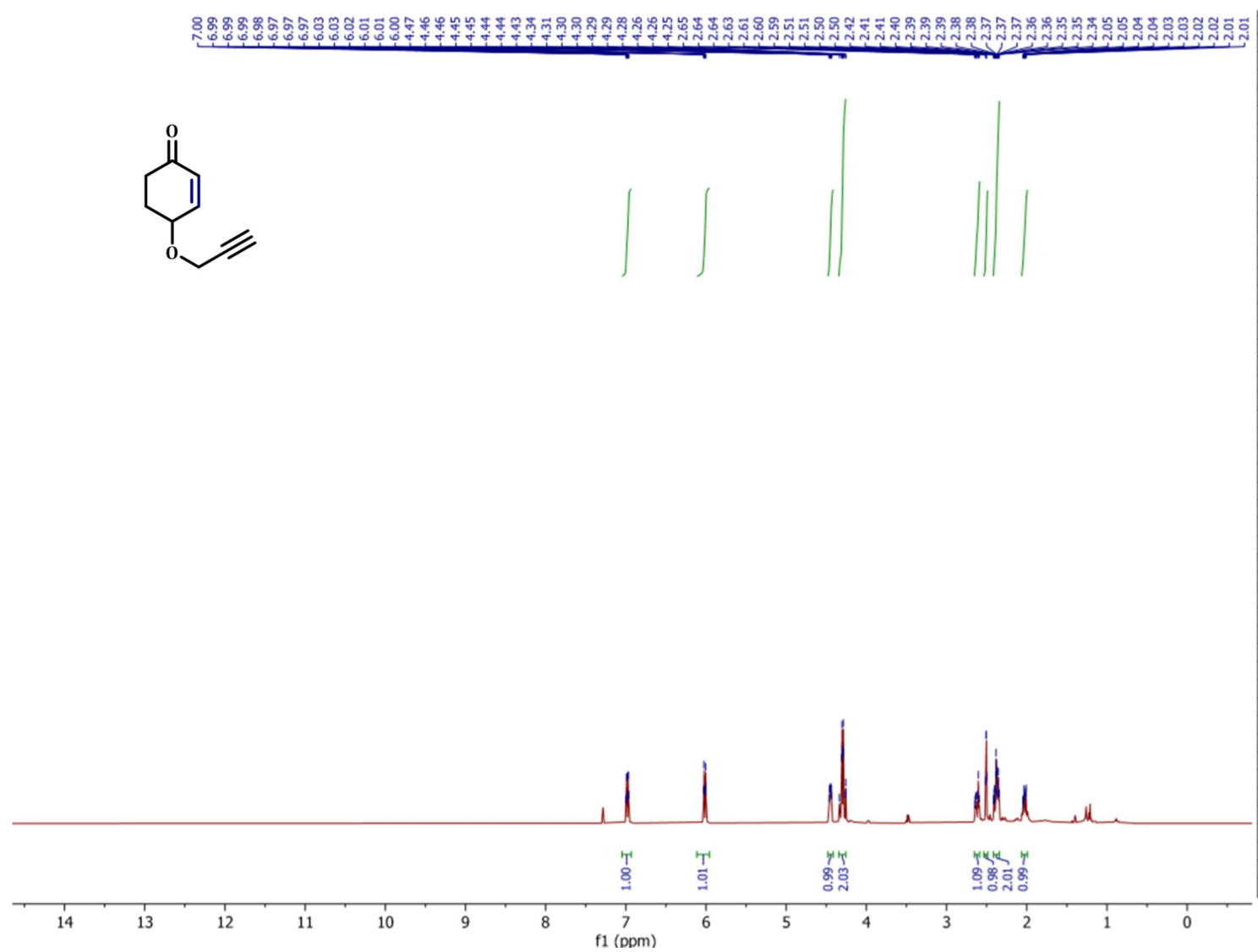
^1H NMR (400 MHz, CDCl_3) of compound 7



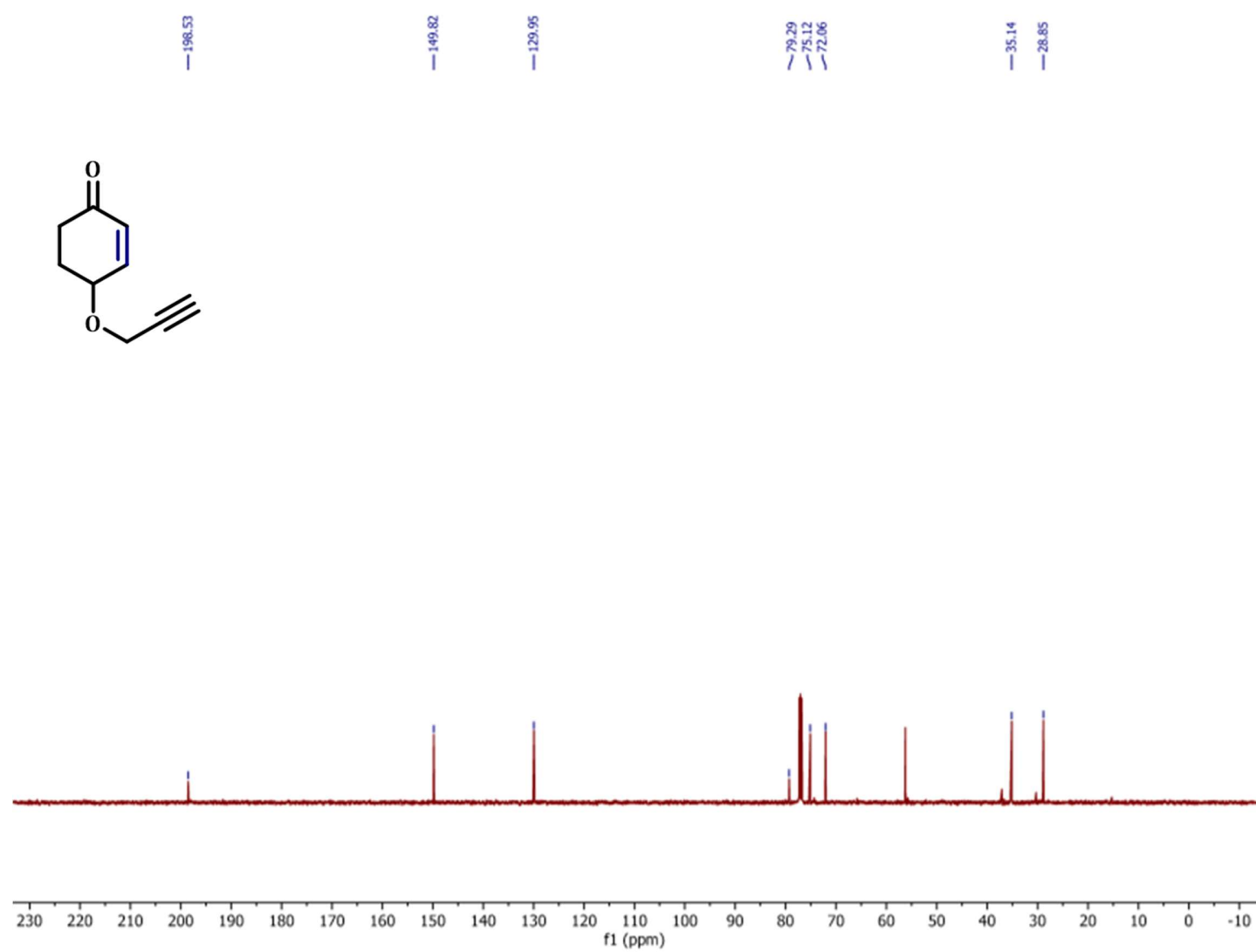
^1H NMR (400 MHz, CDCl_3) of compound **8**



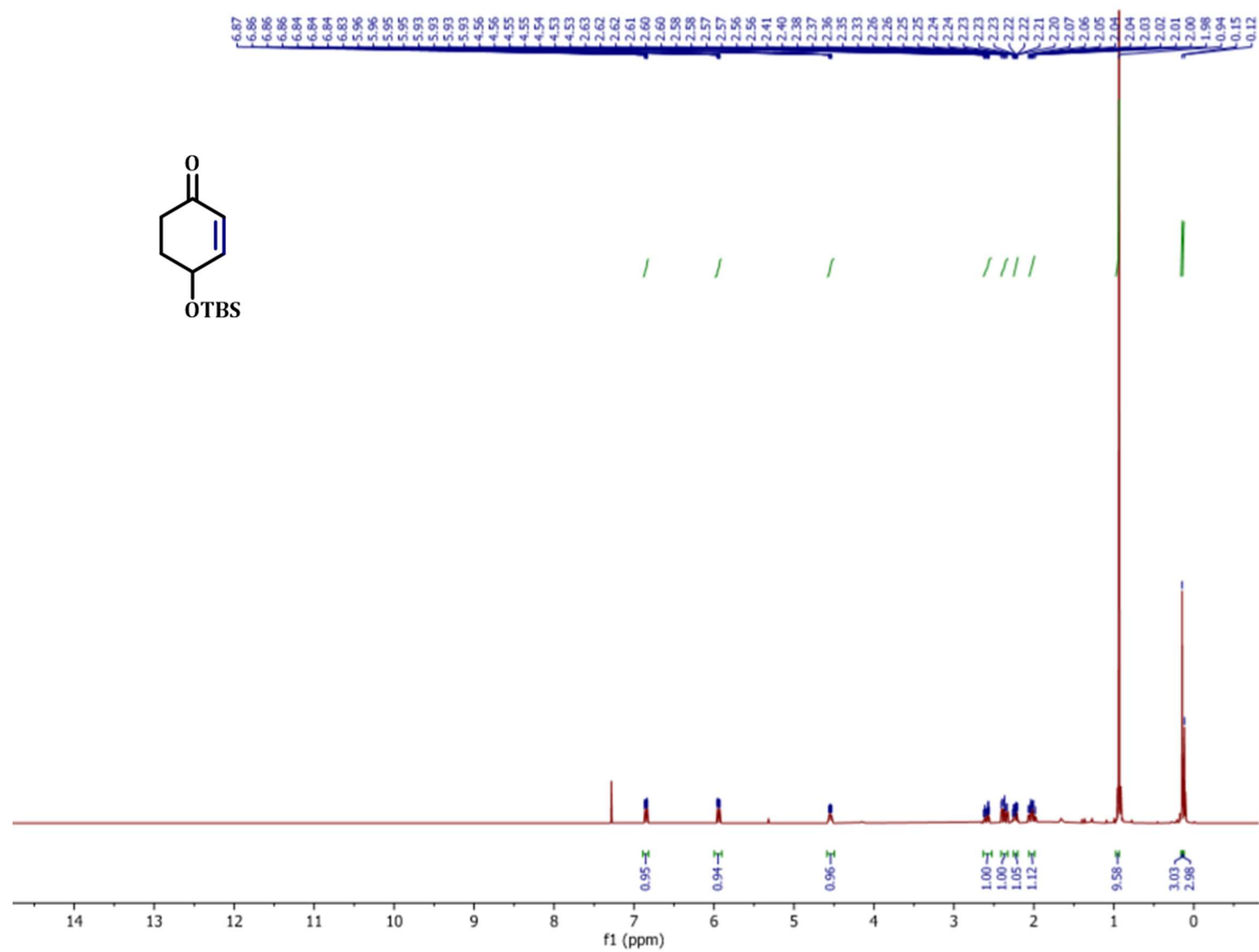
^1H NMR (500 MHz, CDCl_3) of compound **10**



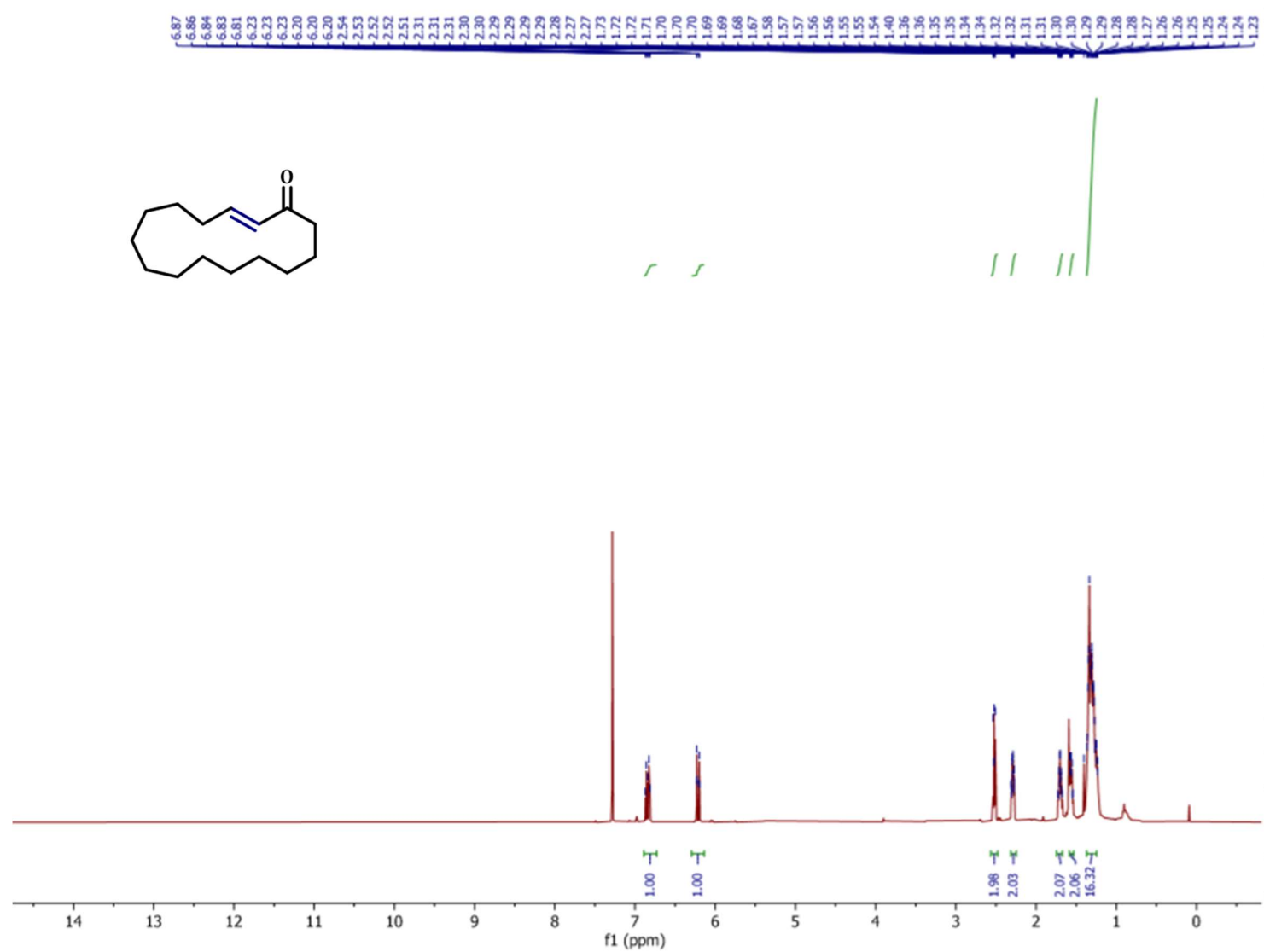
^{13}C NMR (126 MHz, CDCl_3) of compound **10**



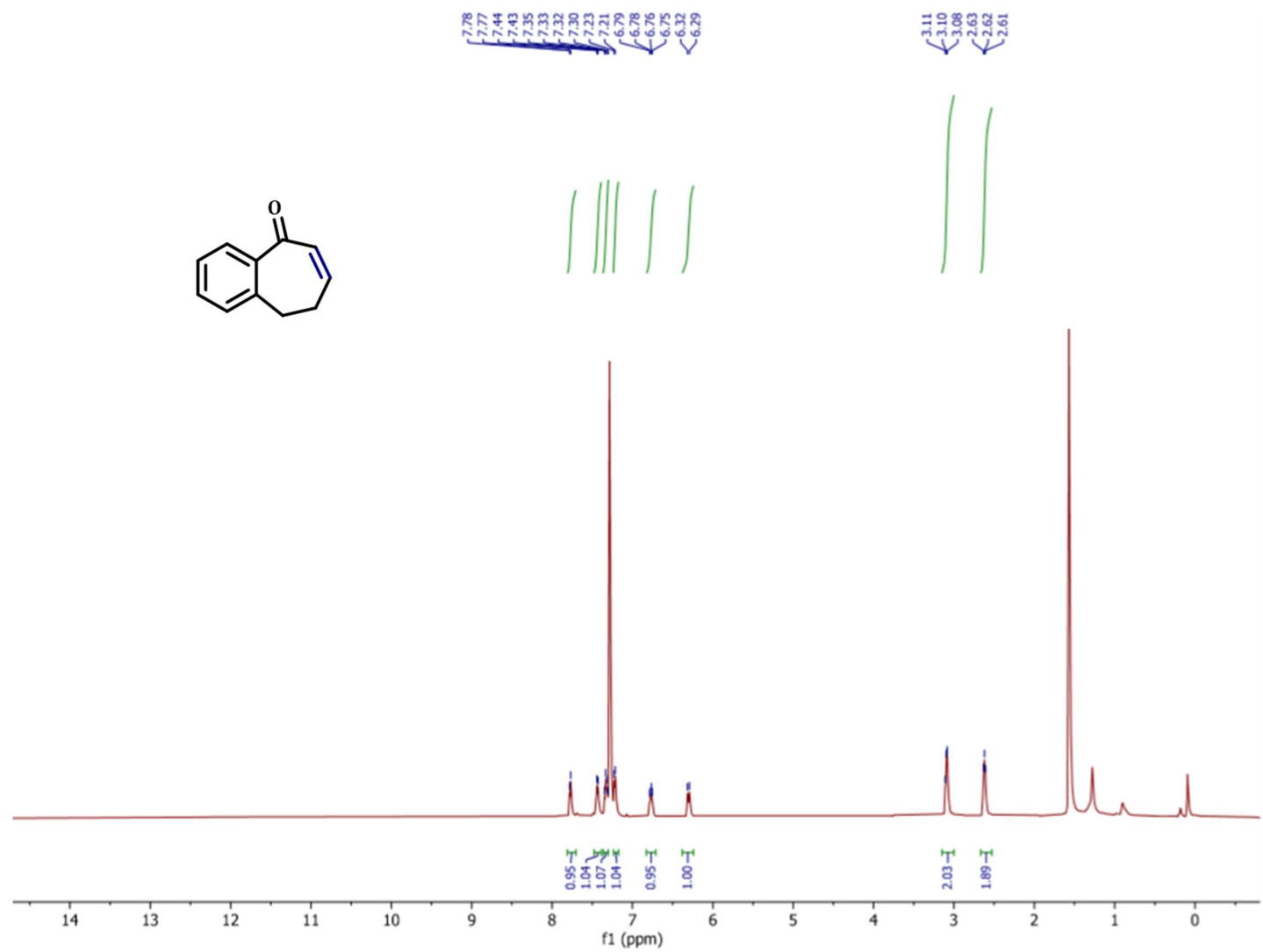
^1H NMR (400 MHz, CDCl_3) of compound **11**



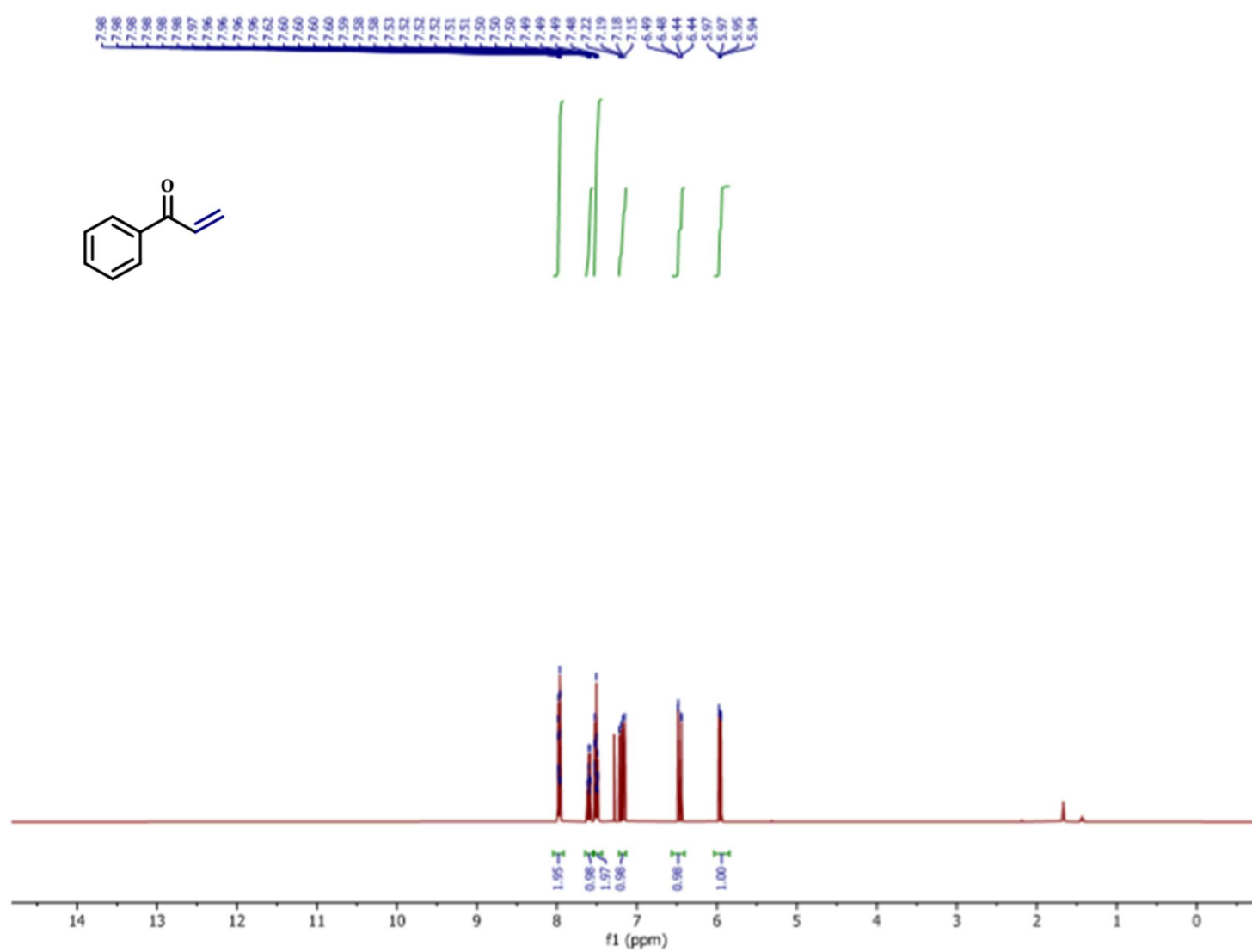
^1H NMR (500 MHz, CDCl_3) of compound **12**



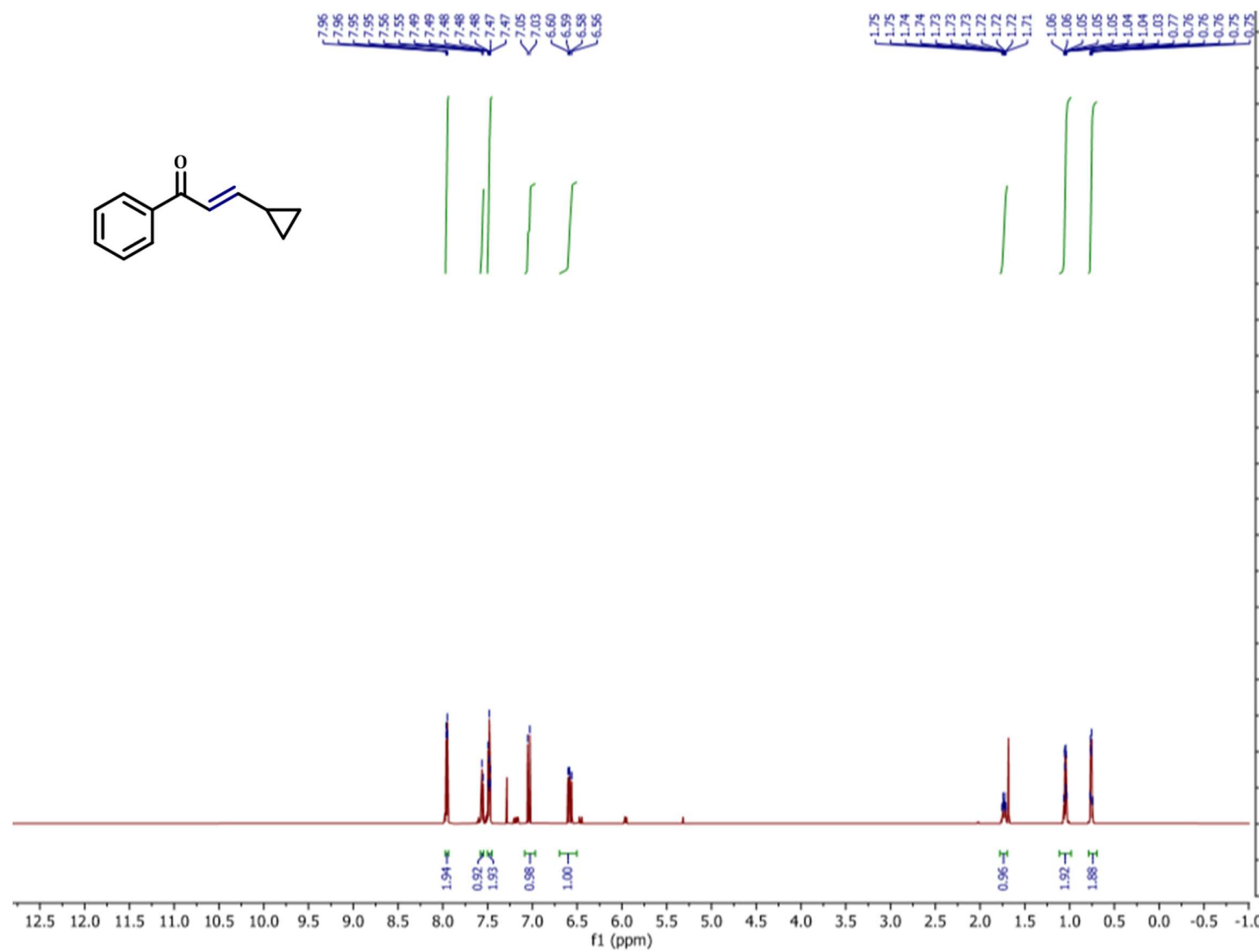
^1H NMR (500 MHz, CDCl_3) of compound **13**



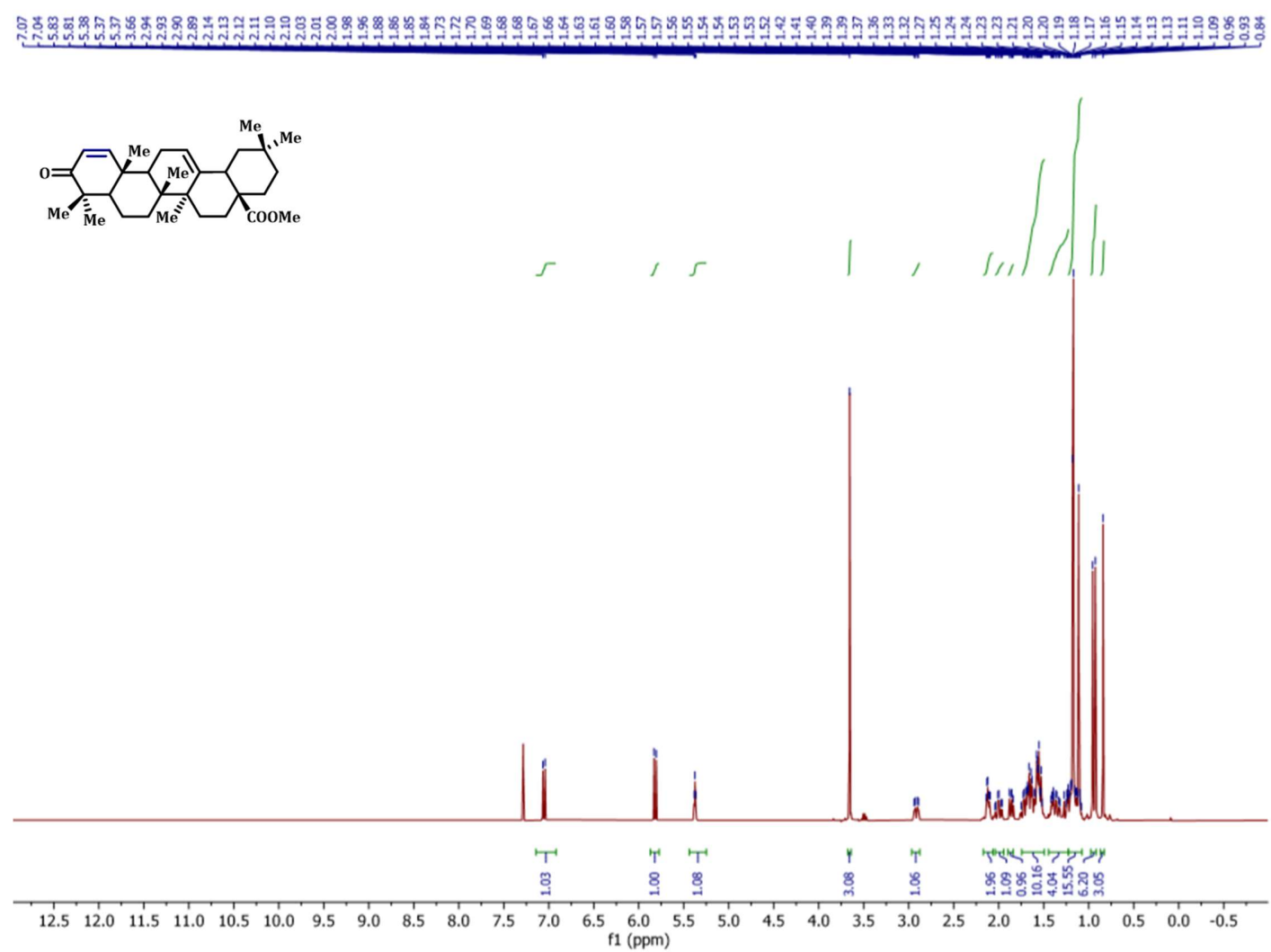
^1H NMR (400 MHz, CDCl_3) of compound **14**



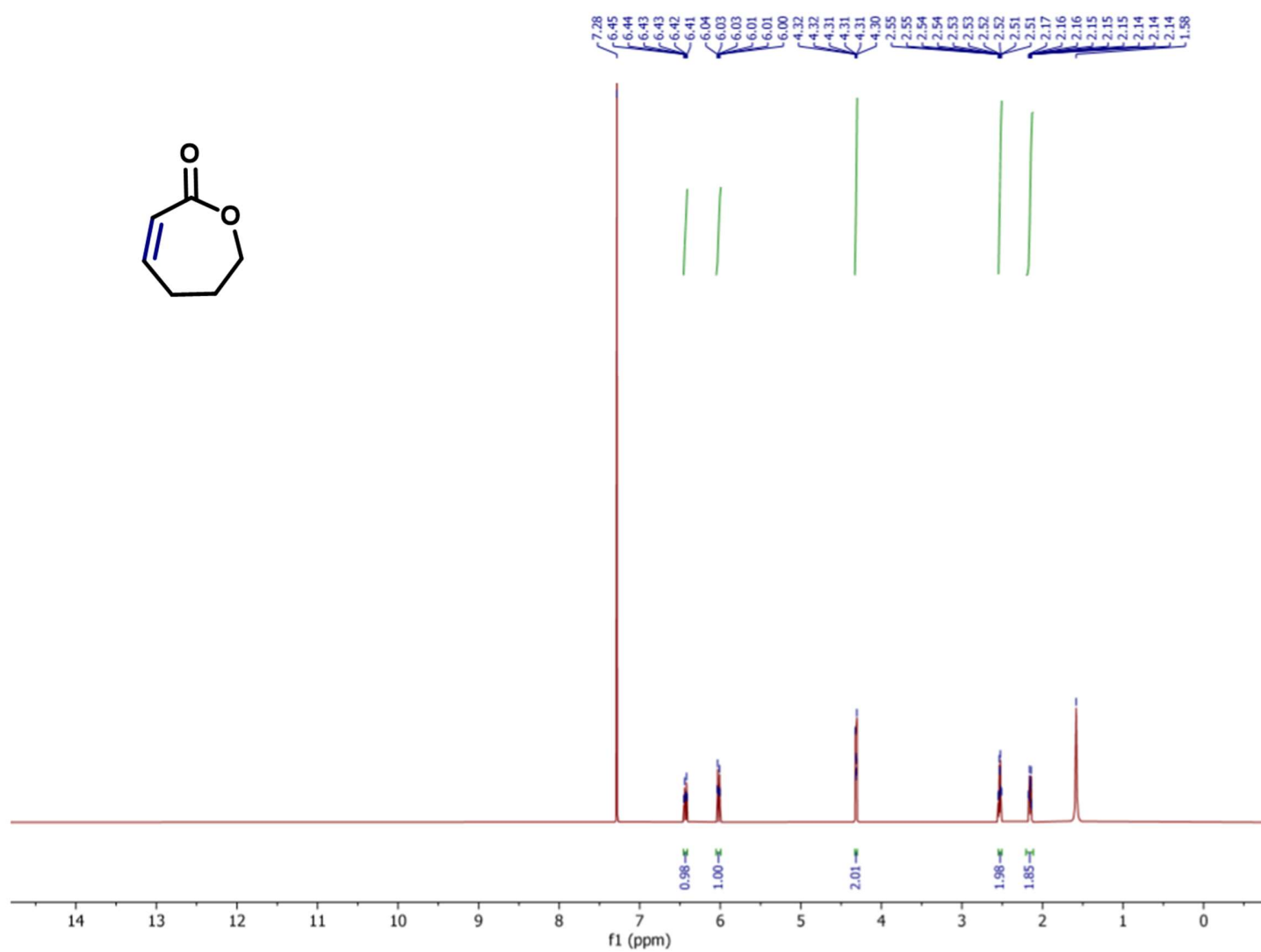
^1H NMR (600 MHz, CDCl_3) of compound **15**



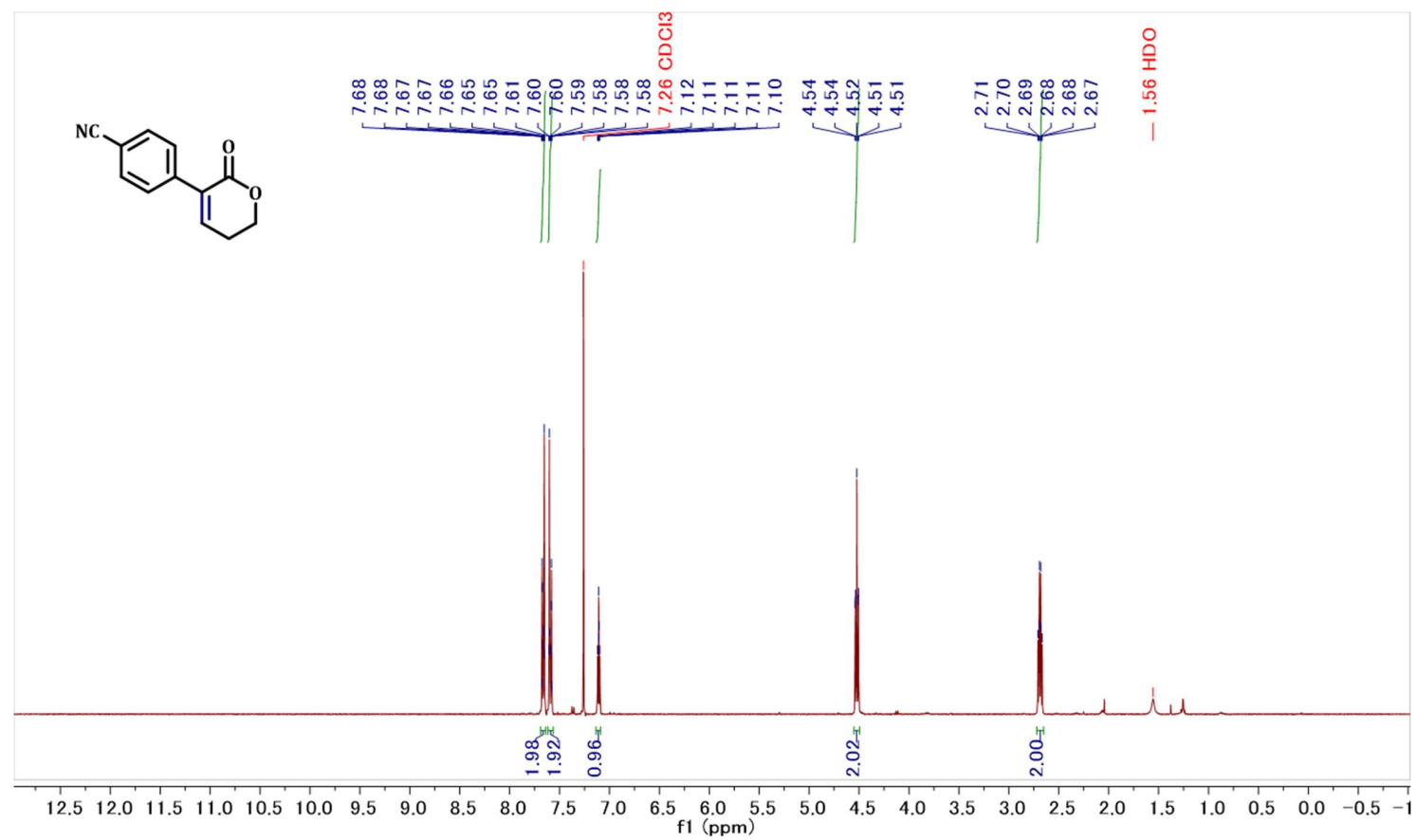
^1H NMR (400 MHz, CDCl_3) of compound **17**



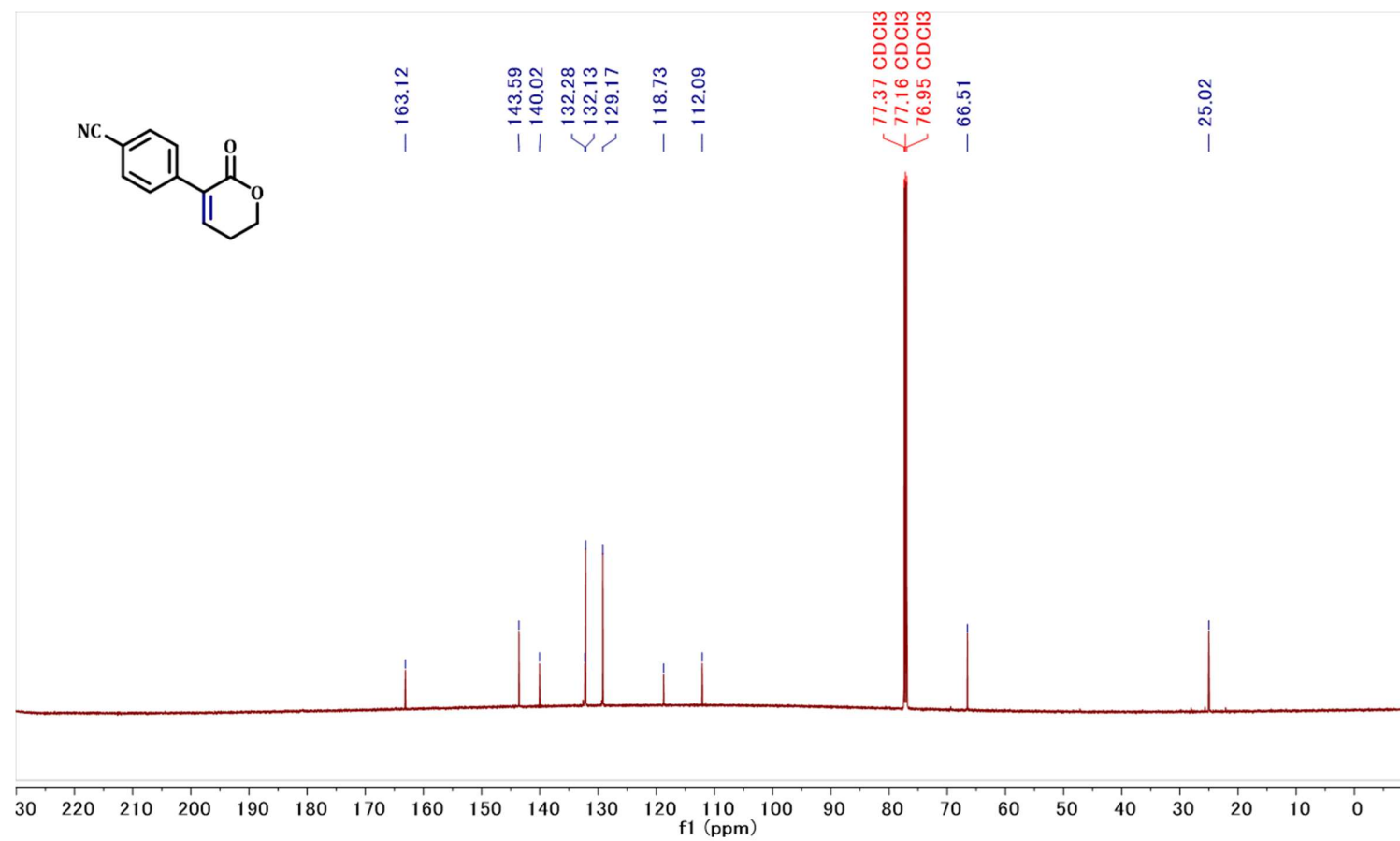
^1H NMR (400 MHz, CDCl_3) of compound **19**



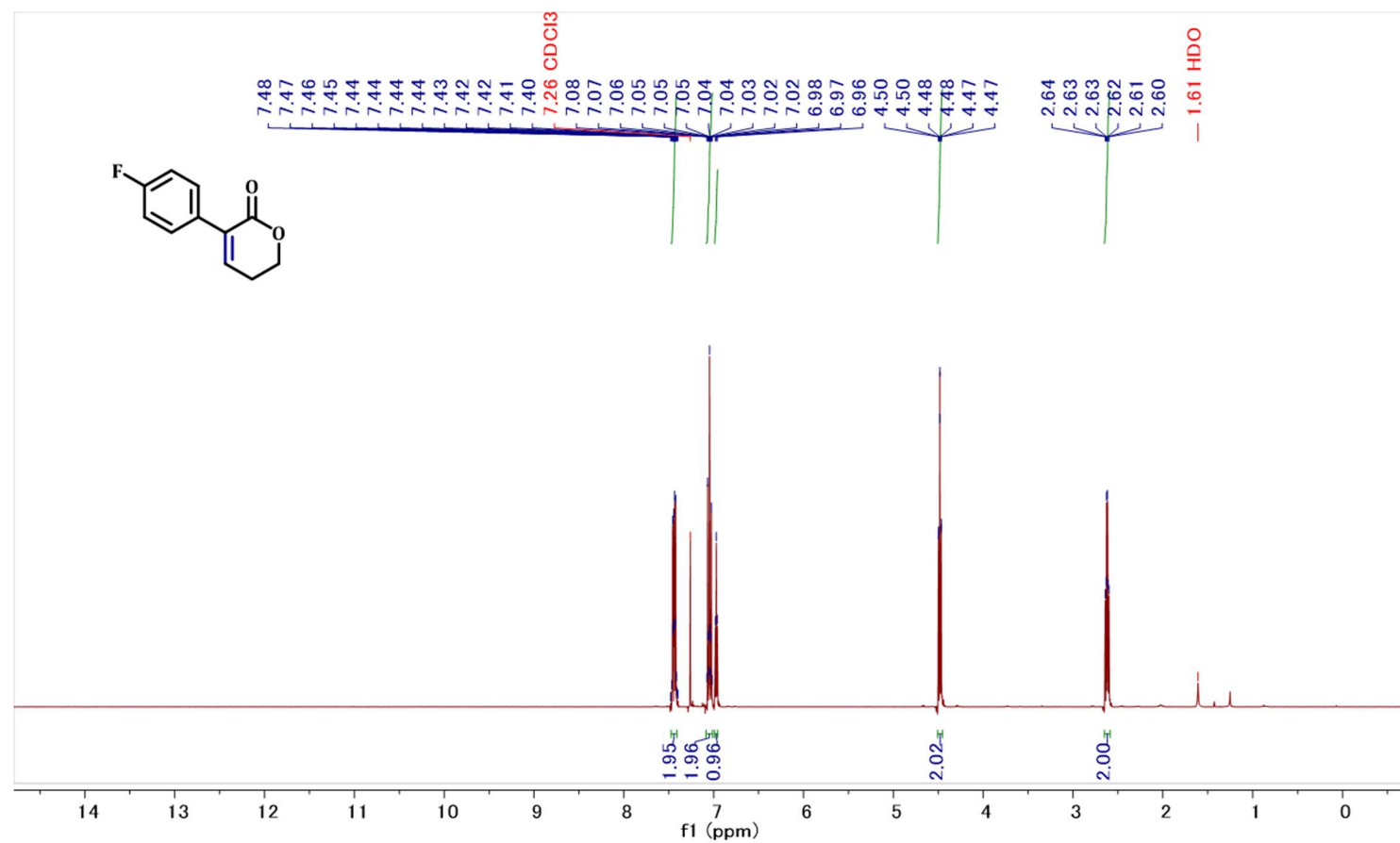
^1H NMR (400 MHz, CDCl_3) of compound **20**



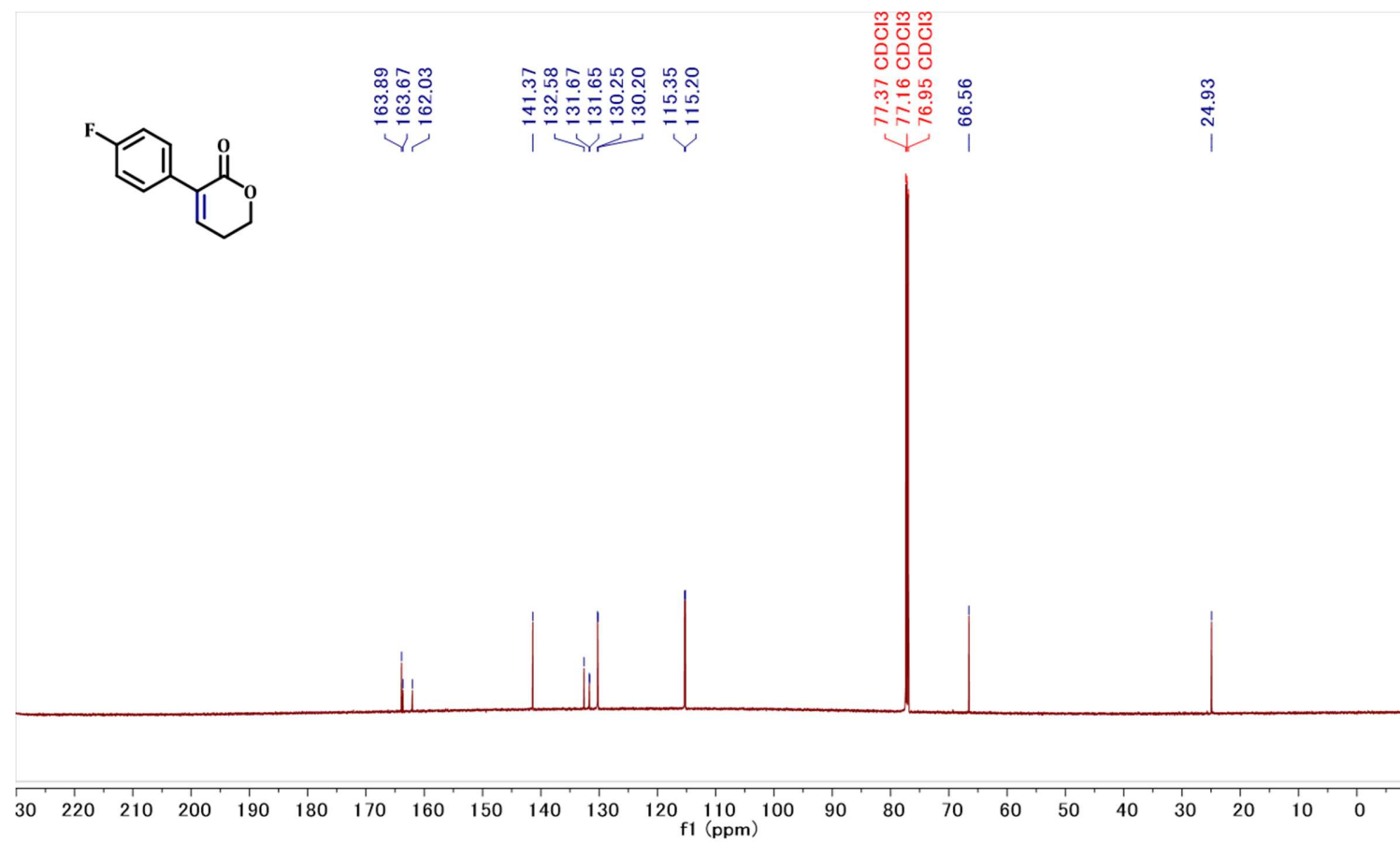
^{13}C NMR (151 MHz, CDCl_3) of compound **20**



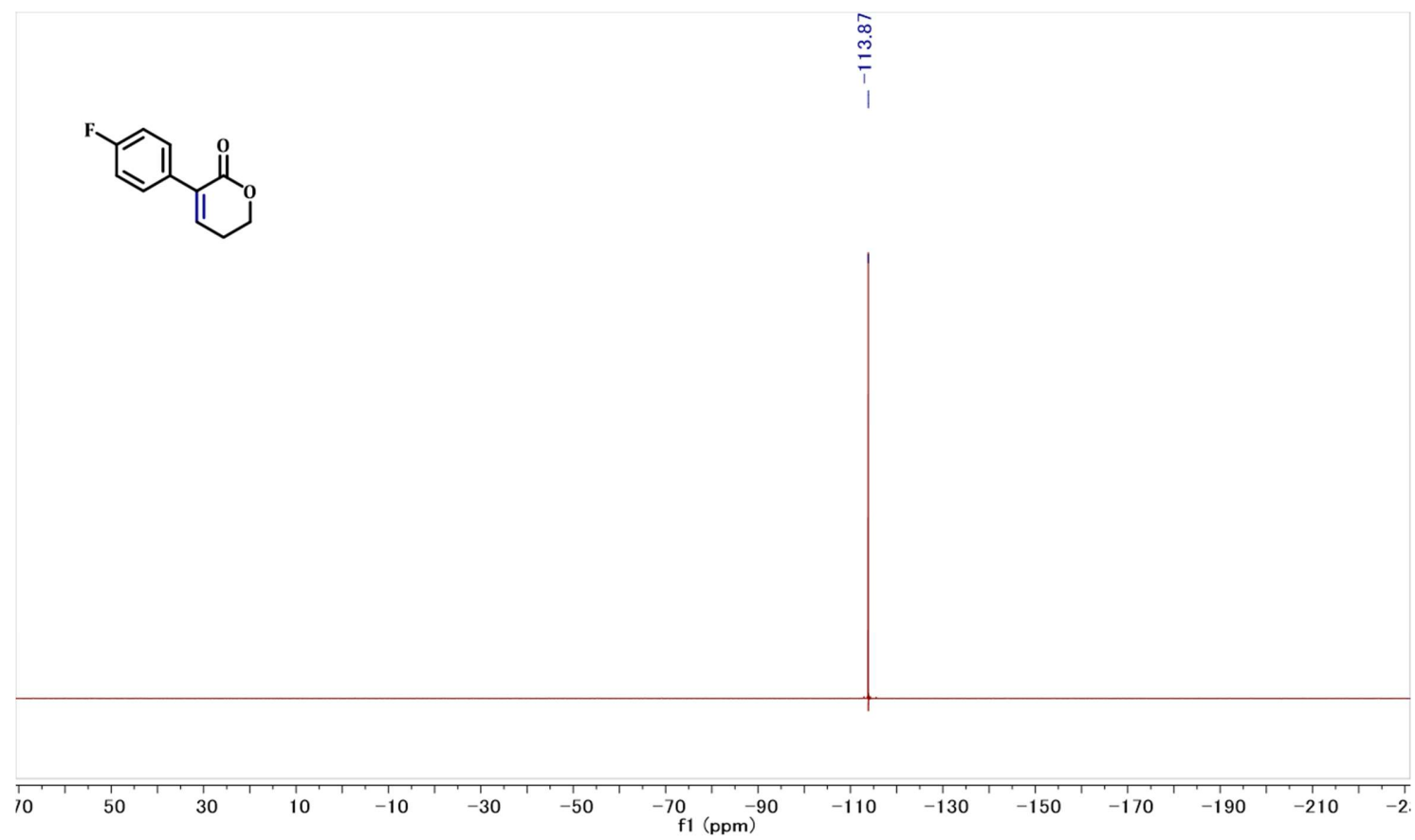
^1H NMR (400 MHz, CDCl_3) of compound **21**



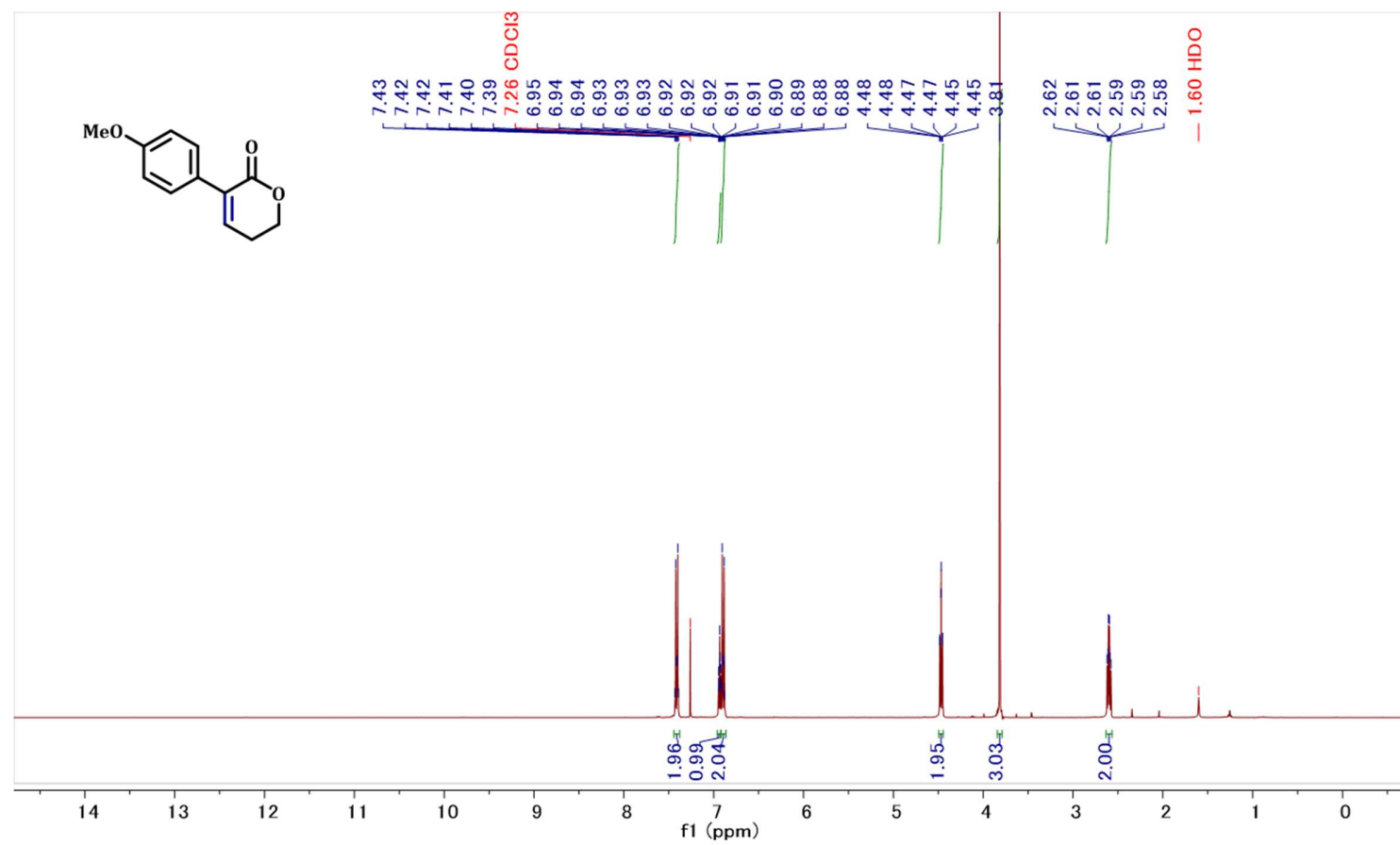
^{13}C NMR (151 MHz, CDCl_3) of compound **21**



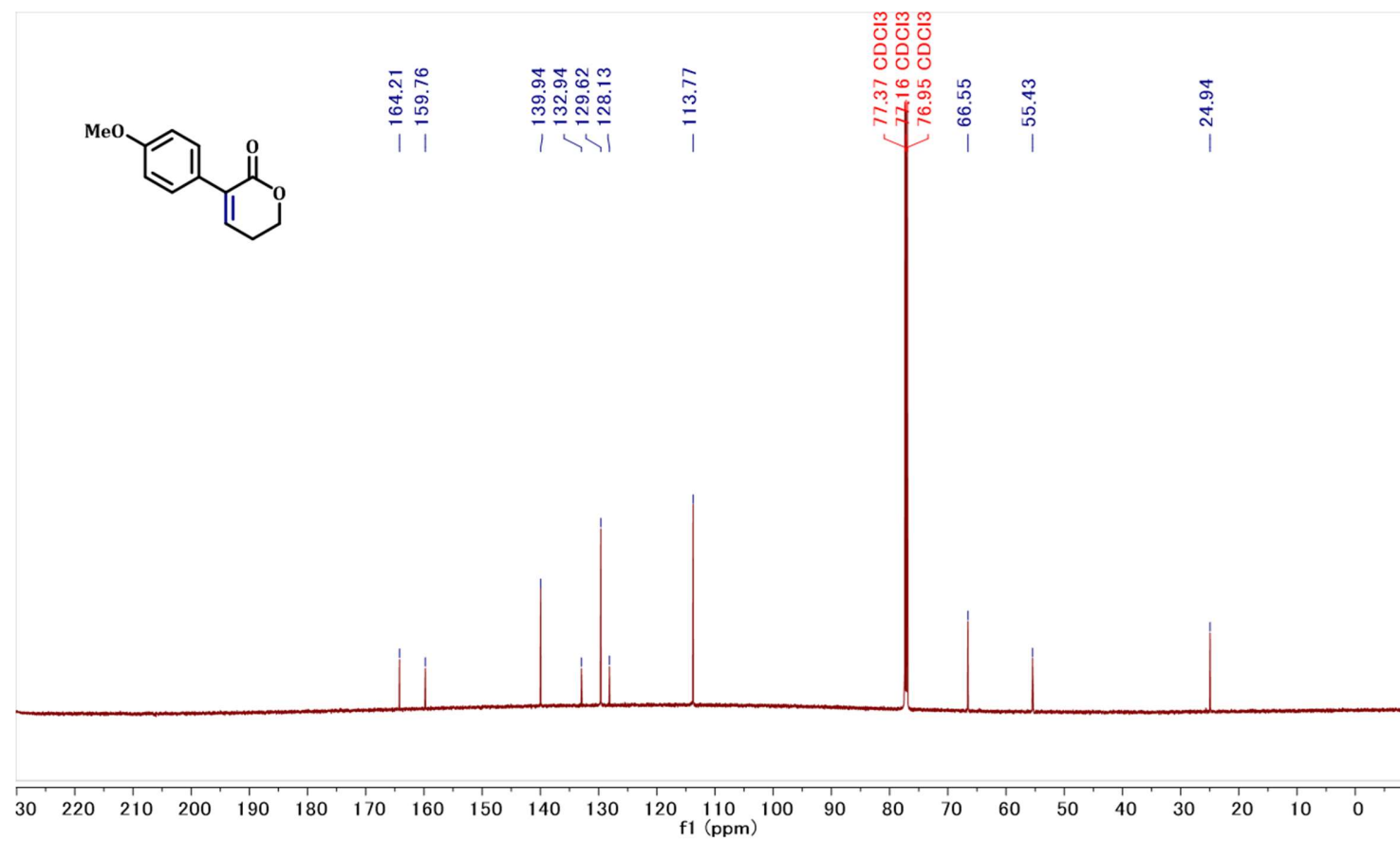
^{19}F NMR (376 MHz, CDCl_3) of compound **21**



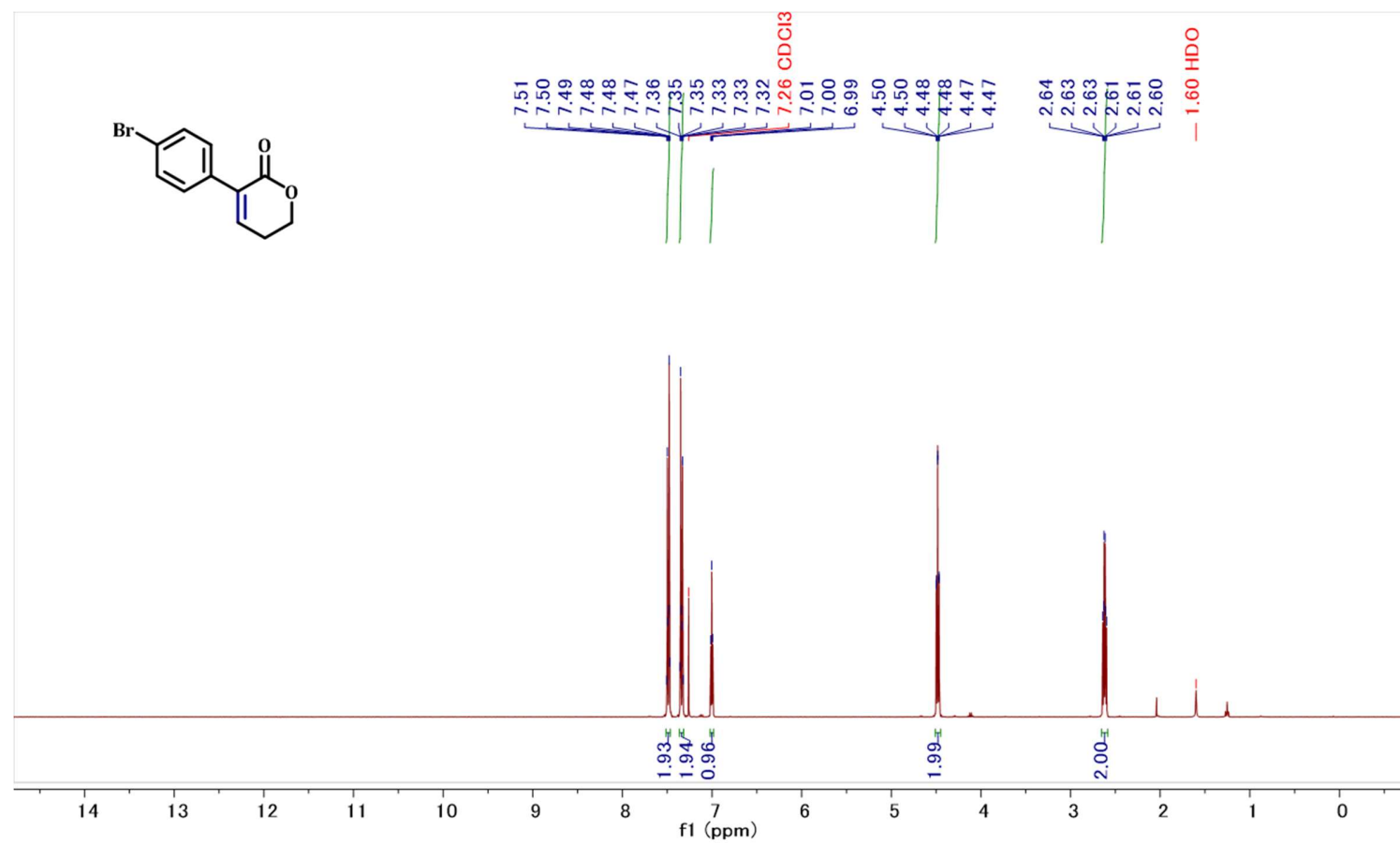
^1H NMR (400 MHz, CDCl_3) of compound **22**



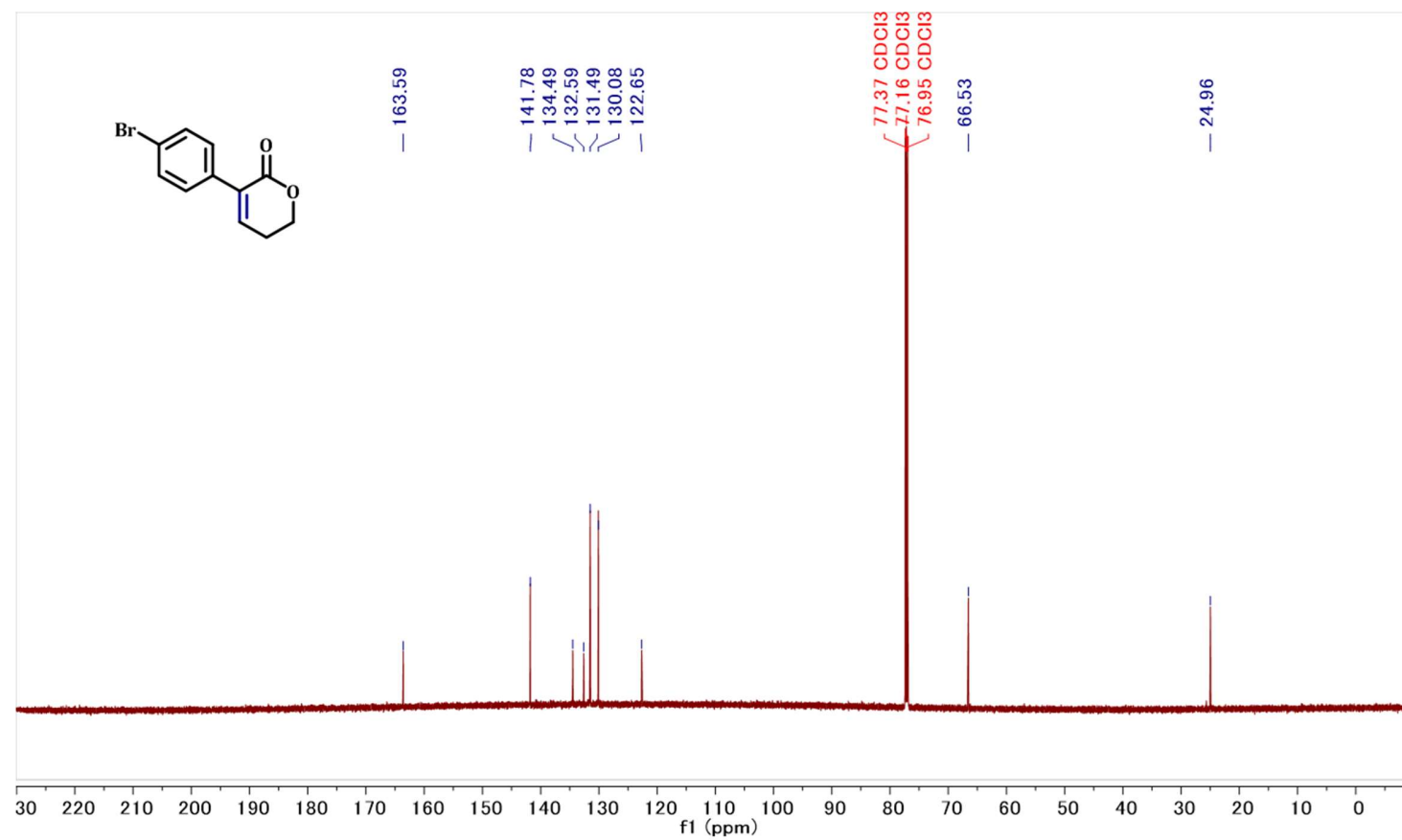
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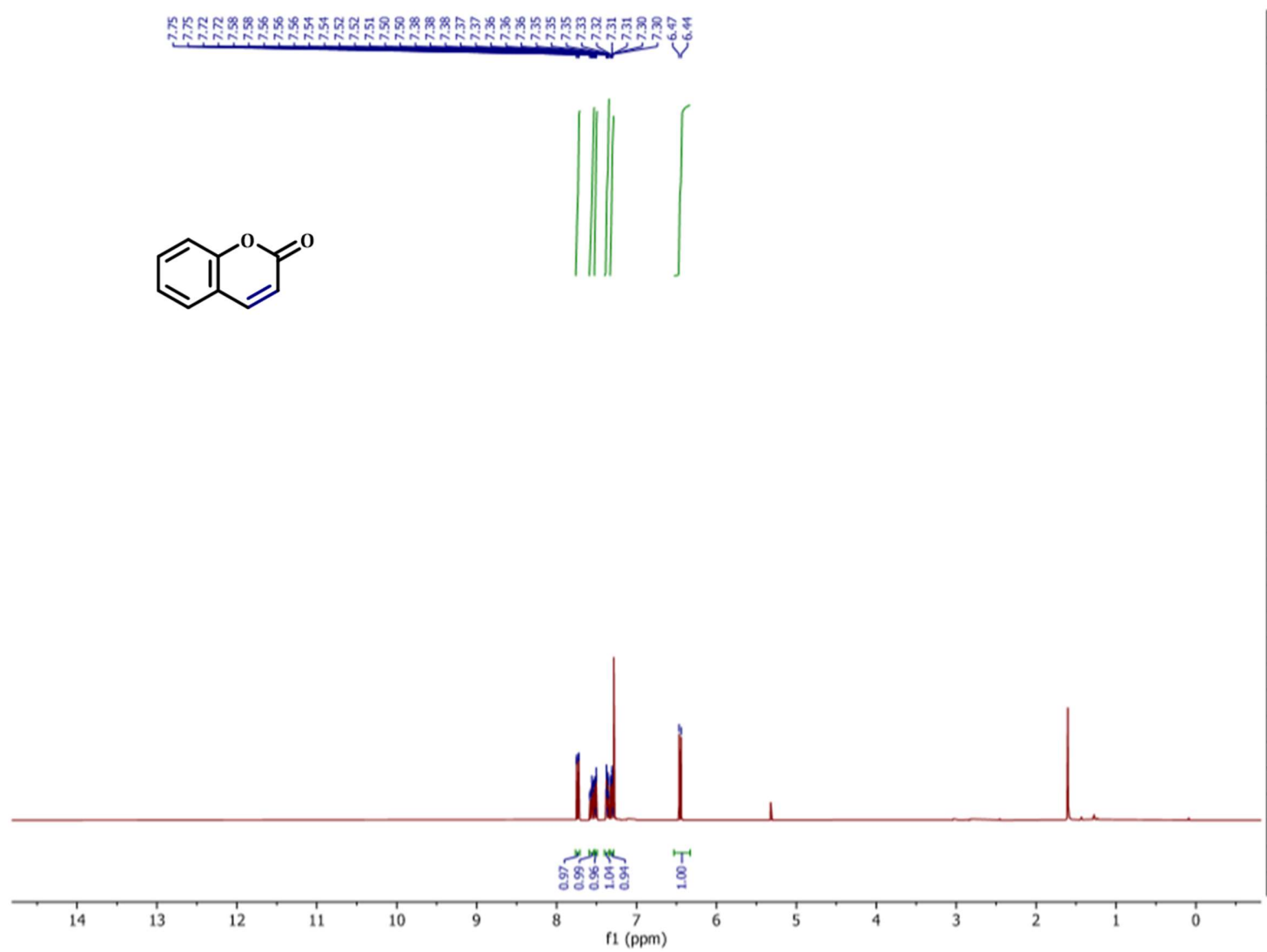
^1H NMR (400 MHz, CDCl_3) of compound **23**



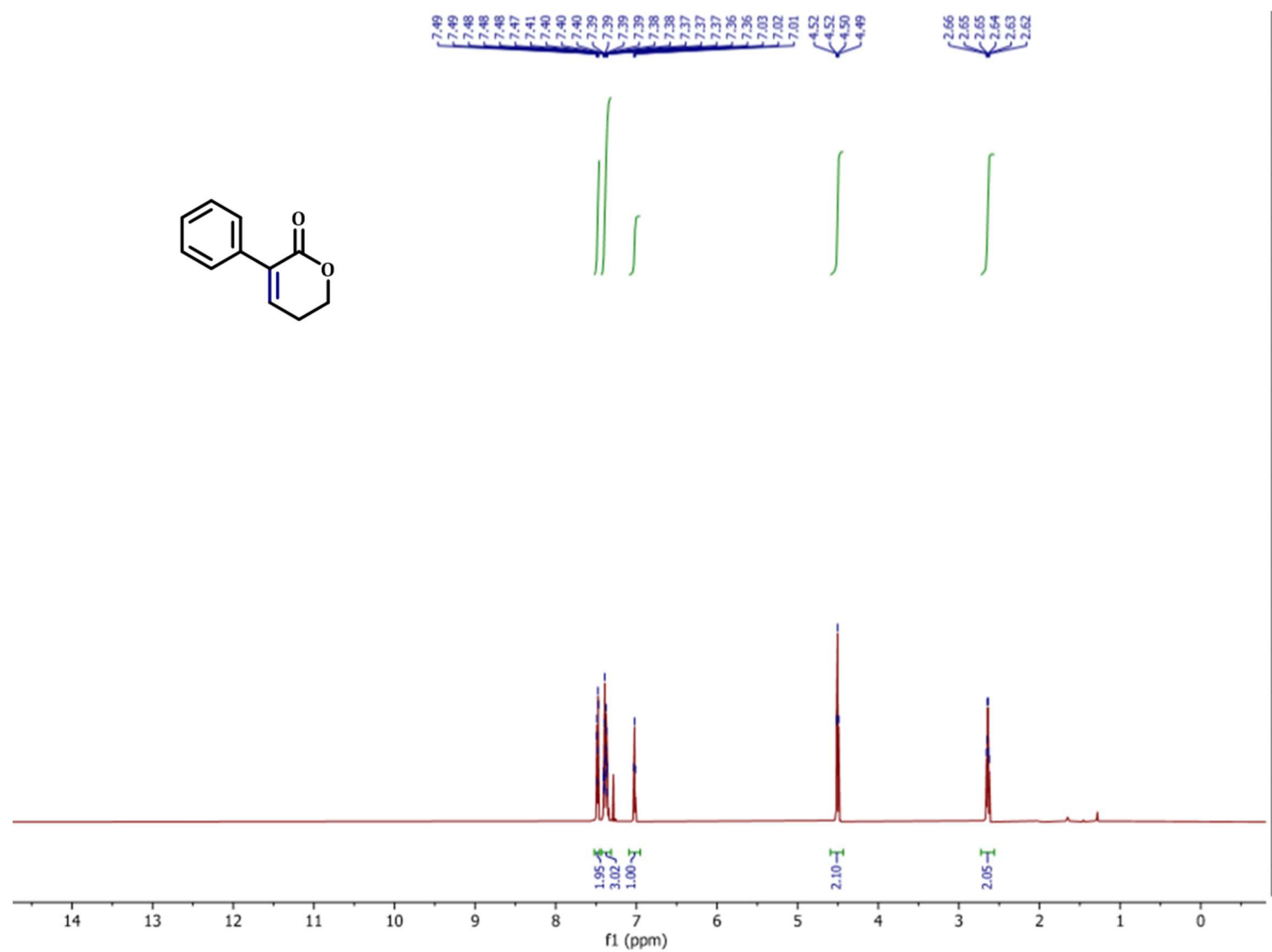
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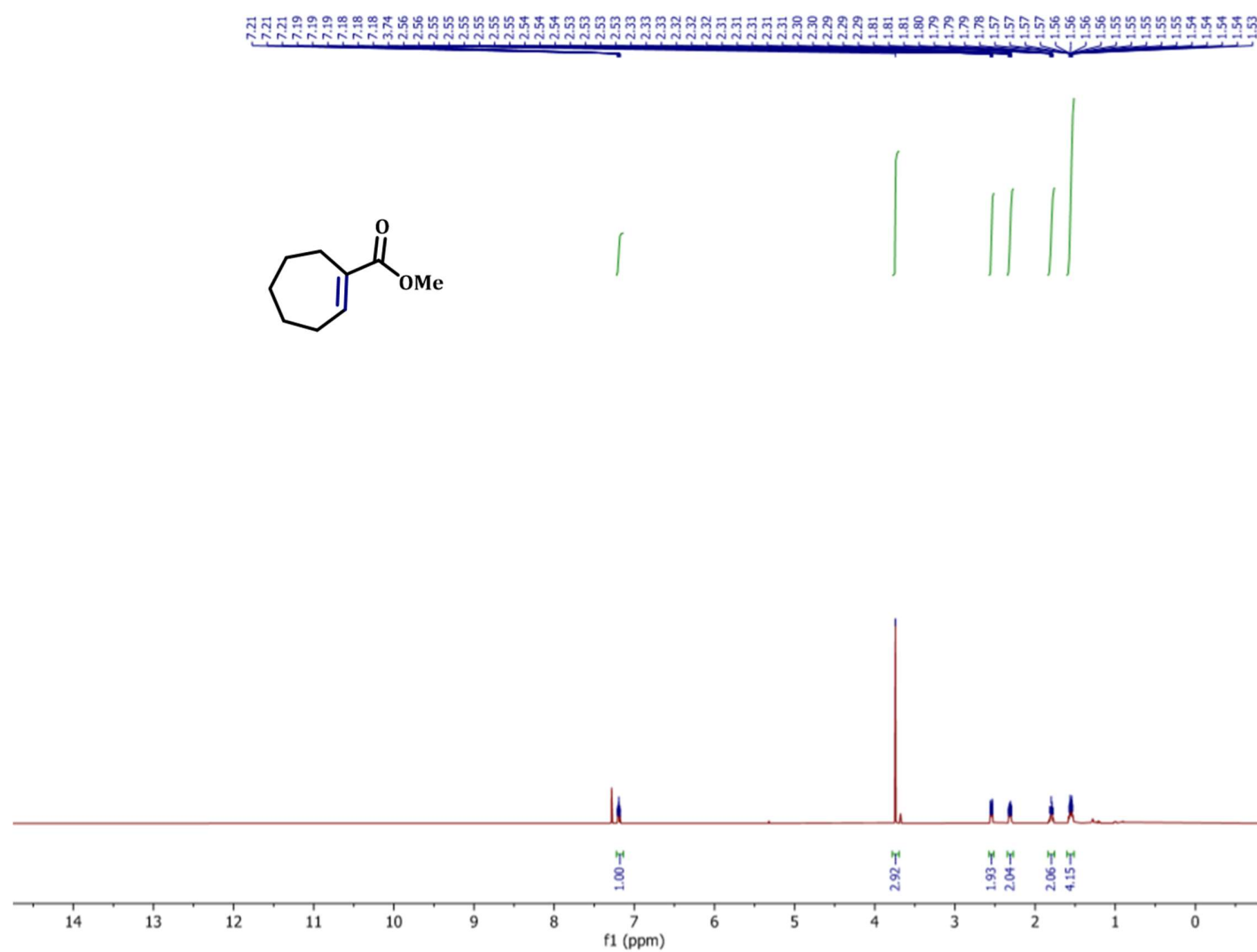
^1H NMR (400 MHz, CDCl_3) of compound **24**



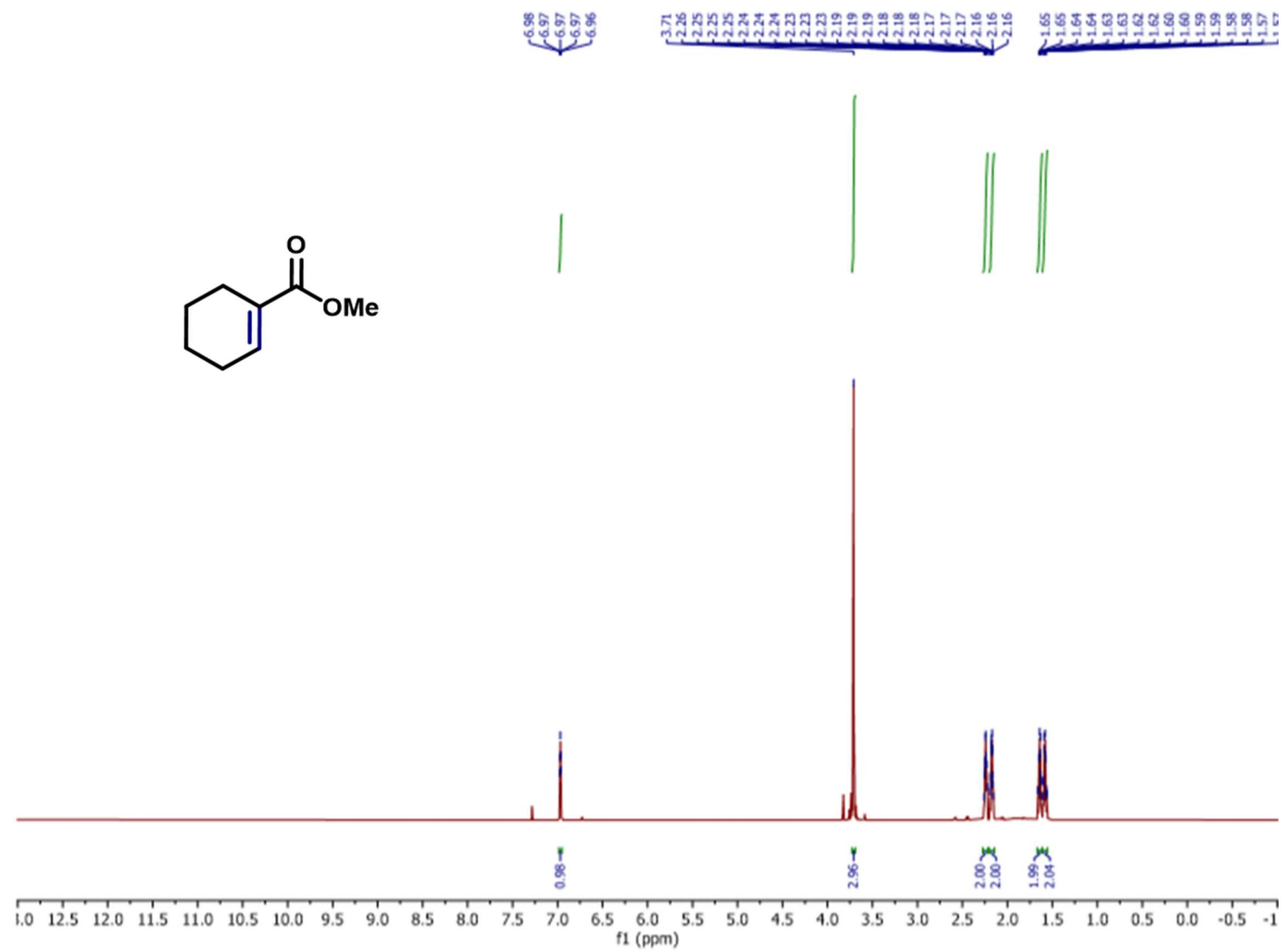
^1H NMR (500 MHz, CDCl_3) of compound **25**



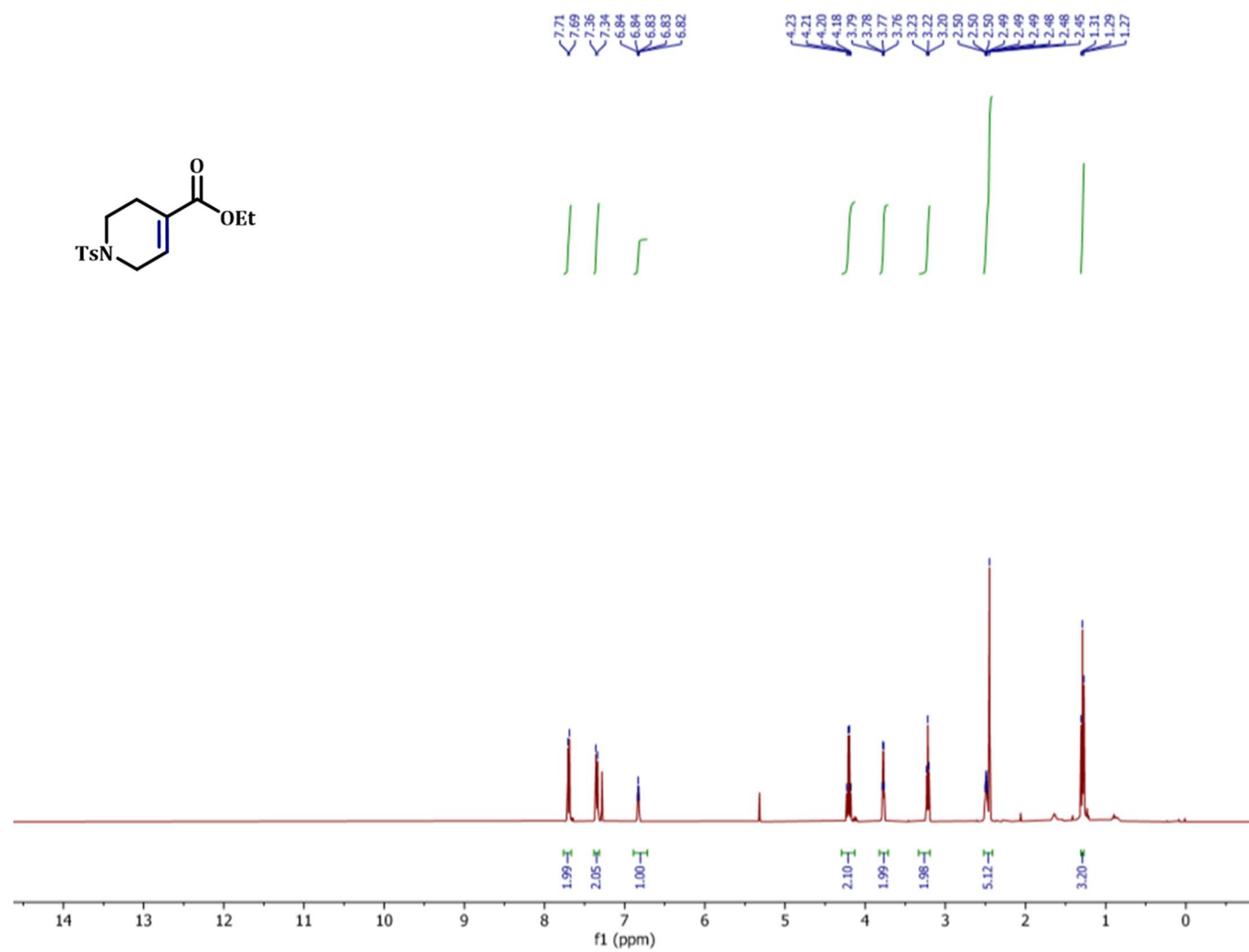
^1H NMR (500 MHz, CDCl_3) of compound **26**



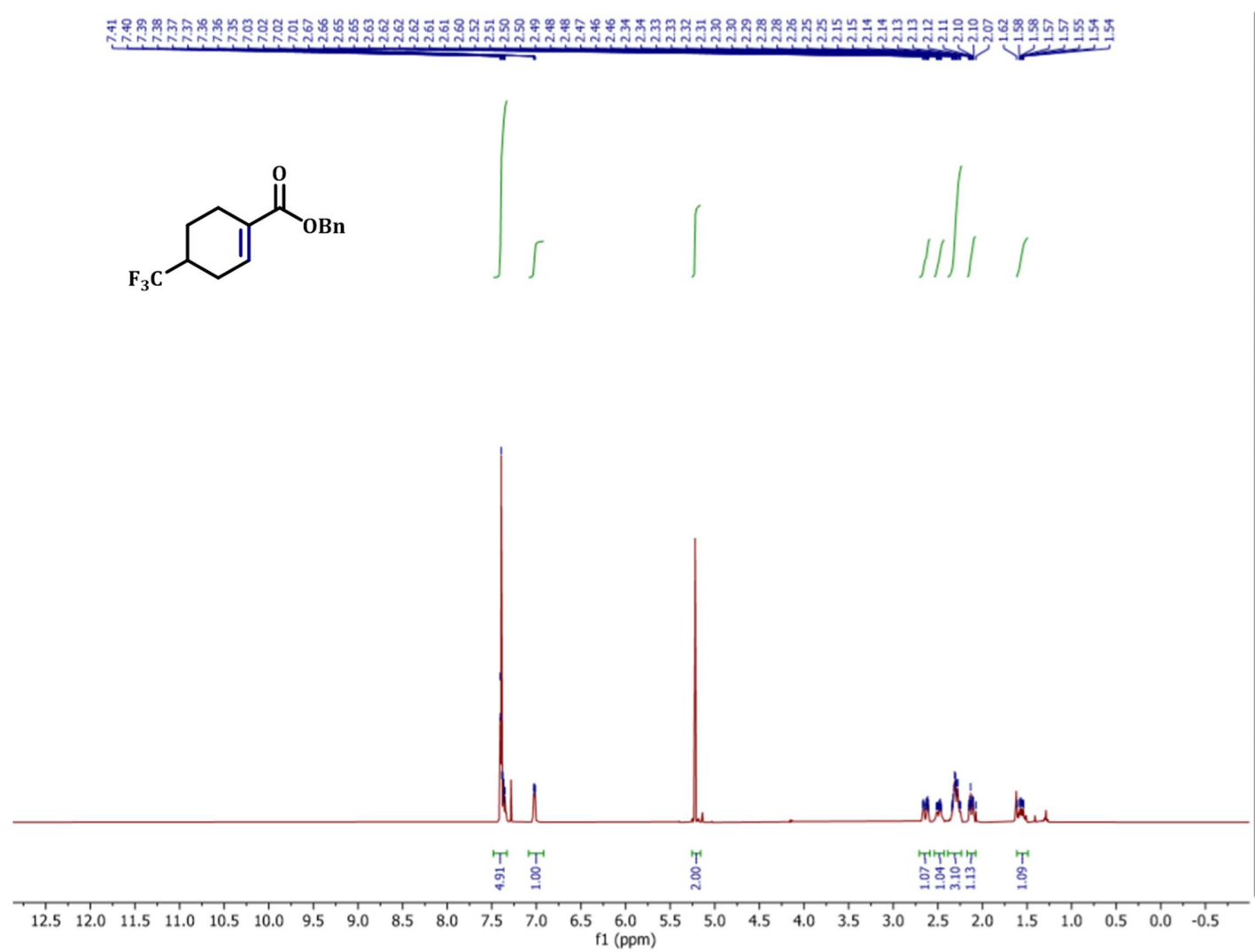
^1H NMR (400 MHz, CDCl_3) of compound **27**



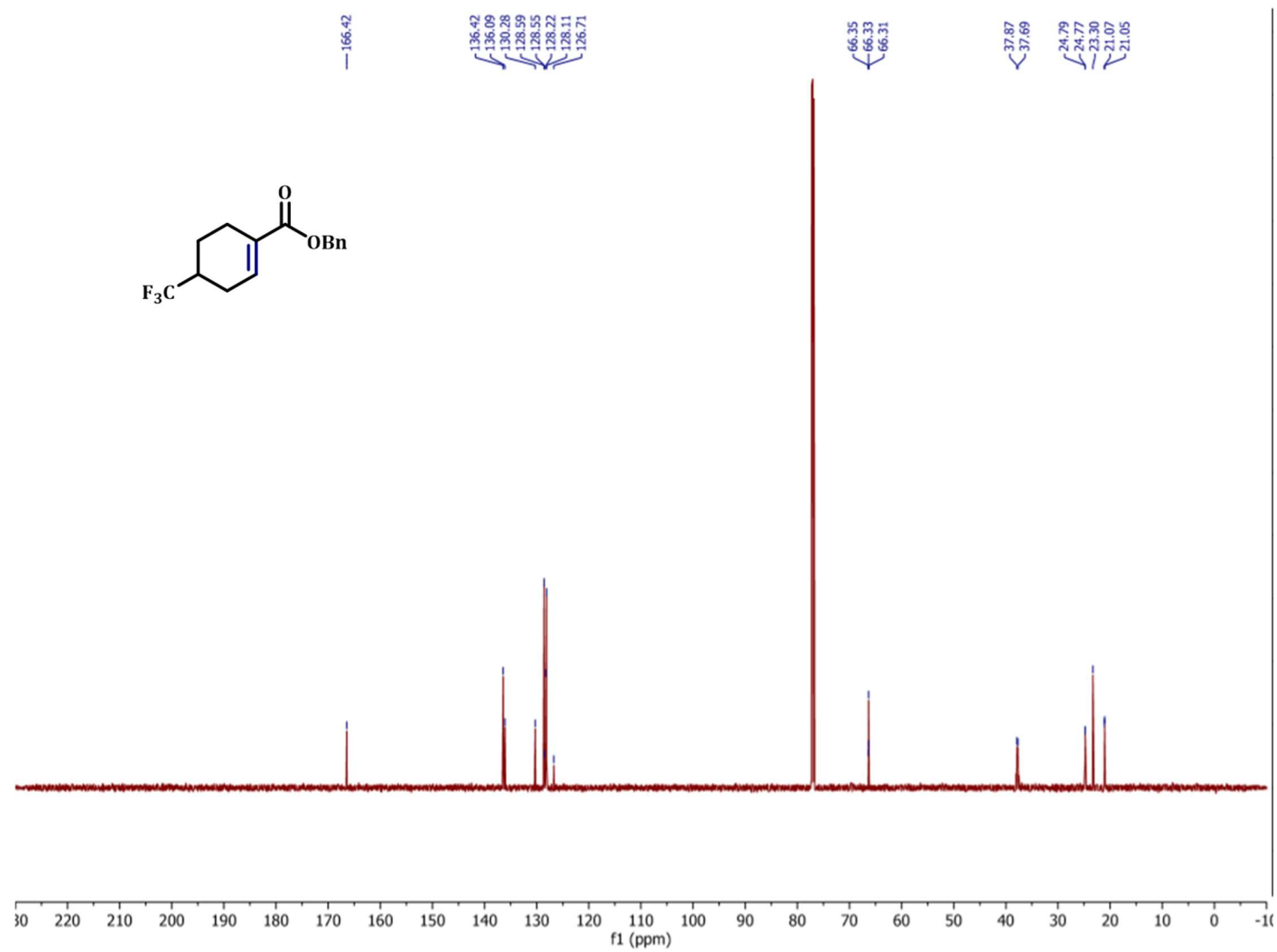
^1H NMR (400 MHz, CDCl_3) of compound **28**



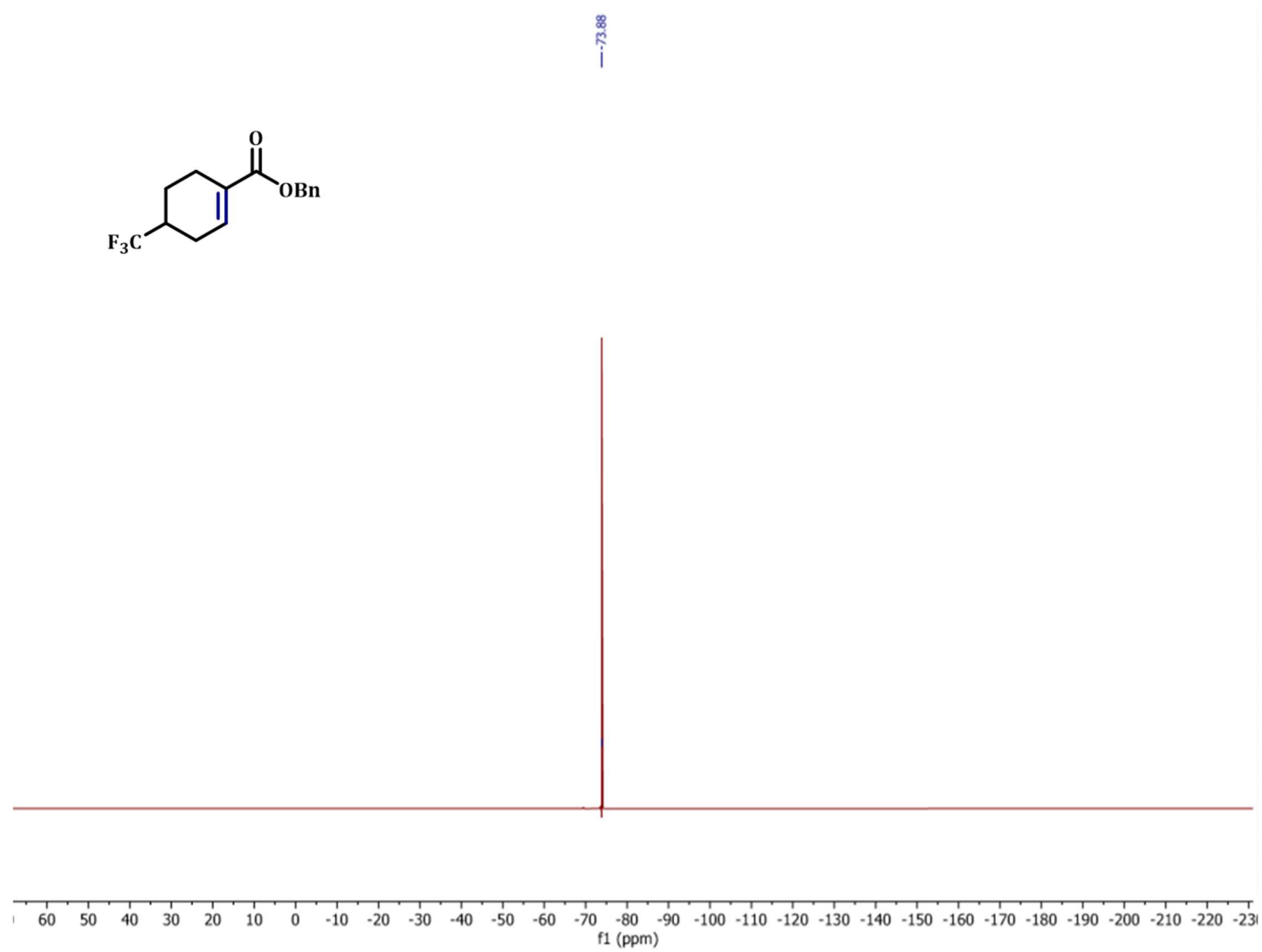
^1H NMR (400 MHz, CDCl_3) of compound **29**



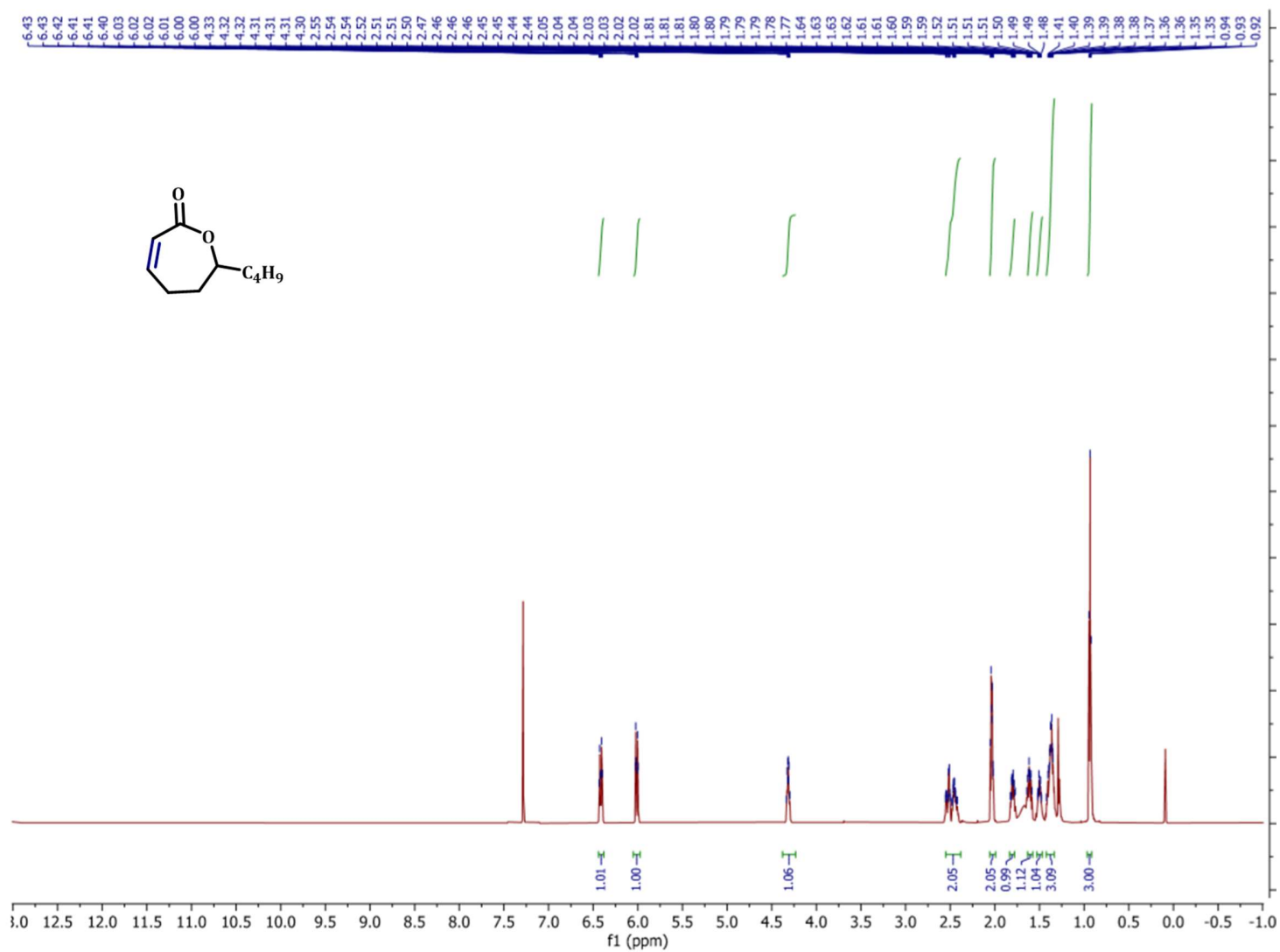
^{13}C NMR (151 MHz, CDCl_3) of compound **29**



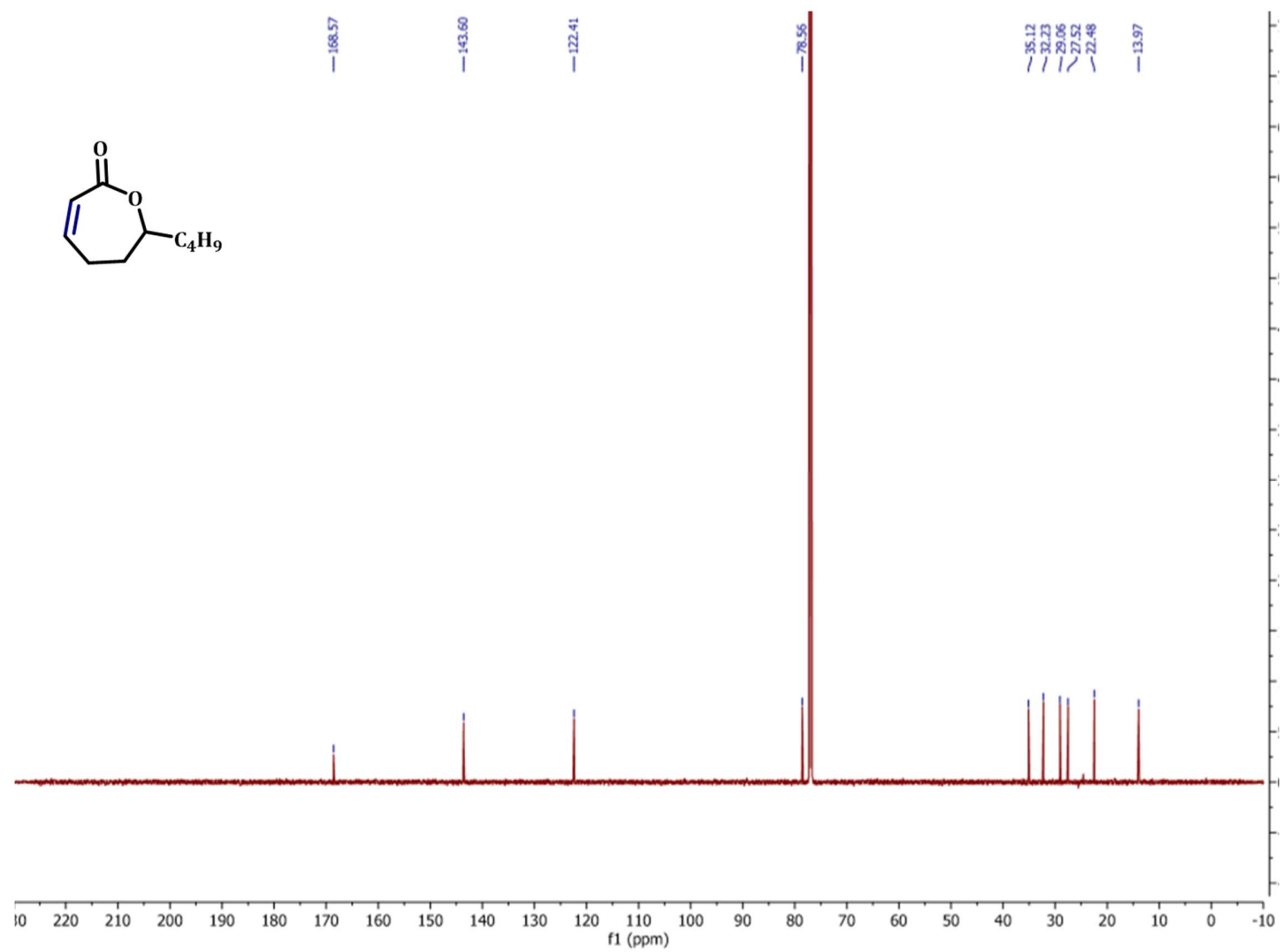
^{19}F NMR (376 MHz, CDCl_3) of compound **29**



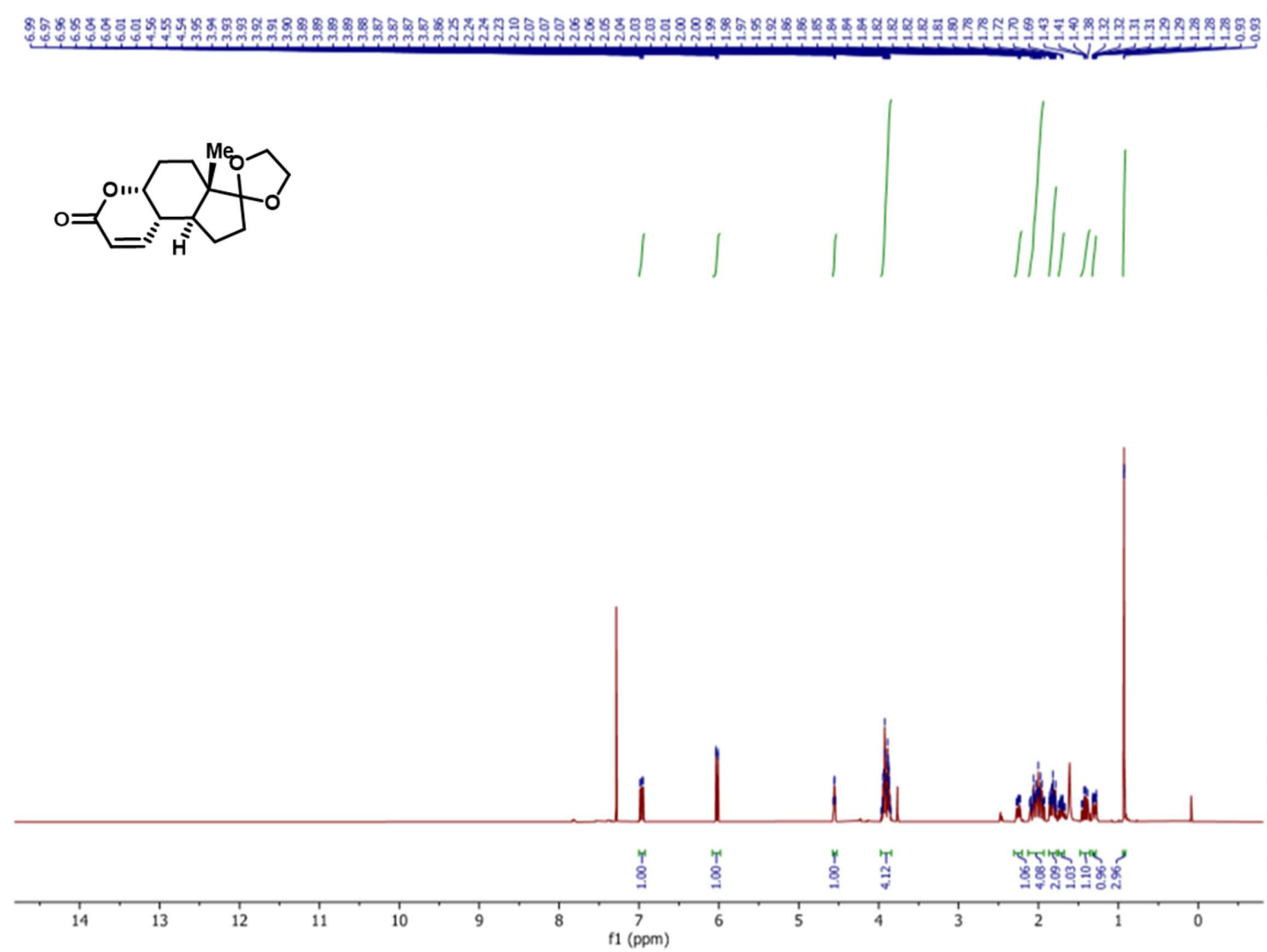
^1H NMR (600 MHz, CDCl_3) of compound **30**



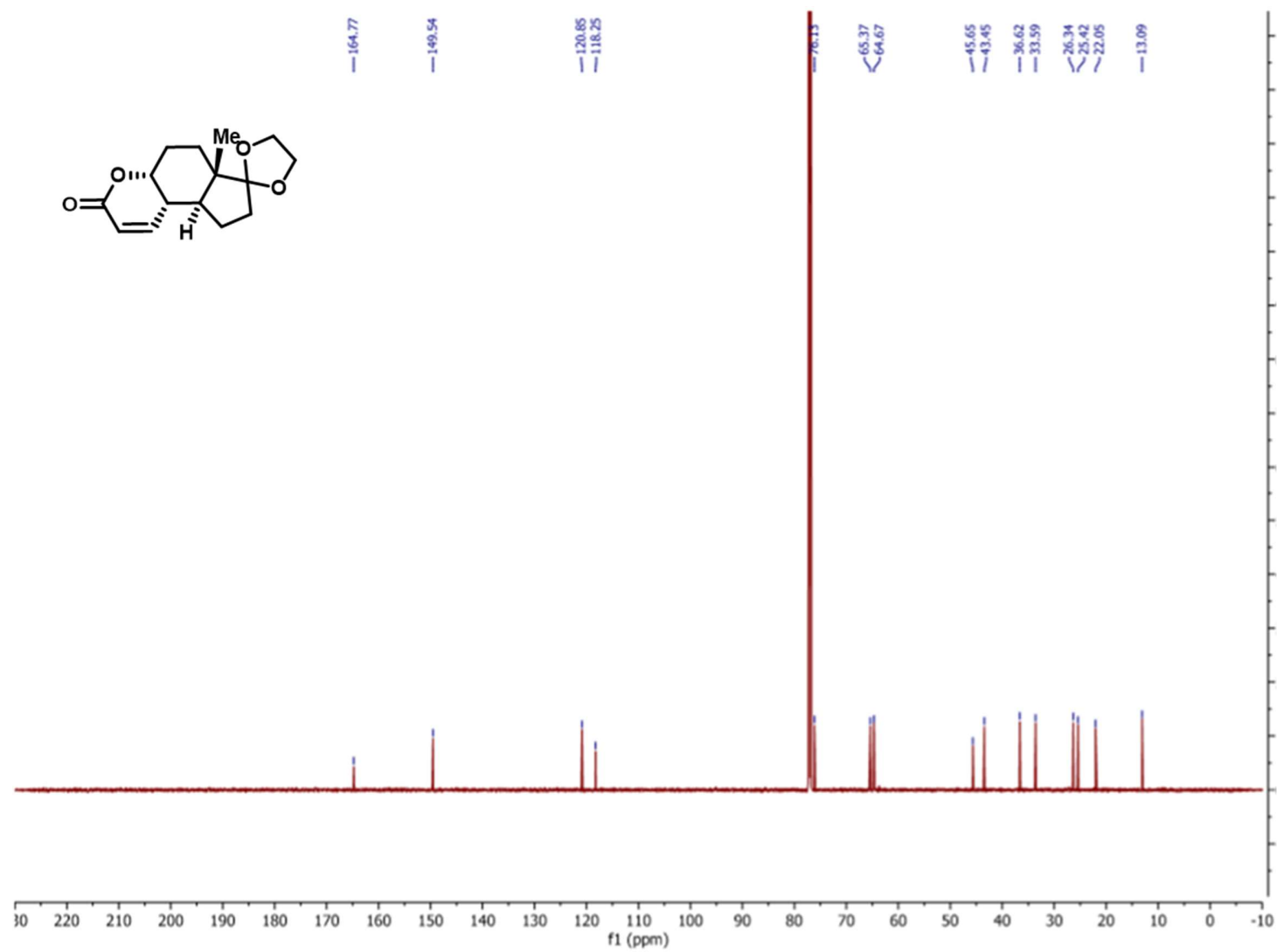
^{13}C NMR (151 MHz, CDCl_3) of compound **30**



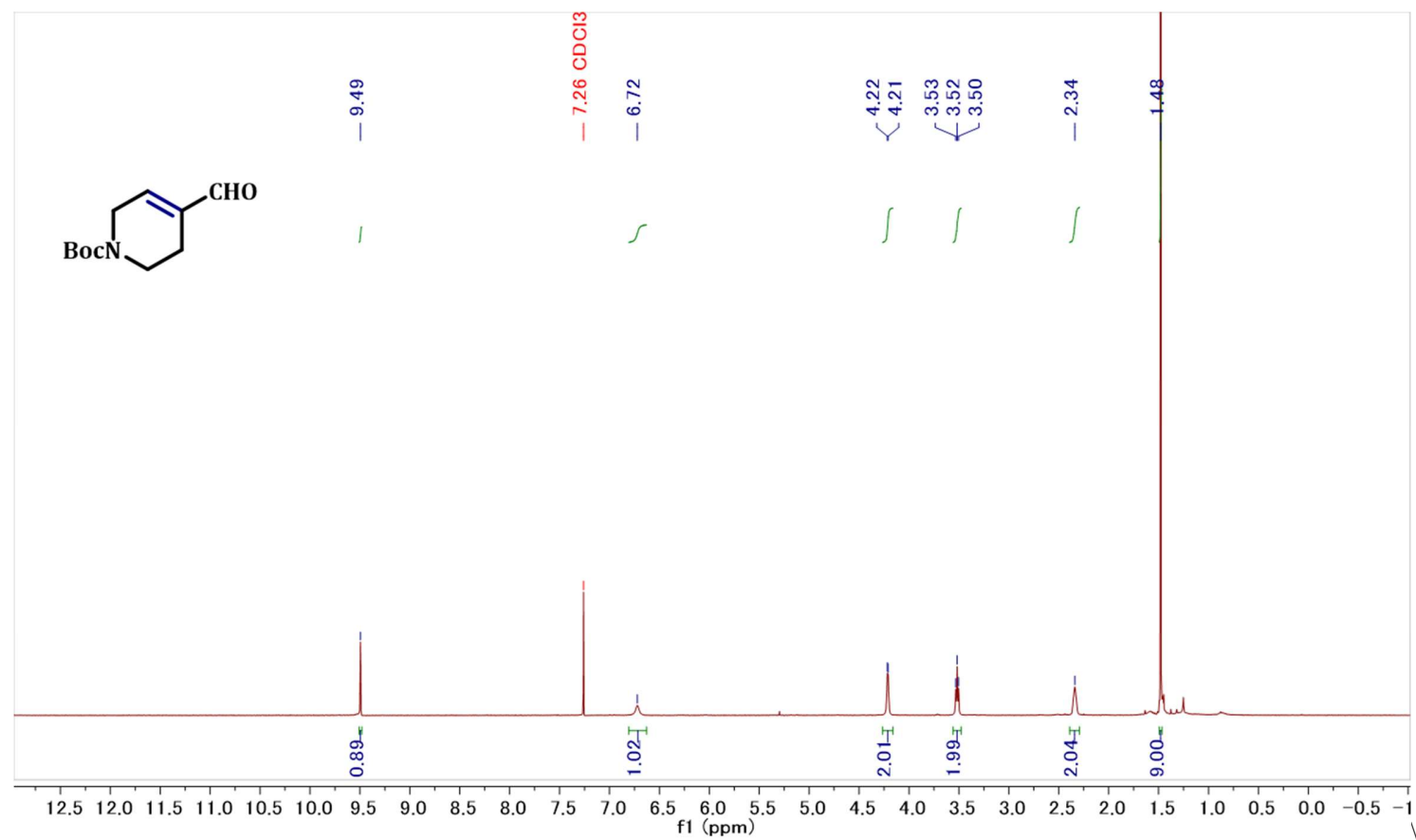
^1H NMR (400 MHz, CDCl_3) of compound **31**



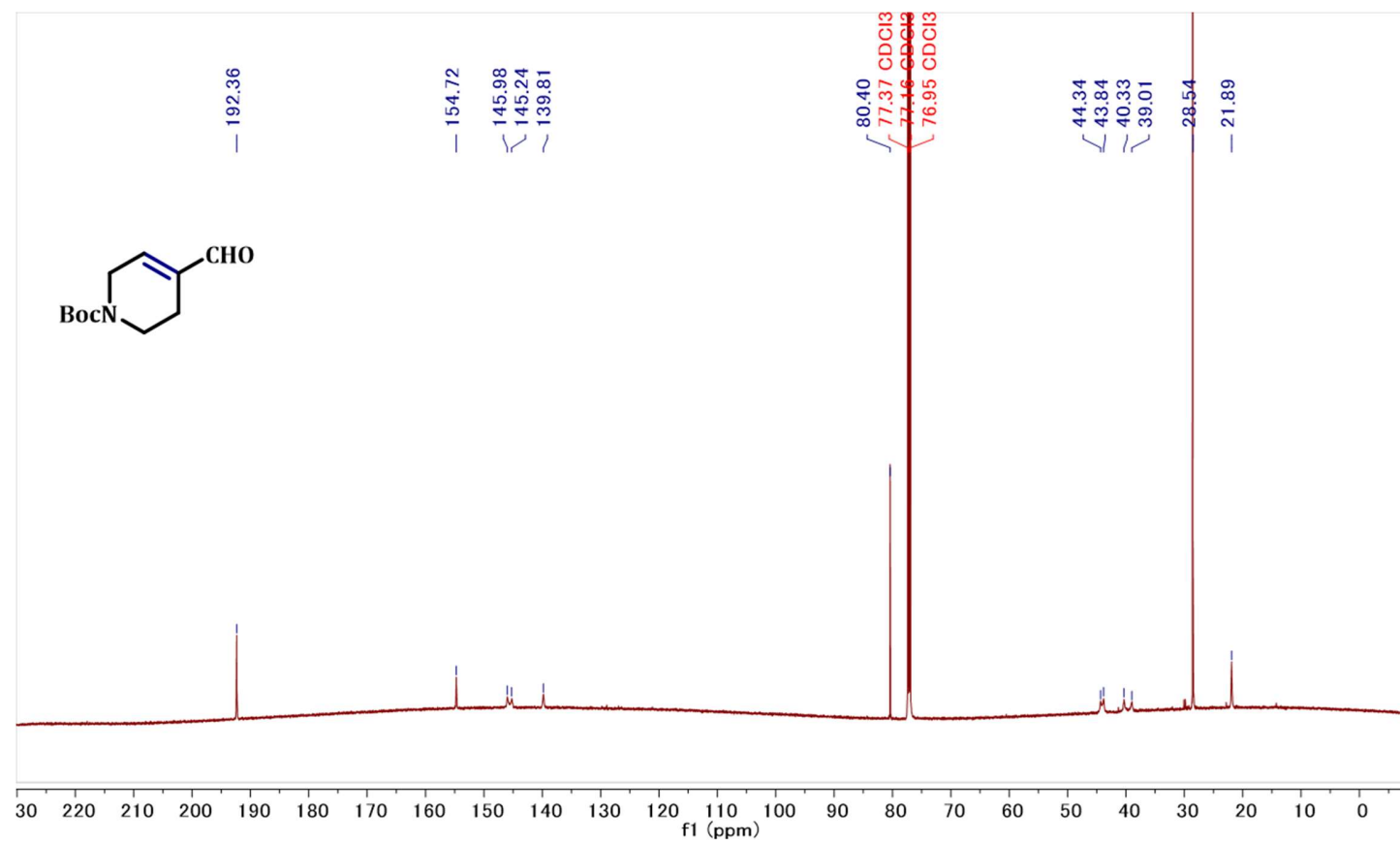
^{13}C NMR (151 MHz, CDCl_3) of compound **31**



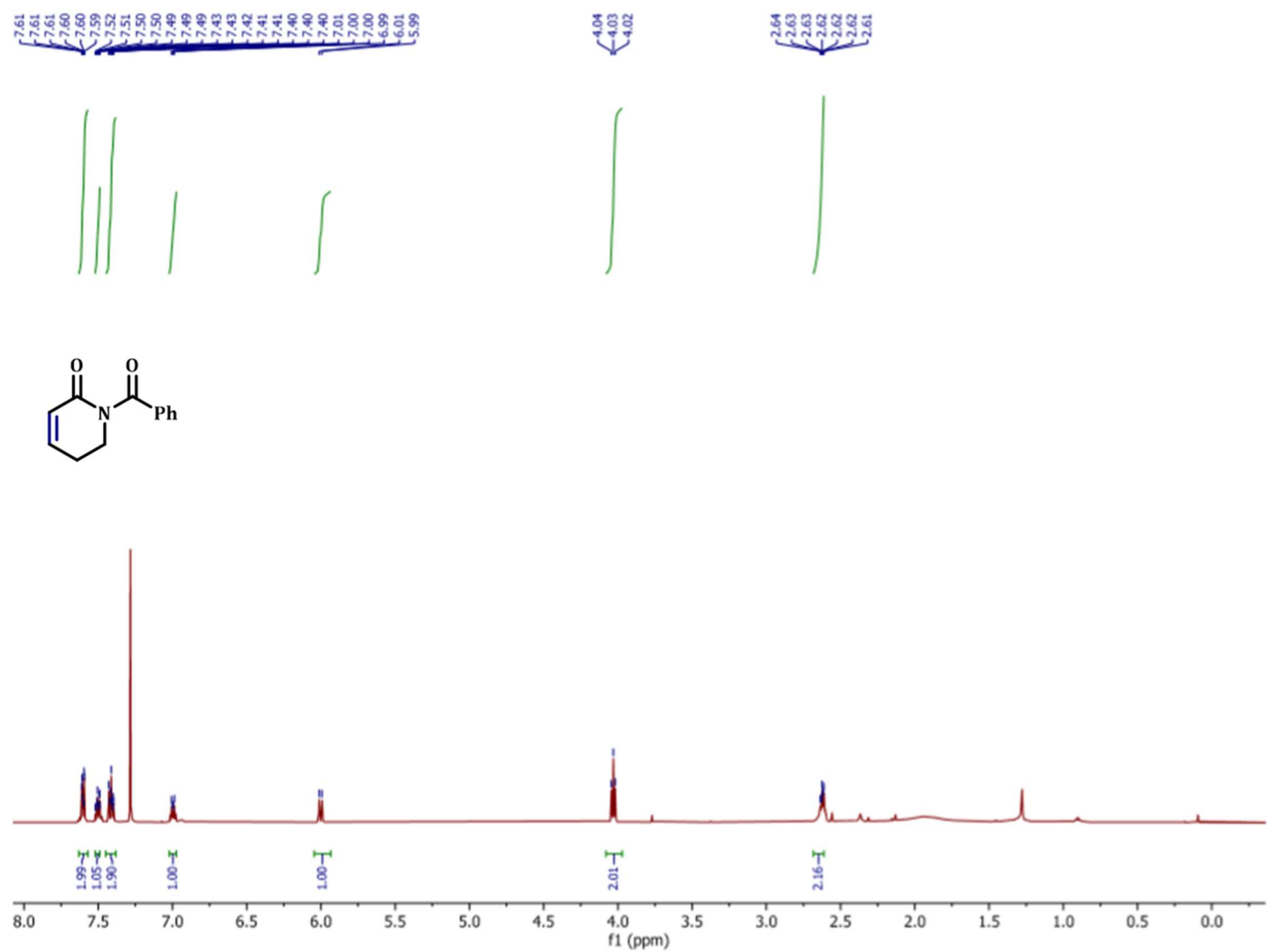
^1H NMR (400 MHz, CDCl_3) of compound **34**



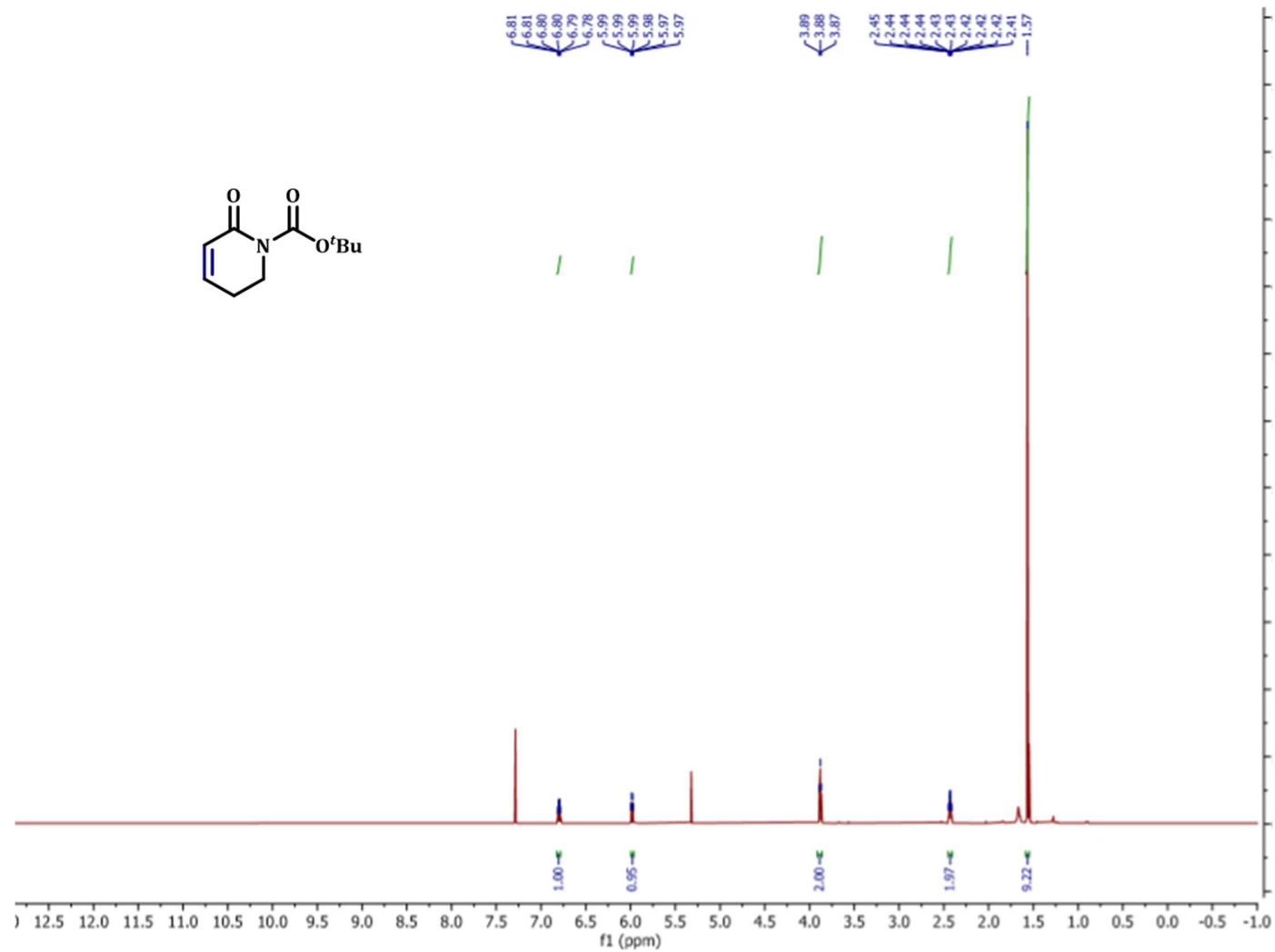
^{13}C NMR (151 MHz, CDCl_3) of compound **34**



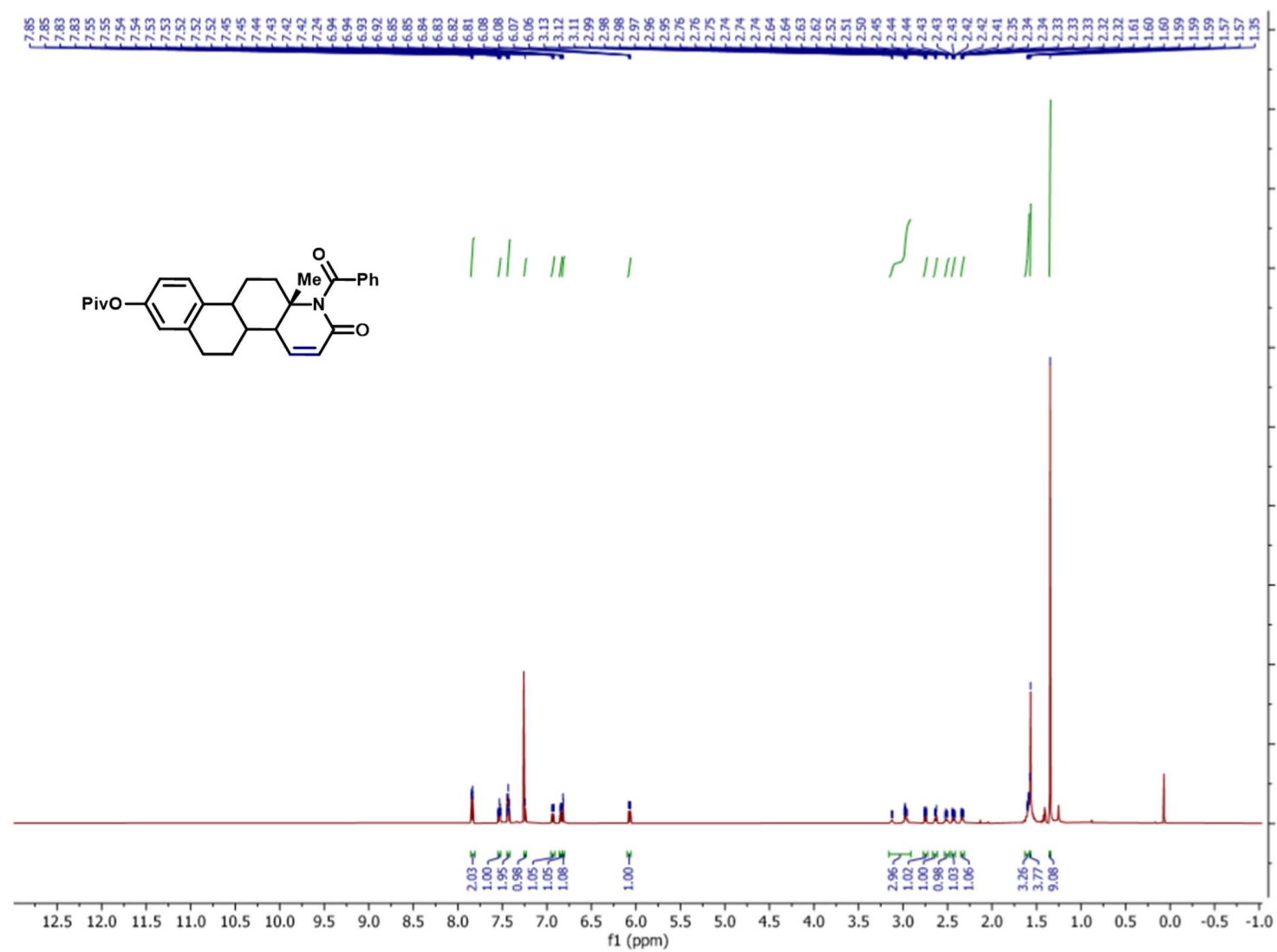
^1H NMR (500 MHz, CDCl_3) of compound **35**



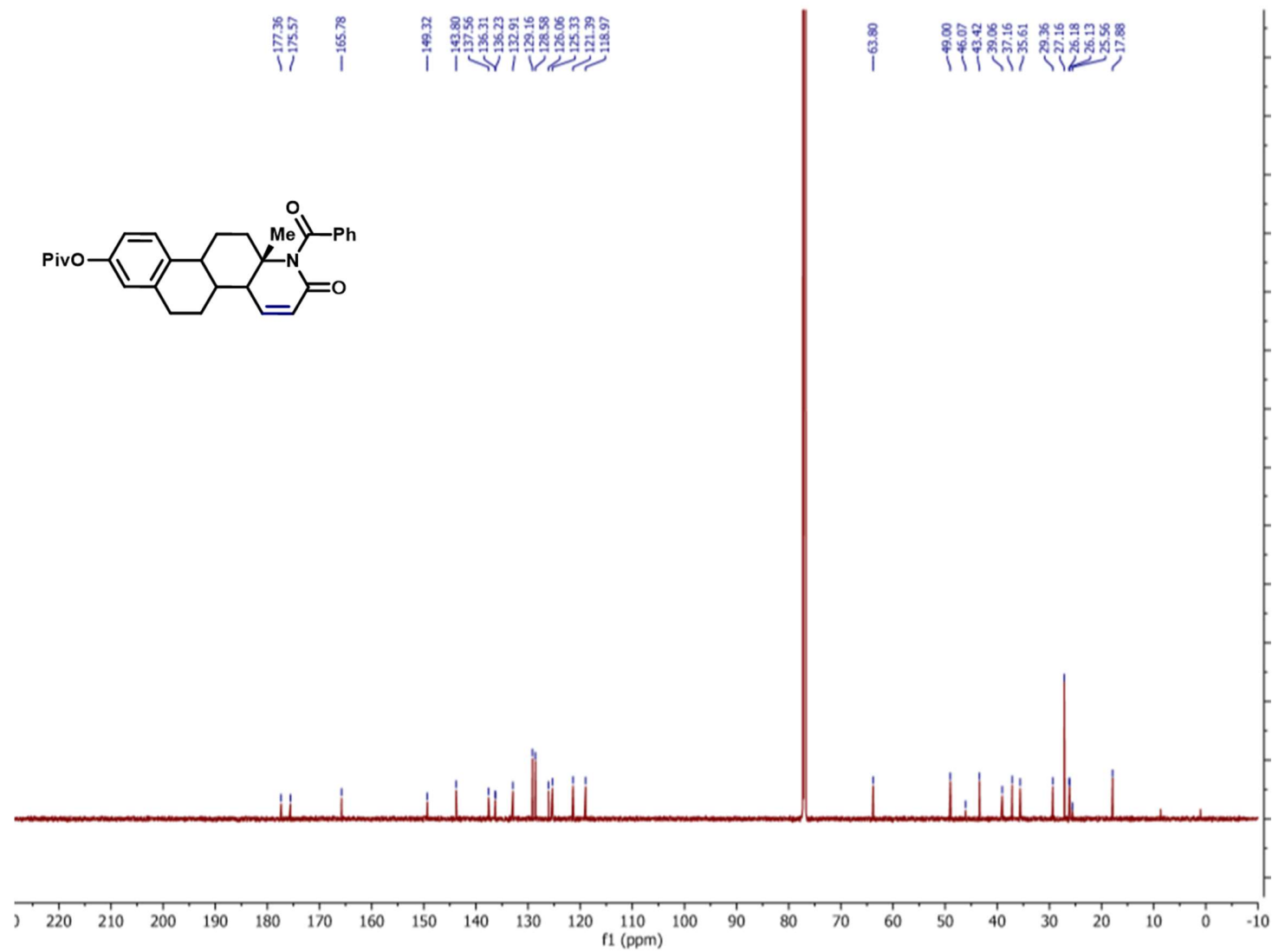
^1H NMR (600 MHz, CDCl_3) of compound **36**



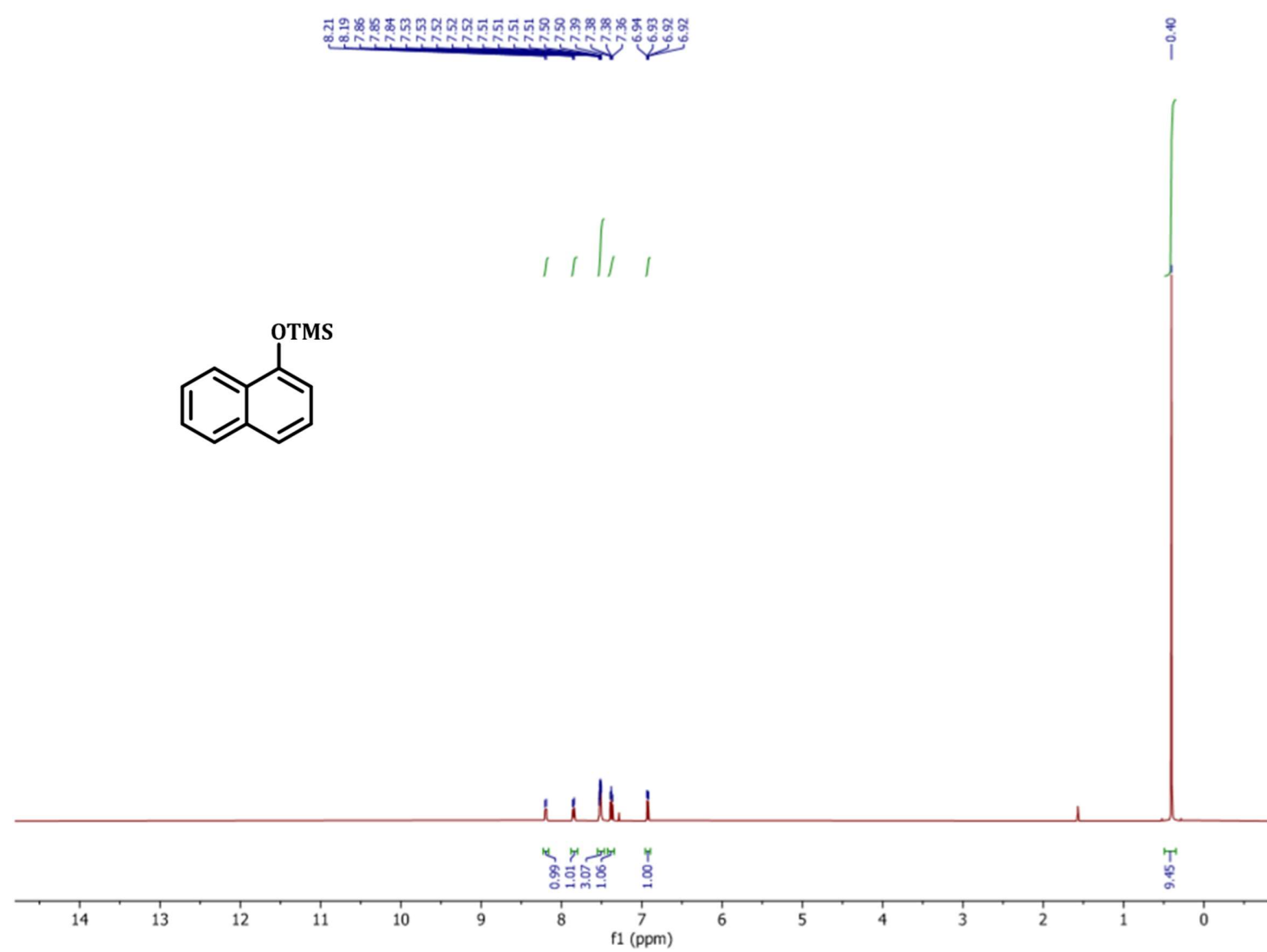
^1H NMR (600 MHz, CDCl_3) of compound **37**



^{13}C NMR (151 MHz, CDCl_3) of compound **37**



^1H NMR (500 MHz, CDCl_3) of compound **47**



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