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„Formal C2-Homologation of Isothiocyanates to Imino-thietanes“

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"Habe nun, ach! Philosophie,
Juristerei und Medizin,
Und leider auch Theologie!
Durchaus studiert, mit heißem Bemühn,
Da steh ich nun, ich armer Tor!
Und bin so klug, als wie zuvor."

— Johann Wolfgang von Goethe

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Thank you all very much,

Andreas-Lorenz Heß

Contents

Abstract

Gegenstand dieser Arbeit der Einbau einer CH_2-CH_2-Gruppe in ein Isothiocyanatstartmolekül mit dem Ziel der Ausbildung eines viergliedrigen Ringsystems. Dabei werden Lithiumcarbenoide als CH_2-Donoren verwendet. Bei dem stufenweisen Einbau zweier einzelner Methylen-Einheiten, zugeführt durch die Carbenoide, entsteht ein stabiles schwefelhaltiges Ringsystem, ein Iminothietan. Diese seltene Stoffklasse besitzt eine außerordentliche chemische Stabilität. Des Weiteren weist die Reaktion eine hohe Chemoselektivität auf und toleriert eine Vielzahl reaktiver funktioneller Gruppen am Isothiocyanatstartmaterial. Eine weitere Besonderheit ist die direkte Anwendbarkeit der Methode auf ein Kohlenstoffelektrophil - in diesem Fall ein Isothiocyanat - ohne die Notwendigkeit der Installation eines Heteroatoms als Startpunkt der Verlängerung, wie es z.B. mit Bor im Rahmen der Matteson-Verlängerung klassischerweise der Fall ist. Die hier behandelte Stoffklasse ist in der verfügbaren Literatur bislang nur wenig beschrieben und könnte eine wichtige Rolle bei der Entwicklung neuer Methoden für die Produktion von Synthesebausteinen sowie als Startmaterial im Bereich der medizinischen Chemie spielen.

This work focuses on the insertion of a CH_2-CH_2 group into an isothiocyanate with the aim of forming a four-membered ring system. Thereby, lithium carbenoids function as CH_2 donors. With the consecutive insertion of two single methylene units a stable sulfur-containing ring system is formed, an imino-thietane cluster. This rare class of compounds is exceptionally stable. Furthermore, the reaction shows a high degree of chemoselectivity as demonstrated by the tolerance to a variety of reactive moieties attached to the starting materials used. Another special feature is the direct applicability of the method to a carbon scaffold - in this case a isothiocyanate - without the need of heteroatomic linchpins as seen, for example, in the boron-depending Matteson-Homologation. The class of substances analysed in this work has so far received only little attention in the available literature but could play a significant role in the development of new ways to access building blocks for chemical synthesis as well as starting materials in the field of medicinal chemistry.

1 Introduction

A crucial and versatile reaction in the field of preparative chemistry is the homologation reaction allowing the modular assembly of complex carbon scaffolds.[1] The classical and widely applied example of a homologation reaction is the Arndt-Eistert reaction.[2–4] Hereby an acyl halide reacts with diazomethane forming an α-diazoketone which upon elimination of N_2 forms a highly reactive carbene intermediate. However, a major disadvantage of diazomethane is its dangerous nature.[5, 6] It's highly toxic[7] and may explode on contact with sharp edges such as scratches in glass.[8] This makes working with diazomethane in chemical laboratories particularly dangerous. Therefore a wide variety of safe alternative reagents for homologation reactions have been developed over time. From this plethora of reactions, ranging from Morita-Baylis-Hillman[9] and Wittig[10] to Corey-Chaykovsky[11] and more, the Köbrich reaction[12] is particularly noteworthy (figure 1). It utilizes so called "carbenoid molecules"[13], molecules mimicking the reactive behaviour of carbene without its hazardous properties mentioned above. The term "carbenoid" describing this similarity was later coined by Closs and Moss in 1964.[14]

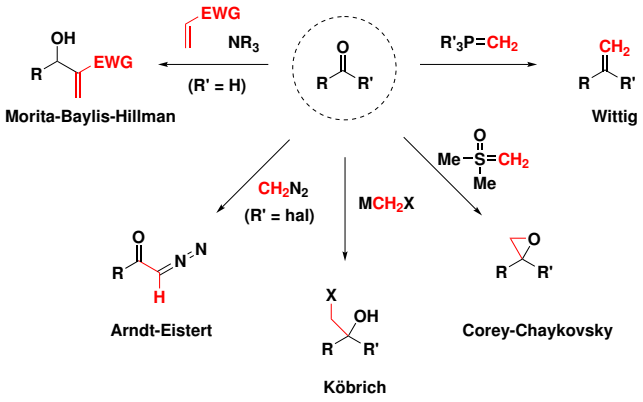


Figure 1: Classical homologation reactions.

The following is a general overview of carbenoids, their preparation and electrophilic partners.

1.1 Carbenoids

In a direct comparison between carbenes and carbenoids the chemical differences become obvious. Carbenes consist of a central carbon atom with two bound moieties and a lone electron pair forming an electron sextet composition at the center carbon resulting in a highly reactive divalent species seeking fulfilment of an electron octet.[15] Carbenoids on the other hand already hold eight electrons in the valence shell, thus fulfilling the octet rule (figure 2).

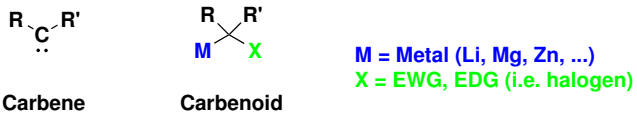


Figure 2: Comparison of carbenes and carbenoids.

Ambiphilicity of carbenoids

The constitution of carbenoids is particularly interesting. Consisting of a metal atom on one side and an electron withdrawing group on the other side of the carbon their unique ambiphilic property is established allowing them to react in a nucleophilic as well as an electrophilic fashion depending on the reaction conditions.[16] Two parameters are significant in regards to this dichotomy: **(1)** the temperature and, **(2)** the type of metal involved. It's generally agreed upon that nucleophilic properties dominate with electropositive metals (*i.e.* Li, Mg) at predominantly low temperatures while electrophilic characteristics arise with less electropositive metals such as Zn at relativley higher temperatures (figure 3). Therefore, hard nucleophiles tend to prefer carbonyl homologation, while soft nucleophiles tend towards olefin cyclopropanation (Simmons-Smith chemistry).[16, 17]

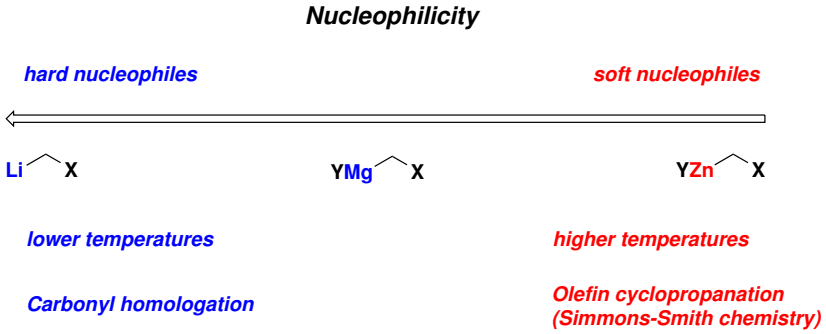


Figure 3: Differences in nucleophilicity of metal carbenoids.

An explanation of this behaviour is possible considering the different ionization forms carbenoids could theoretically depict. With a negative charge located at the carbon they become nucleophilic. *Vice versa*, a positive charge creates electrophilic properties (figure 4).[16]

Over all, the properties of a carbenoid can change depending on the polarity of the bonds formed in the course of a reaction.

With the appropriate reaction conditions applied the negative partial charge located at the carbenoid allows a nucleophilic addition to an electrophile **(i)**. Subsequently, the electronic properties of the carbon shift towards positive charge due to the strong electron-withdrawing characteristics of the electrophilic residue and the halide **(ii)** (figure 5). The now altered electronic environment of the added carbon creates electrophilic properties, thus allowing further nucleophilic additions by another carbenoid.[17]

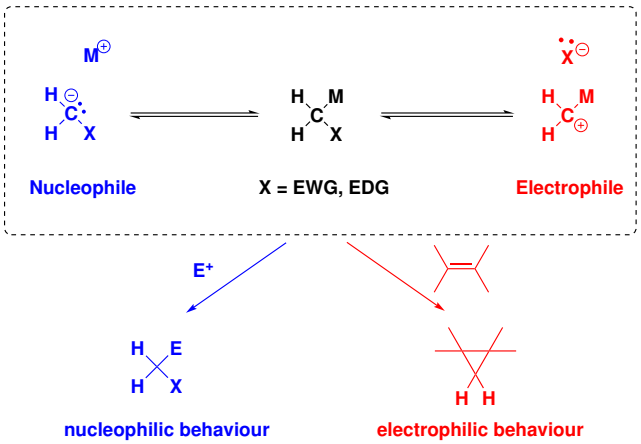


Figure 4: Ambiphilicity & reactivity of carbenoids.

In general, the major advantage carbenoids possess is the ability to install a functionalized carbon atom on a molecular grid capable of undergoing further elaboration.[16] This typical trait enables the theoretical design of new tactics in chemical synthesis (figure 5).[17]

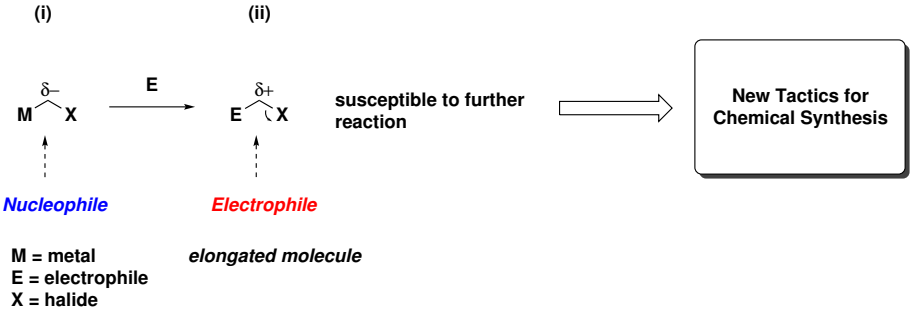


Figure 5: Novel synthesis tactics using metal carbenoids.

This ambiphilicity of carbenoids becomes clear regarding the epoxidation of carbonyls[18, 19] – and analogously the aziridation[20, 21] of imines. In both cases the nucleophilic carbenoid reacts with the electrophile (carbonyle or imine) forming a β-halohydrine or β-haloamine. The freshly created halomethyl group now posesses electrophilic character. Through intramolecular attack by the nucleophilic alkoxide (or amide) a three-membered epoxide or aziridine ring is formed. With the difference of reacting intramolecularly, the mechanism is basically identical to the general concept described above (figures 5 and 6).

The well established Matteson homologation proceeds in an analogous manner. The only difference is the dependence on boronic esters as linchpins for a successful reaction. Other than that, the mechanism follows the same process of nucleophilic addition, change of electronic properties followed by another nucleophilic addition and so on (figure 27).[22, 23]

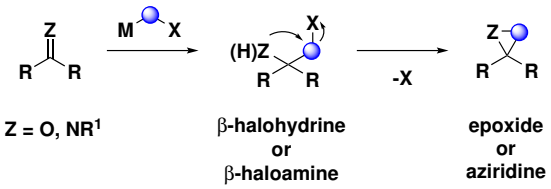


Figure 6: (Aza)-carbonyl epoxidation or aziridation.

1.2 Stability of Carbenoids

Despite the promising properties for chemical synthesis, the use of carbenoids is challenging due to their limited stability. The short spatial distance of the substituents located at the same carbon promotes internal coordination of the metal with the halogen. This causes α-elimination – the dissociation into free carbene and the corresponding metal halide (figure 7).[12, 13, 24]

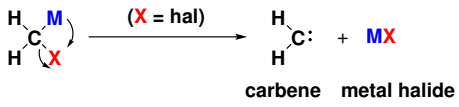


Figure 7: Deleterious α-elimination.

Establishing ways to stabilize carbenoids to expand their use in synthesis have been of great interest in the field. Cainelli first established the feasibility of the reaction at -78°C through Barbier conditions (the organometallic reagent is created *in-situ*).[25] Although there was no consensus on the matter of temperatures for decades, reaction conditions at -78°C became widely accepted as good compromise between reactivity and stability after the contributions by Matteson and Barluenga in the later 20th century.[26–28] Villieras had also demonstrated the importance of adding lithium halides to the reaction mixture as well as highlighted the use of ethereal-type solvents (i.e. THF, Et_2O).[29] Both modifications of the methodology increase stability of the carbenoid through coordinative effects. Additional Lewis-acids (*i.e.* LiBr, LiI, $LiClO_4$) coordinate the halogen of the carbenoid, while ethereal-type solvents act Lewis-basic and coordinate the metal.[29, 30] This way the carbenoid is being captured and preserved long enough for a reaction to succeed with reasonable yields. Another way of preventing α-elimination was introduced by Magnus in 1977[31]. By chemically modifying the carbenoid with a stabilizing trimethylsilane group (TMS) a comparably effective solution to the problem was found, although an additional removal step becomes necessary (figure 8).

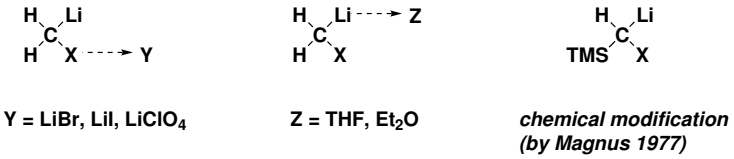


Figure 8: External stabilization.

1.3 Preparation of Carbenoids

Carbenoids can be prepared by one of the following methods described.

Lithium-halogen exchange

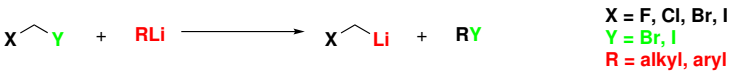


Figure 9: Preparation of monohalolithium carbenoids *via* Li/X exchange.

The most common preparation method for generating carbenoids is *via* lithium-halogen exchange. It is conducted on widely commercially available dihalomethanes with organolithium to afford halomethyllithium.[32] MeLi and *n*-BuLi have proven to be optimal metal sources for this method.[30] The widely utilized and commercially available MeLi-LiBr (2.2M in Et_2O) also provides LiBr as Lewis-acidic additive and furthermore Et_2O as ethereal-type solvent, both of which contribute to the stabilization of the newly formed carbenoid as mentioned above.[16, 33, 34] Therefore, it has become the reagent of choice for this method (figure 9).

Lithium-proton exchange

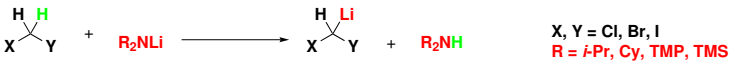


Figure 10: Preparation of dihalolithium carbenoids *via* Li/H exchange.

Another very common method for the preparation of carbenoids is *via* lithium-proton exchange. Thanks to the excellent conversion rate and velocity of the lithium-halogen exchange mentioned above, deprotonation is not very common for the generation of monohalogenated carbenoids, but all the more for dihalomethyl-carbenoids.[35–38] The CH-acidic proton can easily be abstracted with the use of lithium amide bases such as lithium diisopropylamide (LDA), lithium tetramethylpiperidide (LTMP) or lithium-bis(trimethylsilyl)amide (LiHDMS) creating the desired dihalogenated lithium carbenoid (figure 10).[16]

Lithium-sulfinyl exchange

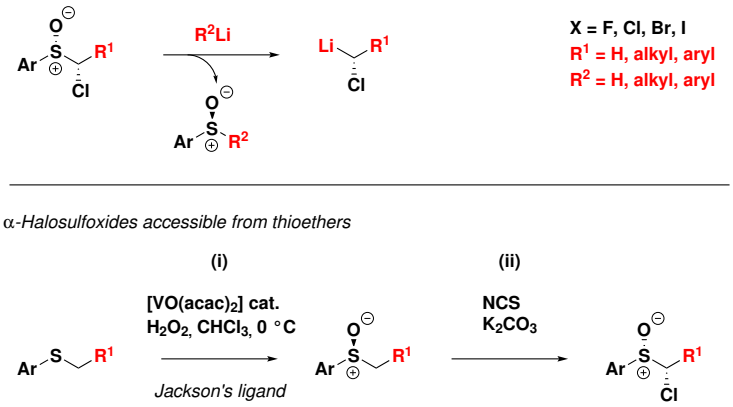


Figure 11: Preparation of monohalolithium carbenoids *via* Li/sulfinyl exchange.

In this third method reported by Blakemore[39–41] and Hoffmann[42–44], suitable for lithium carbenoids and magnesium carbenoids, the exchange takes place at the sulfinyl group of a chiral aromatic sulfoxide. Notably, carbenoids created this way afford configurational stability making them particularly appealing for asymmetric synthesis.[16]

Unfortunately, α-halosulfoxides are not commercially available and have to be prepared - by asymmetric sulfoxidation of the corresponding thioether **(i)** directly followed by halogenation **(ii)** (figure 11).[16]

Lithium-tin exchange

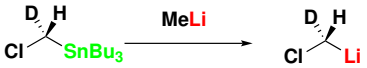


Figure 12: Preparation of monohalolithium carbenoids *via* Li/Sn exchange.

The most recent contribution to the set of methods came in 2008 from Hammerschmidt using chiral stannane chlorides. The exceptional configurational stability of carbenoids created this way is to be emphasized in particular.[45] Even the chemically unstable fluoromethyl lithium is accessible and synthetic operations using it become feasible for the first time.[46] However, the set-up requires temperatures below -95°C and still affords only moderate yields. A further drawback is the necessity to prepare the chloromethylstannane starting material from the corresponding tributylstannyl-methanol derivative since direct precursors are not commercially available. The transformation occurs under Appel conditions (PPh_3 + $COCl_2$, in CCl_4) and allows the preparation of enantiopure material.[46]

1.4 Electrophilic partners

Several kinds of electrophilic substrates are regarded as reactive counterparts for carbenoids. The following have been examined in this context:

Carbonyls

Probably the most extensively examined electrophiles for carbenoid reactions are carbonyl-containing functionalities like ketones and aldehydes. The addition of a halomethyllithium to an aldehyde or a keton results in the formation of a β-halohydrin, which can subsequently be converted to an epoxide through addition of bases or even easier by allowing the mixture to warm-up to room temperature (figure 13). This has independently been shown by Cainelli[25, 47], Villieras[29] as well as Matteson[26, 27] later on.

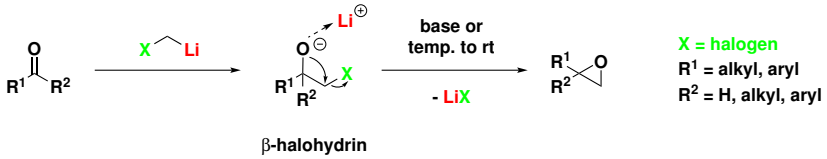


Figure 13: Ring closure of an aldehyde or ketone to an epoxide.

Even challenging substrates with reactive functional groups chemoselectively yield the desired β-halohydrin product as recently shown by Pace *et al.* on unsaturated cyclic enones. By tweeking the reaction conditions it was possible to prevent further reactions on the product like epoxidation or homologation.[48] Also the highly chemoselective approach to *spiro*-epoxyoxindoles starting from numerous functionalized isatins was later reported by the same group (figure 14).[49]

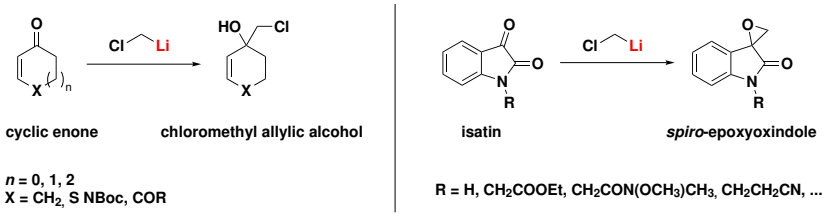


Figure 14: Cyclic enones and isatins as electrophilic substrates.

Imines

Analogous to carbonyls, imines react with chloromethyllithium to form aziridines following an increase in temperature. This was described by Savoia *et al.* in 2006.[50] Requirement for the successful reaction with high stereocontrol and exceptional yields is the presence of a 2-pyrimidine fragment enabling the chelation of the carbenoid. This way the nucleophilic properties of the carbenoid are increased allowing an attack on the weak electrophilic imine functionality. The lack of this coordinative nitrogen prevents a successful outcome (figure 15). Moreover, no reactivity was

observed in the case of sterically severely hindering substituents on the imine nitrogen.[50] Furthermore, chemocontrol becomes very challenging in the presence of additional electrophilic sites due to the lower electrophilicity of the imine. Esters in particular cannot be chemoselectively separated from imines thus both get attacked simultaneously.[50] Nonetheless, β-haloamines and the affiliated lithium amides have proven to be useful intermediate stages for the preparation of aziridines.[51–55]

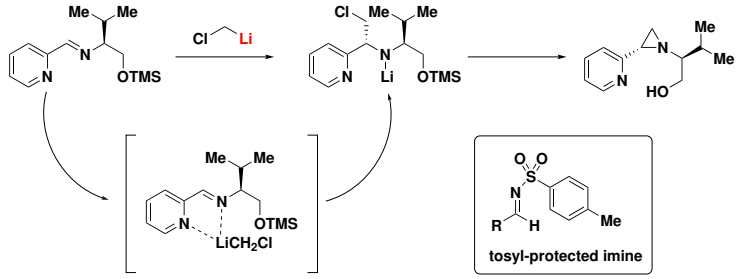


Figure 15: Aziridation of 2-pyridinimines with chloromethyllithium.

Concellón reported an advantage in the use of sulfonyl-protected (e.g. tosyl-protected) imines which increase the electrophilicity by electron-withdrawing effects. It was possible to prevent the cyclization step by acidic removal of the protection group and thus generating β-chloroamines (figure 15).[20, 21]

Esters and Weinreb amides

Ketones (as well as aldehydes) serve as very significant building blocks for organic syntheses since they can easily be used to create sophisticated structures.[56, 57] Therefore, it is of great interest to specifically create this class of compounds. As they are highly electrophilic themselves, difficulties arise in stopping nucleophilic additions conducted on them at the appropriate stage and preventing the generation of unwanted carbinols which result from over-addition of nucleophiles.

Furthermore, by having two reactive functionalities, halogenated ketones serve as versatile intermediates which can easily be homologenated and used for subsequent synthesis. Their isolation is of great interest in the field.[58] In the early 1990s Barluenga did pioneering work in the field of homologation of esters using carbenoids to access this class of compounds – α-*haloketones*.[18, 30] His work allows the single nucleophilic addition of a carbenoid using Barbier-type conditions at -78°C preventing the formation of carbinols. This highly innovative approach is possible by creating a stable tetrahedral intermediate[59] which upon quenching releases the desired α-haloketone (figure 16).

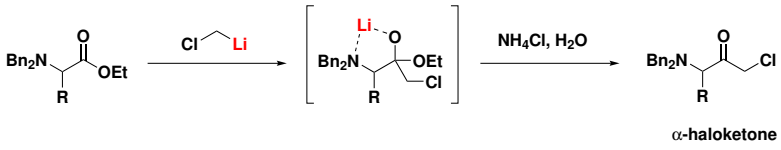


Figure 16: Barluenga's homologation of esters.

Unfortunately, the reaction does not occur when unsubstituted amines or amides are present in α-position to the ester functionality, as demonstrated by Izawa in 2001.[60, 61] In the case of the nitrogen being acidic – *i.e.* carrying a proton – the carbenoid abstracts the hydrogen instead of attacking the ester. The team then implemented *N*-protected 3-oxazolidin-5-ones as replacement for α-aminoesters. After nucleophilic attack by a carbenoid and acidic hydrolysis the desired chloromethylketone is generated (see figure 17) [60, 61] – the downside of this method being the harsh conditions necessary to obtain the product – *e.g.* the need for HCl 6N. A lot of functionalities do not stand up to this environment.

The use of some kind of protection group for the amino moiety was also proposed by Hilpert in an analogous problem concerning homologation of esters[62] and yet further pursued by Izawa's group with the use of *N*-diphenylmethyliden-protected amino acid esters.[61]

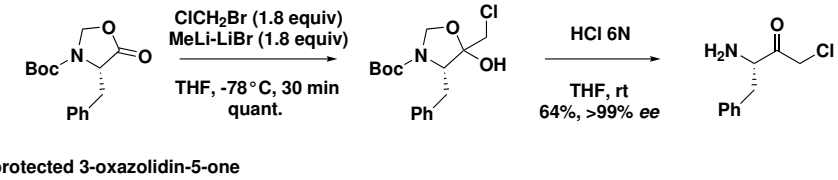


Figure 17: Izawa's *N*-protected 3-oxazolidin-5-one approach to alpha-halomethylketones.

A method that does not require protection groups was demonstrated by Pace and De Kimpe in 2013 in their work on α-arylamino-α'-chloroacetones.[63] They showed that the stability of the intermediate complex depends on the properties of the substituent in α-position. While electron-donating groups (EDG) on the nitrogen enable the reaction, electron-withdrawing substituents (EWG) prevent it. A stable intermediate is only formed through chelation of the lithium ion with basic nitrogen, keeping the complex intact. This makes a variety of substrates unsuitable for this method (figure 18).

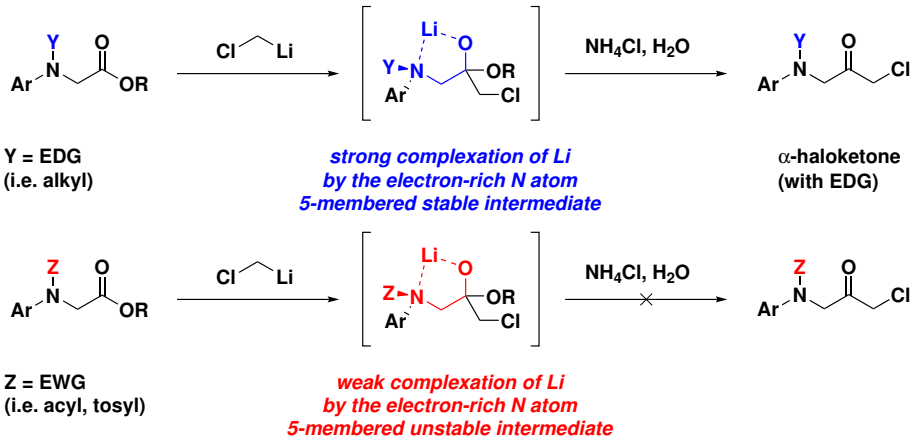


Figure 18: Pace's mechanistic explanation for the behaviours of esters.

A definite solution to this problem was deployed by the use of Weinreb amides[64] instead of esters. This contribution represented a valuable step in the development of this method, as the intermediate complex became independent of the nature of said nitrogen and also displayed exceptional stability.[65–67]

An explanation for this unusual behaviour becomes evident when examining the complex formed (figure 19). Other than with esters, the tetrahedral intermediate is additionally stabilized *via* – or rather primarily because of – the methoxy group of the Weinreb amide and remains stable for long enough to prevent a second addition of $LiCH_2X$. Only after acidic hydrolysis the desired product is formed and the remaining organometallic remnants destroyed. This allows the preparation of a variety of chloromethylketones independently of the properties of the nitrogen.

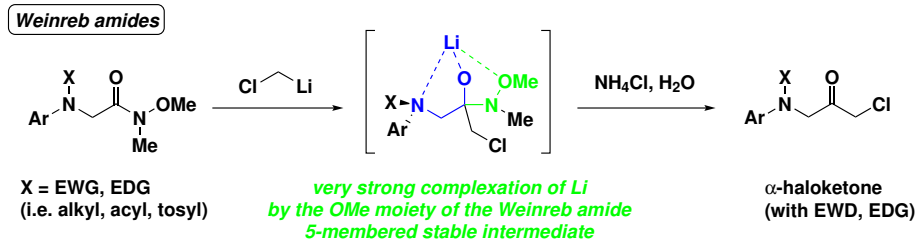


Figure 19: Pace's mechanistic explanation for the behaviours of Weinreb amides.

Even α,β-unsaturated-α'-haloketones are accessible using this approach without side products such as carbinols, 1,4-addition products or Simmons-Smith-type cyclopropanes being generated.[33, 34] The Simmons-Smith reaction is the free-radical addition of a carbenoid to an olefin resulting in cyclopropanation. The method workes also with cyanomethyllithium instead of halogenated carbenoids yielding various functionalized α-cyanoketones (figure 20).[68]

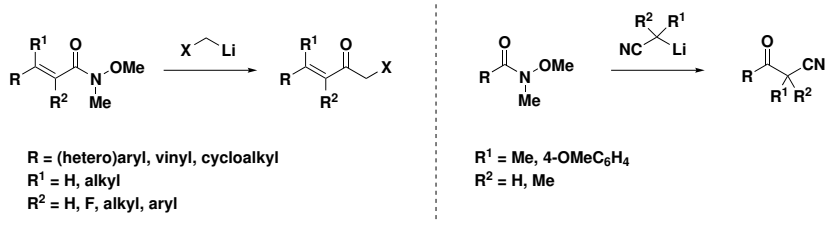


Figure 20: Pace's synthesis of α,β-unsaturated-α'-haloketones and α-cyanoketones.

Heterocumulenes

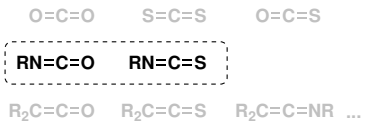


Figure 21: Heterocumulenes.

Heterocumulenes consist of cumulative double bonds between at least three consecutive atoms, containing carbon and heteroatomes in different compositions. They include isocyanates, isothiocyanates, carbon dioxide, carbon diimides, carbon disulfides, etc (figure 21).[69] In this context, the focus will be on iso(thio)cyanates whose electrophilic reactivity becomes apparent through examining the electronic resonance structure (figure 22).[70] The central carbon is strongly deprived of electrons, resulting in a severe increase in reactivity towards nucleophiles.

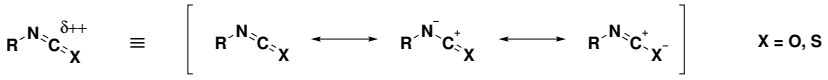


Figure 22: Electronic resonance structure of iso(thio)cyanates.

Isocyanates: Isocyanates in particular are important electrophilic reagents in organic synthesis and as such susceptible to nucleophilic attacks since they possess an increased intrinsic reactivity compared to structurally analogous isothiocyanates.[69]

Historically, the first use of iso(thio)cyanates was reported by Gillman in 1924 as effective reagents for the titration of organometallic compounds like organolithium and Grignard-reagents (RMgX) for the purpose of creating (thio)amides.[71] This discovery received only little recognition[72, 73] and only perceived attention when Bode described the formation of highly sterically hindered amides in 2012 using an analogous method with isocyanates and Grignard-reagents.[74] In 2016 Martin contributed further to the case by introducing nickel-catalized hydroamidation of alkynes.[75]

To the present, iso(thio)cyanates are regarded as privileged starting materials due to their exceptional electrophilicity and the practically neglectable influence of nitrogen-bound substituents on the transformation process.[76]

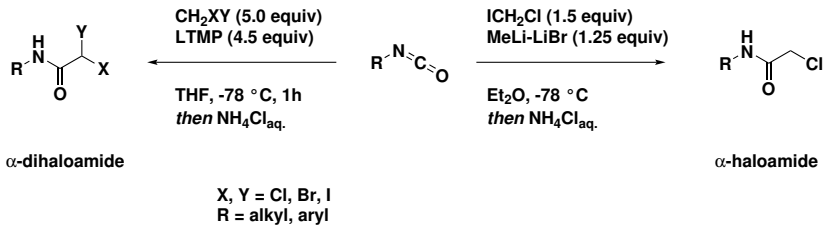


Figure 23: α-(di)haloamides from isocyanates.

In 2013 the Pace group developed an effective synthesis of α-haloamides[33, 37] by reacting isocyanates with lithium (di)halocarbenoids (figure 23). The method

turned out to be highly productive and did not require any subsequent purification steps. The nearly complete preservation of chiral information contained in optically pure isocyanates was observed in reactions with both dihalogenated and monohalogenated carbenoids and should be emphasized in particular. Also worth mentioning is the exceptional chemoselectivity observed in bromine-containing aromatic as well as olefinic substituents, neither of which were attacked during the reaction. This simple method seems to be especially attractive compared to classical approaches, as it does not rely on the nucleophilicity of the amine and is less affected by steric hindrance on the isocyanate.[16, 76] Furthermore, the selection of appropriate isocyanates and carbenoids enables the targeted synthesis of a variety of desired haloamides.[33, 37, 77]

Also starting from isocyanates, formamides become accessible through nucleophilic addition using Schwartz-reagent as ideal hydride-donor.[78] Although treatment with other hydride-based reducing agents is conceivable, only this approach exhibits sufficient chemoselectivity. Other hydride-based reducing agents, like $LiAlH_4$ either result in full reduction to *N*-methylamines or turn out to be incompatible with a lot of functionalities ($NaBH_4$).[79] The importance of correctly sequencing transformations is highlighted by a Matteson homologation conducted on an aromatic isocyanate with boronic ester substituent. After initial reduction to the corresponding formamide the homologation can proceed flawlessly resulting in a homologated formamide otherwise not accessible this way.[78]

Isothiocyanates: The application of the same protocol to isothiocyanates with the goal to access α-halothioamides (figure 24) was unsuccessful and resulted in complex reaction mixtures.[16, 76]. Possibly because of the limited stability of these species, as reported by Lawesson.[80]

Thioamides are valuable building blocks used for the synthesis of heterocyclic structures.[81] The usual approach to thioamides requires harsh reaction conditions, long reaction times and the use of unpleasantly smelling thionating agents. The Pace group designed a protocol using a variety of isothiocyanates and organolithium compounds to access thioamides to overcome these disadvantages (figure 24).[77] The method is compatible even with highly sterically hindered substrates and gives excellent yields.

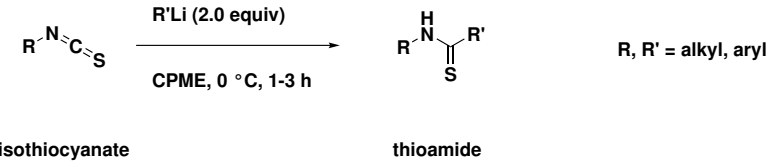


Figure 24: Thioamides form isothiocyanates.

Through transmetallation of an organolithium compound to a Gillman's reagent (R_2CuLi) the chemoselective addition to an isothiocyanate with additionally present ester functionality is feasible, leaving the ester unaltered. Furthermore, no racemization takes place upon addition to chiral substrates. Even stereoselectivity with excellent diastereomeric ratio can be achieved in the presence of chiral ligands or (-)/(+)-sparteine, as shown by the formation of enantiopure *N*-Boc-pyrollidine and Hoppe's carbamate (figure 25).

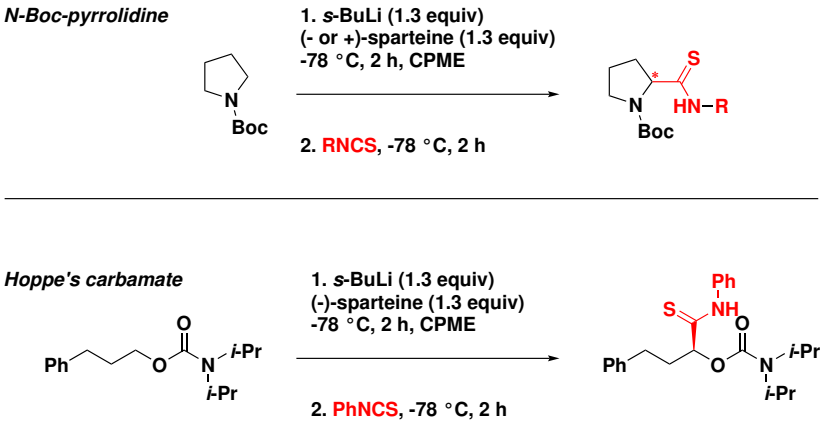


Figure 25: *N*-boc-pyrrolidine and Hoppe's carbamate.

1.5 Homologation

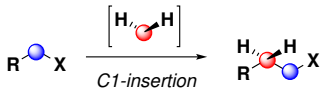


Figure 26: Formal C1 insertion.

A homologation is a chemical reaction that converts the reactant to the next member of the homologous series – a sequence of compounds distinguished by repeating functional motifs that usually consist of gradually extended CH_2 units (C1 insertion) (figure 26).

As stated above, homologation reactions are of great importance for the preparation of sophisticated carbon molecular grids and can be achieved *via* addition reactions. Three distinctive types of addition reactions are characterized: **(1)** electrophilic addition, **(2)** nucleophilic addition and **(3)** free-radical addition. In this context, the focus will be on nuclephilic additions.

Carbenoids are well suited for the purpose of homologation, as they are ambiphilic in character and can act as nucleophiles as well as electrophiles during the course of the reaction, depending on the reaction conditions. They can readily provide the desired methylene units.

Nevertheless, the iterative insertion of these units into a pre-existing carbon scaffold poses a difficult problem to grasp, not least because of the limited stability of the organometallic reagents used in the process.[17]

One approach to overcoming this problem was introduced by Matteson in 1980 with the implementation of boronic esters as privileged electrophilic linchpins enabling carbenoid-based iterative synthesis of organic molecules (figure 27).[22, 82] The significance of this methodology was later highlighted and elaborated by Aggarwal[83] and simultaneously Blakemore[84]. Aggarwal utilized Matteson's method for the assembly-line synthesis of natural substances – (+)-kalkitoxin and (+)-hydroxyphthioceranic acid.[85]

The exceptional stability of the intermediate boronic esters[86, 87] and the multitude of nucleophilic carbon donors[85, 88–90] render the Matteson Homologation an indispensable contribution to the portfolio of preparative chemistry.

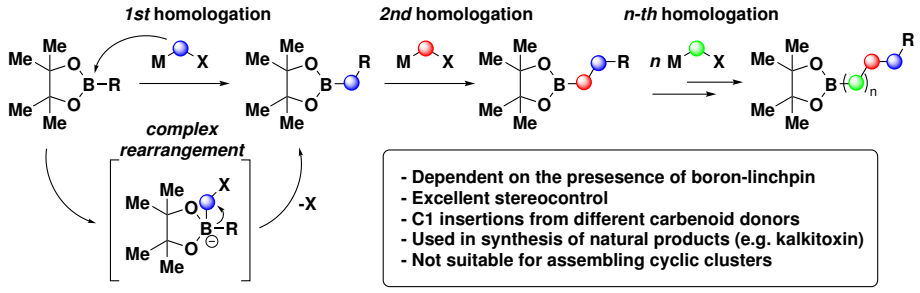


Figure 27: Matteson Homologation of boronic esters.

Nevertheless, the methodology requires the formation of an intermediate boronic ester and cannot be carried out directly on the carbon scaffold. Finding ways to conduct homologations directly on the carbon backbone without the necessity of heteroatomic linchpins will save reaction steps and can be considered a desirable goal in chemical synthesis. Unfortunately, the development of such direct approaches is not yet explored sufficiently.[91]

In previous years, the Pace group has focused on homologations of C-electrophiles using lithium carbenoids as a reactive organometallic reagents, demonstrating the selective formation of *gem*-chloro-trifluoromethylaziridines or *gem*-halomethyl-trifluoromethylaziridines[92, 93] as well as bis-trifluoromethyl-β-diketimidates.[94] By controlling the stoichiomeric ratio of the process a distinction between single and double insertions is assured (figure 28).[92]

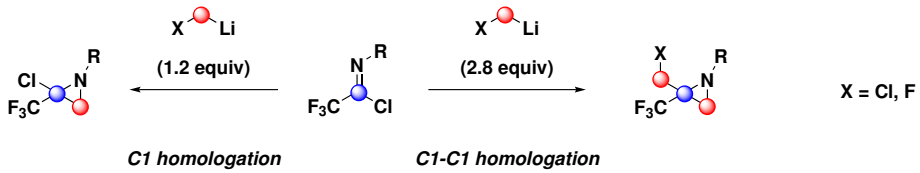


Figure 28: Single or double homologation of trifluoroacetimidoyl chloride depending on stoichiometric ratio.

These reactions are attributed to the carbonyl-oxiran preparative chemistry, in which a *three-membered ring system* is created by the addition of one carbenoid-delivered CH_2 unit.

For the approach to a *four-membered ring system*, a formal C2 insertion *via* nucleophilic addition into a competent electrophile would be required. The electrophile of choice for that matter could be an isothiocyanate since it has excellent electrophilic properties. In the course of the reaction, a 2-imino-thietane cluster would form upon ring closure – analogously to the epoxidation (aziridation) described above. Although 2-imino-thietanes have been reported in previous publications, none of them were obtained *via* nucleophilic addition. Instead, cycloadditions[95–97], recyclisation[98], photochemical isomerisation[99] or even unexpected occurance as side-products[100, 101] have been reported (figure 29).[91]

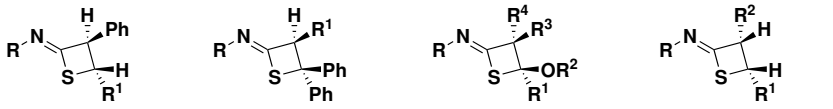


Figure 29: Previous imino-thietanes reported.

The attempt to directly introduce a nucleophilic C2 unit into an electrophilic scaffold can be problematic since the necessary nucleophiles – with MCH_2CH_2X structure – tend to dissociate by β-elimination, since halogens (X) are good leaving groups.[102, 103]

Inspired by an unexpected observation in Pace's previous work on isothiocyanates, the team decided to specifically approach a hypothetical imino-thietane cluster formation by modifying the protocol applied in the finding.[17, 91, 104] In this previous work, Pace's group tried to adapt the protocol for the preparation of α-haloamides through the addition of halocarbenoids to isocyanates[17] to work with isothiocyanates with the aim to obtain the corresponding analogue. Surprisingly, no α-halothioamides were formed, instead a stable four-membered ring system was obtained as primary product – an 2-iminothietane (figure 30).[91, 104]

Hence, the idea has arisen to design a specific protocol for the selective addition of two carbenoid-delivered methylene units to an isothiocyanate with the goal of achieving ring formation and thus successfully furnishing the desired 2-imino-thietane cluster.[91]

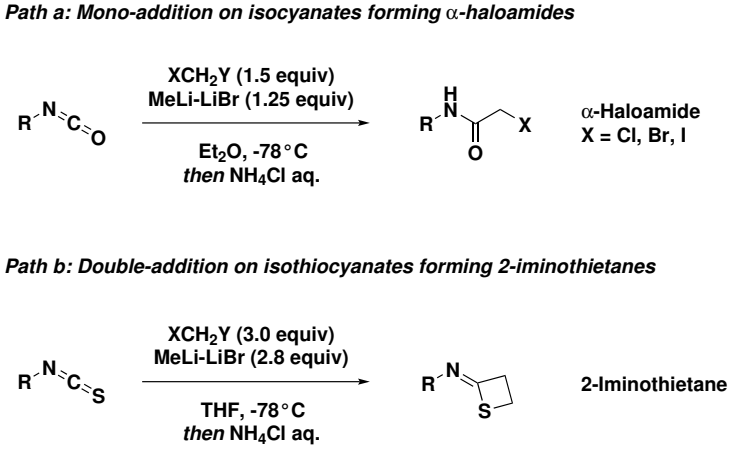


Figure 30: Nucleophilic addition on iso(thio)cyanates.

The preparation, elaboration and implementation of such a protocol is the subject of this work.

2 Thesis

This work deals with the hypothesis of consecutively adding two carbenoid-delivered CH_2-units to an isothiocyanate electrophile resulting in a net-CH_2-CH_2 insertion, followed by ring-closure to furnish the desired 2-imino-thietane schaffold. The optimal conditions for this reaction are established and the scope of the reaction is discussed. Furthermore, a reaction using deuterated-carbenoids to prove the carbon-source is designed and the formation of the ring system proven by X-ray analysis.

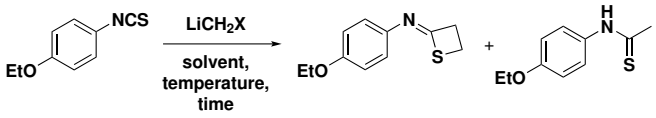
Finally, the chemical stability and reactivity of the ring system is evaluated on the basis of subsequent reactions carried out on the imino-thietanes mentioned and, in addition, the possible applications of the class of compounds briefly presented.

2.1 General procedure for the synthesis of four-membered imino-thietanes

The isothiocyanate starting material (1.0 equiv) was weighed in an oven-dried 100 ml round-bottom flask, put under argon atmosphere and dissolved under constant magnetic stirring in 3 mL of dry THF. Bromoiodomethane (3.0 equiv) was added and the flask was submerged in an acetone/dry ice cooling bath to reach -78°C. Then, a precooled solution of MeLi-LiBr (2.2M in Et_2O, 2.8 equiv) was added dropwise through a syringe and stirring continued for 5 more minutes before the reaction was quenched with saturated aqueous NH_4Cl solution and allowed to reach room temperature. The reaction mixture was then extracted with Et_2O (3 x 10 mL), the organic extracts were combined, washed with brine and dried over Na_2SO_4 before being filtered into a clean round-bottom flask. The solvent was evaporated under reduced pressure and the crude product was analyzed by ^{1}H-NMR. After further purification by column chromatography on silica gel the final product was obtained.

3 Results & Discussion

3.1 Optimization Study



4-Ethoxyphenyl-isothiocyanate **Imino-thietane** **Thioamide** ***(not formed)***

Entry	XCH_2Y (equiv)[a]	Metalating agent	T (min)	Isolated yield [%]
1	$ClCH_2I$ (3.0)	MeLi-LiBr (2.8)	5	Complex mix.
2	$ClCH_2I$ (3.0)	MeLi-LiBr (2.8)	60	Complex mix.
3[b]	FCH_2I (3.0)	MeLi-LiBr (2.8)	5	69
4[b]	FCH_2I (3.0)	MeLi-LiBr (2.8)	15	45
5[b]	FCH_2I (3.0)	MeLi-LiBr (2.8)	60	Complex mix.
6	**$BrCH_2I$ (3.0)**	**MeLi-LiBr (2.8)**	**5**	**82**
7	$BrCH_2I$ (3.0)	MeLi-LiBr (2.8)	15	54
8	I_2CH_2 (3.0)	MeLi-LiBr (2.8)	5	71
9[c]	Br_2CH_2 (3.0)	MeLi-LiBr (2.8)	5	65
10[d]	$BrCH_2I$ (3.0)	MeLi-LiBr (2.8)	5	Complex mix.
11[e]	$BrCH_2I$ (3.0)	MeLi-LiBr (2.8)	5	9
12[f]	$BrCH_2I$ (3.0)	MeLi-LiBr (2.8)	5	Traces
13	$BrCH_2I$ (3.0)	MeLi-LiBr (5.8)	5	80
14[g]	$BrCH_2I$ (3.0)	MeLi-LiBr (1.1)	5	27
15	$BrCH_2I$ (3.0)	*i*-PrMgCl-LiCl	5	No reaction
16[d]	$BrCH_2I$ (3.0)	*i*-PrMgCl-LiCl	5	No reaction

[a] $LiCH_2X$ reagents were generated under Barbier conditions. [b] $LiCH_2F$ was generated in a 1:1 ν/ν mixture of THF and Et_2O. [c] Thioamide was also formed in 20% isolated yield. [d] Reaction run at -40°C. [e] Reaction run in Et_2O. [f] Reaction run in toluene. [g] No mono-homologated product was detected.

Table 1: Reaction optimization.

The general reaction described in table 1 shows the possible products of the process, an imino-thietane being the result of carbenoid attacks on the isothiocyanate and a thioamide as the result of competitive MeLi addition. Since the latter was not formed at all – with one exception when using Br_2CH_2 (entry **9**) – it can be concluded that a complete and effective formation of the carbenoid has taken place.

Different dihalomethane precursors for the generation of carbenoids as well as two kinds of metalating agent were examined. By furthermore altering reaction time from 5 and 15 to eventually 60 minutes the most beneficial conditions were established and individual yields were calculated and compared (table 1).

4-Ethoxyphenyl-isothiocyanate was chosen as the model substrate for the reaction optimization. Different kinds of carbenoid precursors were evaluated. The carbenoid was created by lithium-iodine-exchange with the exception of lithium-bromine-exchange in one case (entry **9**). The use of $ClCH_2I$ as precursor led to the formation of chloromethyllithium ($LiCH_2Cl$) which resulted in a complex mixture at 60 min as well as 5 min reaction time (entry **1** and **2**). Switching to FCH_2I created the highly reactive $LiCH_2F$ which managed to form the desired ringsystem only in mediocre yields and only after short reaction times. Quenching after 15 respectively 60 minutes resulted in reduced yields and in increasingly complex mixtures confirming the necessity of short reaction durations (entries **3** to **5**). Only mediocre yields were also achieved using I_2CH_2 as precursor (entry **8**). The best results were accomplished with $BrCH_2I$, forming the carbenoid bromomethyllithium ($LiCH_2Br$). Again it was necessary to quench after 5 minutes to avoid loss of product, supposedly by decomposition events. The use of solvents other than THF – (Et_2O (entry **11**) and toluene (entry **12**) – greatly reduced yields to only trace amounts. Increasing the reaction temperature to -40°C resulted in a complex mixture probably due to the thermolability of carbenoids (entry **10**). A substantial excess of nucleophile did not affect the results, while reducing the amount lowered yields considerably, thus showing the necessity of establishing the optimal ratio to increase results and avoid waste of material (entries **13** and **14**). The use of magnesium instead of lithium in the generation of carbenoids showed no reactivity at all – even at higher temperatures (entries **15** and **16**).[91]

3.2 X-Ray Crystallographic Study

Using X-ray crystallographic analysis of the obtained 4-ethoxyphenyl-imino-thientane, the geometric structure could be shown (figure 31).[91] Very small torsion angles (C7-S1-C9-C8 **0.76°**, C9-C8-C7-S1 **0.91°** and C1-N1-C7-S1 **1.82°**) were measured showing the near-planarity of the four-membered ring system, which differentiates CH_2-CH_2-homologated rings from previously described thietanes, due to the *sp2*-hybridization of the imino-function.[105] The internal angles of the ring (C9-C8 C8-C7 **84.65°**, S1-C9 C9-C8 **87.65°**, C7-S1 S1-C9 **77.01°**) differ from typical *sp3* angles. In addition the angle at the carbonyl-C (S1-C7 C7-C8 **95.27°**) is divergent from a conventional *sp2* angle.

The S1-C9 bond (**1.835 Å**) is longer than an average *sp3*-hybridized C-S bond (**1.817 Å**) but shorter than a C-S bond (**1.847 Å**) of an unsubstituted thientane. The C8-C9 bond (**1.541 Å**) corresponds to the average CH_2-CH_2 distance of an unsubstituted thietane.

These findings confirm the thietane-ring formation and the – in comparison with a plain thietane structure – higher ring tension induced by the imino-group.[91]

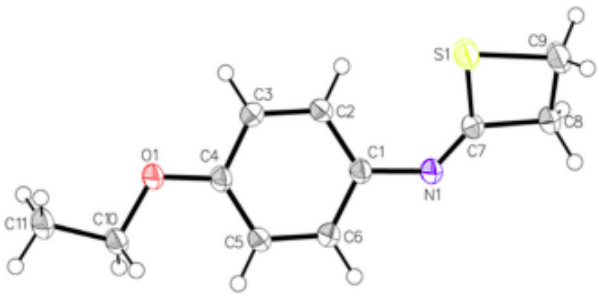


Figure 31: X-ray structure.

3.3 Scope of the Reaction

The next step after having determined the optimal reaction conditions and confirming the assembled structure was to evaluate the scope of the CH_2-CH_2-homologation reaction. A diverse range of differently substituted isothiocyanates were used for this purpose. An overview of the resulting compounds including the obtained yields is reported in figure 32.

Besides the unsubstituted phenylisothiocyanate, which worked flawlessly as substrate (**11**), a wide range of halogenated benzene functionalities as well as ethereal moieties were tested for use in this protocol. Electron-withdrawing groups like alkylethers in para- and meta-position were very well tolerated (**2**-**5**). Upscaling the reaction gave consistent results (**2**). The phenoxy- or trifluoromethoxy-functionalities behaved similarly to the alkyl ethers (**6** and **7**). These exercise an even stronger electron pull on the bond than the ethers mentioned above. Furthermore, disubstituted functions like the methylenedioxy group (**8**), which can also be regarded as an acetal, or dimethoxyethers (**5**) proved to be compatible with the protocol. Also other chalcogens such as sulfur and selenium compound - respresented as thioether (**9**) and selenoether (**10**) - did not substantially affect the reaction. Intriguingly, in the case of phenylselenoether (**10**), no lithium-seleno exchange took place leaving this functionality intact. Halogen functions like fluorine, chlorine and bromine at various positions on the aromatic ring are suitable for the methodology (**12**-**17**), remaining untouched. This opens up the feasability of further organic operations on these moieties. Electron-donating groups, such as *i*-propyl (**22**) and the bicyclic indanyl system (**23**) can also be present in the starting material. Also unsaturated hydrocarbon moieties (**24**-**25**) were applicable to the protocol and astonishingly, no carbenoid-driven cyclopropanation occured on the vinyl-substituted compound (**24**), neither deprotonation of the alkyne (**25**) which could have been expected due to the basic conditions the protocol implies. This finding states the *remarkable chemocontrol* possible with this methodology. Further confirming that finding even highly electrophilic substituents represented by an ester (**26**) and a nitrile (**27**) could withstand a nucleophilic attack by the carbenoid under described conditions, thus preserving their chemical integrity and confirming the impressive versatility of the reaction. Moieties able to invalidate the correct formation of the carbenoid nucleophile like nitrogen-centered substituents (**28**-**31**) did not affect the homologation in a significant manner. Interestingly, the reaction showed a selective approach to 1,4-diisothiocyanatobenzene (**32**) only forming one imino-thietane scaffold leaving the other identical substituent intact, even with substantial excess of carbenoid and thus showing the reactivity of the three-membered thiirane interme-

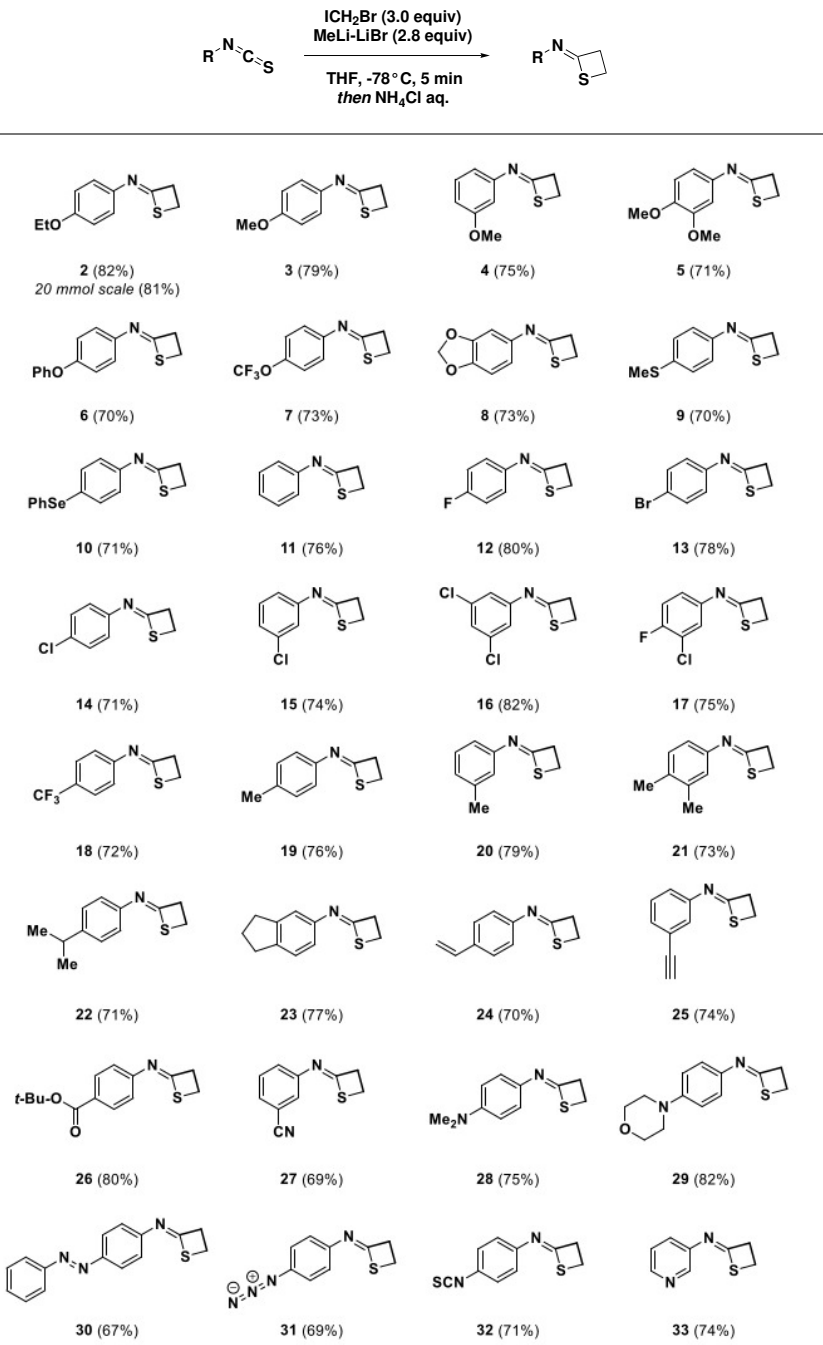


Figure 32: Scope of the homologation.

diate described in the mechanism below. Ultimately, the presence of heteroaromatic rings presented in the form of 3-pyridylisothiocyanate (**33**) did also not affect the imino-thietane formation.[91]

3.4 Prove of Carbenoid Source

To provide prove of the carbenoid origin of the two added CH_2 functionalities an experiment using di-deuterated iodomethyllithium ($LiCD_2I$) was conducted. That particular nucleophile was prepared from commercially available di-deuterated diiodomethane (CD_2I_2). The reaction was carried out on 4-ethoxyphenyisothiocyanate (**1**) and according to the protocol. As expected, the installed ethylene fragment in the resulting product (**34**) featured solely deuterated carbons (CD_2-CD_2) thus confirming the stated hypothesis (figure 33).[91]

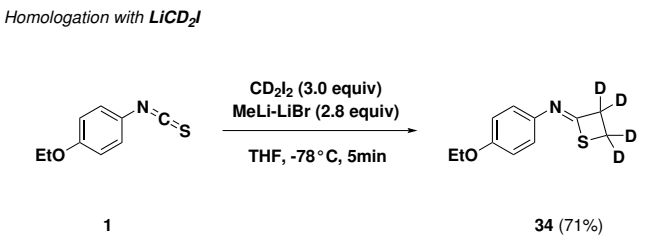


Figure 33: Prove of carbenoid source.

3.5 Mechanism

The proposed mechanism involves the consecutive insertion of two methylene fragments onto the isothiocyanate electrophile. Both CH_2-groups originate from the carbenoids created in-situ in the course of the reaction, as shown above.

In a first step a freshly created carbenoid attacks the highly electrophilic isothiocyanate structure (**I**) resulting in an α-halothioamidate (**II**). The strong nucleophilic property of the thiolate moiety attacks the α-halocarbon forming a thiirane ring (**III**). The high ring tension and strong electronegative pull caused by the neighbouring nitrogen and sulfur atoms create an immense electrophilic carbon which is more likely to react with another carbenoid than an initial isothiocyanate structure. At this point the second nucleophilic attack occurs on the aforementioned carbon forming an β-halothioamidate – now elongated by an ethylene group (**IV**). In a last step the thiolate moiety attacks the terminal β-halocarbon, releasing the halide and forging the desired four-membered ring system (**V**) (figure 34).[91]

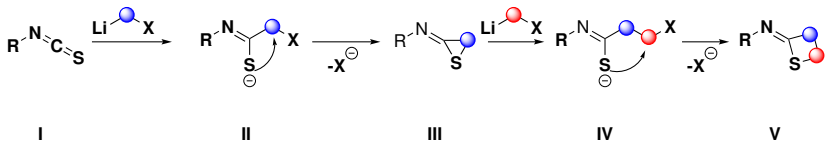


Figure 34: Reaction mechanism.

3.6 Reactivity of the Ring System

I order to check the practicality as building block for synthetic operations the reactivity of the structure was examined. In this respect manipulations on the aromatic ring as well as the imino-thietane function were performed.

3.6.1 Buchwald-Hartwig Amination

In an attempt to examine the chemical integrity of the newly created thietane scaffold whilst altering other parts of the molecule a Buchwald-Hartwig amination on the aromatic ring using 4-bromo-imino-thietane (**13**) as starting material was performed. The reaction succeeded flawlessly as the corresponding product (**35**) was formed and the thioimidate moiety of the molecule was kept preserved (figure 35).[91]

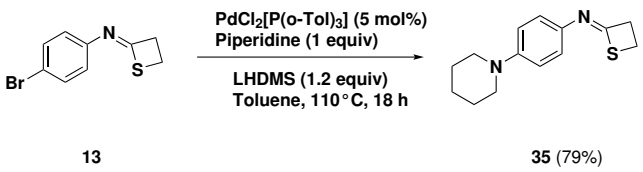


Figure 35: Buchwald-Hartwig amination.

3.6.2 Ring opening with Lithium-aluminium hydride

Another manipulation considering the constructed imino-thietane molecule was the attempt to open the ring using lithium-aluminiumhydride as a nucleophile resulting in the formation of the corresponding γ-amino-mercaptane (**IX**) (figure 36). This observation can be explained by two sequential nucleophilic reductions carried out by hydride anions. In a first step the electrophilic carbon at the center of the NCS-bond is attacked by a hydride forming a tetrahedral intermediate (**VII**) which upon collapse releases thiolate as leaving group. This creates a γ-*N*-phenyliminopropyl mercapto anion (**VIII**) capable of undergoing another reductive attack and thus fashioning the final structure.[91]

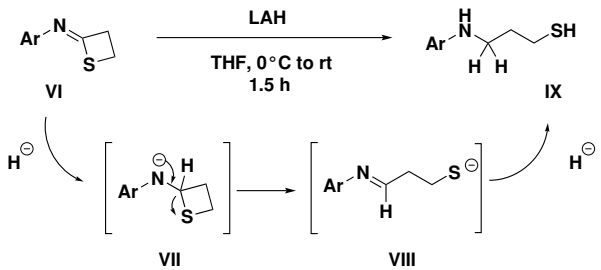
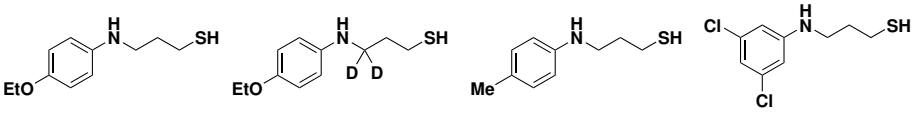


Figure 36: Ring opening with lithium-aluminumhydride.

The reaction was almost quantitative, as can be seen from the molecules formed (**36**-**39**).In the case of (**37**) the reduction was performed using $LiAlD_4$ to confirm the attack on the thioimidate function.[91]



36 (95%) **37** (96%) with $LiAlD_4$ **38** (85%) **39** (92%)

3.7 Outlook

Applications in chemical synthesis

The method described provides a simple and fast procedure for the insertion of an ethylene-fragment into a carbon-based electrophile and can serve as a quick shortcut to approach necessary building blocks for chemical synthesis (e.g. heterocyclic structures).[106, 107] This refers to both imino-thietanes as well as the rapidly and quantitatively obtained aminopropylmercaptanes.

Applications in pharmaceutical chemistry

It's conceivable that imino-thietanes may present a novel class of precursors for the synthesis of biological compounds[106].

Studies on the pharmacophoric properties of imino-thietane structures could enable potential medicinal applications.

Imino-thietanes might have the potential to be used as effective rodent repellents, since thietane-derivates possess predator odor and are avoided by mice.[108]

The possible applications of imino-thietanes and their easily accessible derivatives remain speculative and further studies are needed to adequately answer this question.

4 Conclusion

In conclusion, we studied the formation of four-membered cyclic imino-thietanes beginning with isothiocyanates as starting material and using bromomethyllithium as methylene donor. Through a mechanism of two consecutive C1 homologation and cyclization events the final product could be fashioned. The mechanism leads *via* a first nucleophilic addition of a halomethylene group to an intermediate formation of a C1-homologated α-halothioamidate. Upon ring-closure, a highly reactive imino-thiirane structure - susceptible to further nucleophilic attack - is created which subsequently undergoes a second nucleophilic addition of a carbenoid furnishing a C1-homologated halothioamidate. After a final cyclization, the desired imino-thietane product is obtained.

In investigation of the scope of the reaction using a variety of differently functionalised starting materials such as halogenated isothiocyanates, seleno- or thioethers, amines as well as different kinds of electrophilic groups a prominent degree of chemoselectivity was observed.

Evidence for the carbenoid origin of the homologated carbons was provided by the use of di-deuterated iodomethyllithium. The four-membered ring structure was confirmed by X-ray analysis. An easy access of γ-amino-mercaptanes using $LiAlH_4$ is described as well as the chemical stability of the ring system shown on the example of a Buchwald amination conducted on a bromo-substituted imino-thietane.

Overall, following the strategy described, we conducted the first controlled double CH_2-homologation on carbon electrophiles that does not require heteroatomic linchpins like boron to take place.

5 Experimental

5.1 Instrumentation and General Analytical Methods

Melting points were determined on a Reichert–Kofler hot-stage microscope and are uncorrected. Mass spectra were obtained on a Shimadzu QP 1000 instrument (EI, 70 eV) and on a Bruker maXis 4G instrument (ESI-TOF, HRMS). ^{1}H, ^{13}C, ^{15}N, ^{19}F and ^{77}Se NMR spectra were recorded with a Bruker Avance III 400 spectrometer (400 MHz for ^{1}H, 100 MHz for ^{13}C, 40 MHz for ^{15}N, 376 MHz for ^{19}F and 76 MHz for ^{77}Se) at 297 K using a directly detecting broadband observe (BBFO) probe. The center of the (residual) solvent signal was used as an internal standard which was related to TMS with δ 7.26 ppm (^{1}H in $CDCl_3$), 7.16 ppm (^{1}H in C_6D_6) and δ 77.0 ppm (^{13}C in $CDCl_3$), 128.06 (^{13}C in C_6D_6). ^{15}N NMR (gs-HMBC) spectra were referenced against neat, external nitromethane. ^{19}F NMR spectra were referenced *via* the Ξ ratio (absolute referencing). ^{77}Se spectra were referenced against diphenyldiselane (δ Ph_2Se_2 463 ppm). Spin-spin coupling constants (J) are given in Hz. In nearly all cases, full and unambiguous assignment of all resonances was performed by combined application of standard NMR techniques, such as APT, HSQC, HMBC, HSQCTOCSY, COSY and NOESY experiments. All reactions were performed under an inert atmosphere of argon using standard schlenk techniques. THF was distilled over Na/benzophenone. Starting isothiocyanates were commercially available or prepared as reported. Fluoroiodomethane was supplied from ABCR Germany. Other chemicals were purchased from SigmaAldrich, Acros, Alfa Aesar, Fluorochem and TCI Europe. Solutions were evaporated under reduced pressure with a rotary evaporator. For column chromathography, silica Gel 60 (0.04-0.063 mm) was used. TLC was carried out on aluminium sheets precoated with silica gel 60 F_{254} (Merchery-Nagel, Merk); the spots were visualised under UV light (λ = 254 nm) and/or $KMnO_4$ (aq.) was used as revealing system.

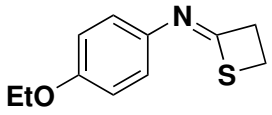
5.2 General Procedure

To a solution of the starting isothiocyanate (1.0 equiv) in dry THF (3 mL) bromoiodomethane (3.0 equiv) was added. Then, a solution of MeLi-LiBr (2.2 M in Et_2O, 2.8 equiv) was added dropwise at -78 °C. After stirring for 5 min at -78 °C, the reaction was quenched with sat. aqueous NH_4Cl. The reaction mixture was allowed to reach room temperature and exhaustively extracted with Et_2O (3 x 10 ml). The combined organic extracts were washed with brine, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The final products were obtained after purification by column chromatography on silica gel.

5.3 Characterization and Spectral Data of the Compounds

5.3.1 Characterization of the compounds

4-ethoxy-*N*-[(2Z)-2-thietanylidene]aniline [2]



By following the general procedure, starting from 4-ethoxyphenyl isothiocyanate (0.179 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **2** was obtained in 82% yield (0.170 g) as a brown solid (mp: 62-65 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

Scaling-up of the reaction (20 mmol) - By following the general procedure, starting from 4-ethoxyphenyl isothiocyanate (3.580 g, 20.0 mmol, 1.0 equiv), bromoiodomethane (13.250 g, 4.52 mL, 60.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 25.45 mL, 56.0 mmol, 2.8 equiv) in dry THF (60 mL), compound **2** was obtained in 81% yield (3.358 g) as a brown solid after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2). *Spectroscopic and spectrometric data match with those reported for the 1.0 mmol scale*

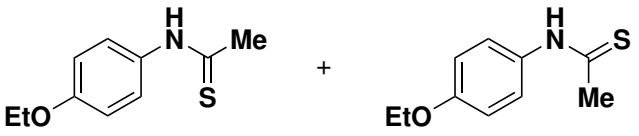
^{1}H NMR (400 MHz, C_6D_6) δ: 7.24 (m, 2H, Ph H-2,6), 6.81 (m, 2H, Ph H-3,5), 3.54 (q, ^3J = 7.0 Hz, 2H, OCH_2), 3.33 (m, 2H, CH_2), 2.39 (m, 2H, SCH_2), 1.08 (t, ^3J = 7.0 Hz, 3H, CH_3).

^{13}C NMR (100 MHz, C_6D_6) δ: 158.0 (C=N), 157.1 (Ph C-4), 141.4 (Ph C-1), 122.7 (Ph C-2,6), 115.4 (Ph C-3,5), 63.4 (OCH_2), 47.1 (CH_2), 20.4 (SCH_2), 14.9 (CH_3).

^{15}N NMR (40 MHz, C_6D_6) δ: -82.5 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{14}NOS^+$: 208.0791 $[M + H]^+$; found: 208.0792.

***N*-(4-ethoxyphenyl)ethanethioamide [2a]**



s-*cis* rotamer s-*trans* rotamer

Obtained in 21% yield (0.041 g) as a yellowish solid (mp: 114 °C), as reported above in Table 1 (Entry 9).

s-*trans* : s-*cis* $\sim$ 1 : 1

s-*cis* rotamer:

^{1}**H NMR** (400 MHz, $CDCl_3$) δ: 8.59 (br s, 1H, NH), 7.50 (m, 2H, Ph H-2,6), 6.90 (m, 2H, Ph H-3,5), 4.03 (q, ^{3}J = 7.0 Hz, 2H, OCH_2CH_3), 2.72 (s, 3H, CH_3), 1.41 (t, ^{3}J = 7.0 Hz, 3H, OCH_2CH_3).

^{13}**C NMR** (100 MHz, $CDCl_3$) δ: 200.3 (C=S), 157.7 (Ph C-4), 130.8 (Ph C-1), 125.7 (Ph C-2,6), 114.6 (Ph C-3,5), 63.7 (OCH_2CH_3), 35.8 (CH_3), 14.8 (OCH_2CH_3).

^{15}**N NMR** (40 MHz, $CDCl_3$) δ: -219.5 (NH).

s-*trans* rotamer:

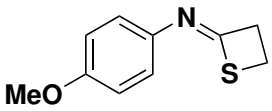
^{1}**H NMR** (400 MHz, $CDCl_3$) δ: 9.31 (br s, 1H, NH), 7.08 (m, 2H, Ph H-2,6), 6.90 (m, 2H, Ph H-3,5), 4.04 (q, ^{3}J = 7.0 Hz, 2H, OCH_2CH_3), 2.45 (s, 3H, CH_3), 1.43 (t, ^{3}J = 7.0 Hz, 3H, OCH_2CH_3).

^{13}**C NMR** (100 MHz, $CDCl_3$) δ: 205.0 (C=S), 158.6 (Ph C-4), 131.5 (Ph C-1), 126.8 (Ph C-2,6), 115.2 (Ph C-3,5), 63.8 (OCH_2CH_3), 29.8 (CH_3), 14.7 (OCH_2CH_3).

^{15}**N NMR** (40 MHz, $CDCl_3$) δ: -217.4 (NH).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{14}NOS^{+}$: 196.0791 $[M + H]^{+}$; found: 196.0792.

4-methoxy-*N*-[(2Z)-2-thietanylidene]aniline (3)



By following the general procedure, starting from 4-methoxyphenyl isothiocyanate (0.165 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **2** was obtained in 79% yield (0.152 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

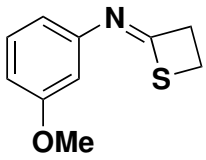
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.22 (m, 2H, Ph H-2,6), 6.77 (m, 2H, Ph H-3,5), 3.33 (m, 2H, CH_2), 3.26 (s, 3H, OCH_3) 2.39 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 158.2 (C=N), 157.7 (Ph C-4), 141.6 (Ph C-1), 122.7 (Ph C-2,6), 114.9 (Ph C-3,5), 54.9 (OCH_3), 47.0 (CH_2), 20.4 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -82.0 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{12}NOS^+$: 194.0634 $[M + H]^+$; found: 194.0640.

3-methoxy-*N*-[(2Z)-2-thietanylidene]aniline (4)



By following the general procedure, starting from 3-methoxyphenyl isothiocyanate (0.165 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **4** was obtained in 75% yield (0.144 g) as a yellow oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

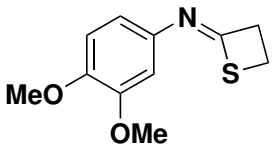
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.11 (m, 1H, Ph H-5), 6.91 (m, 1H, Ph H-2), 6.90 (m, 1H, Ph H-6), 6.62 (m, 1H, Ph H-4), 3.30 (s, 3H, OCH_3), 3.27 (m, 2H, CH_2), 2.33 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 161.2 (Ph C-3), 160.7 (C=N), 150.0 (Ph C-1), 130.4 (Ph C-5), 113.4 (Ph C-6), 111.3 (Ph C-4), 107.1 (Ph C-2), 54.8 (OCH_3), 46.7 (CH_2), 20.1 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -79.4 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{12}NOS^+$: 194.0634 $[M + H]^+$; found: 194.0639.

3,4-dimethyl-*N*-[(2Z)-2-thietanylidene]aniline (5)



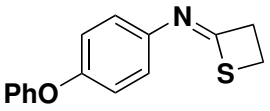
By following the general procedure, starting from 3,4-dimethoxyphenyl isothiocyanate (0.195 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **5** was obtained in 71% yield (0.158 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 6:4).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 6.88 (dd, ^3J = 8.3 Hz, ^4J = 2.3 Hz, 1H, Ph H-6), 6.85 (d, ^4J = 2.3 Hz, 1H, Ph H-2), 6.59 (d, ^3J = 8.3 Hz, 1H, Ph H-5), 3.40 (s, 3H, 3-OCH_3), 3.38 (s, 3H, 4-OCH_3), 3.37 (m, 2H, CH_2), 2.43 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 158.3 (C=N), 150.8 (Ph C-3), 147.8 (Ph C-4), 142.0 (Ph C-1), 112.9 (Ph C-5), 112.8 (Ph C-6), 106.8 (Ph C-2), 55.8 (4-OCH_3), 55.4 (3-OCH_3), 47.0 (CH_2), 20.5 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{14}NO_2S^+$: 224.0740 $[M + H]^+$; found: 224.0741.

4-phenoxy-*N*-[(2Z)-2-thietanylidene]aniline (6)



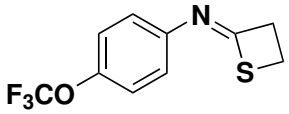
By following the general procedure, starting from 4-phenoxyphenyl isothiocyanate (0.227 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **6** was obtained in 70% yield (0.178 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.15 (m, 2H, Ph 1 H-2,6), 7.03 (m, 2H, Ph 2 H-3,5), 6.93 (m, 4H, Ph 1 H-3,5 and Ph 2 H-2,6), 6.84 (m, 1H, Ph 2 H-4) 3.28 (m, 2H, CH_2), 2.35 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 159.7 (C=N), 158.1 (Ph 2 C-1), 155.0 (Ph 2 C-4), 143.9 (Ph 1 C-1), 130.0 (Ph 2 C-3,5), 123.3 (Ph 2 C-4), 122.8 (Ph 1 C-2,6), 120.1 (Ph 1 C-3,5), 119.1 (Ph 2 C-2,6), 46.9 (CH_2), 20.3 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{15}H_{14}NOS^+$: 256.0791 $[M + H]^+$; found: 256.0786.

***N*-[(2Z)-2-thietanylidene]-4-(trifluoromethoxy)aniline (7)**



By following the general procedure, starting from 4-(trifluoromethoxy)phenyl isothiocyanate (0.219 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **7** was obtained in 73% yield (0.181 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 7:3).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 6.96 (m, 2H, Ph H-2,6), 6.90 (m, 2H, Ph H-3,5), 3.20 (m, 2H, CH_2), 2.29 (m, 2H, SCH_2).

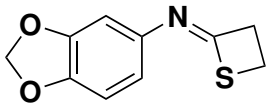
^{13}**C NMR** (100 MHz, C_6D_6) δ: 162.0 (C=N), 147.0 (Ph C-1), 146.4 (q, $^{3}J_{C,F}$ = 1.9 Hz, Ph C-4), 122.5 (Ph C-2,6), 122.3 (q, $^{4}J_{C,F}$ = 0.9 Hz, Ph C-3,5), 121.3 (q, $^{1}J_{C,F}$ = 256.5 Hz, OCF_3), 46.7 (CH_2), 20.1 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -83.5 (C=N).

^{15}**F NMR** (376 MHz, C_6D_6) δ: -57.8 (s, OCF_3).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_9F_3NOS^+$: 248.0351 $[M + H]^+$; found: 248.0350.

***N*-[(2Z)-2-thietanylidene]-1,3-benzodioxol-5-amine (8)**



By following the general procedure, starting from 3,4-methylenedioxyphenyl isothiocyanate (0.179 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **8** was obtained in 73% yield (0.151 g) as a yellow oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

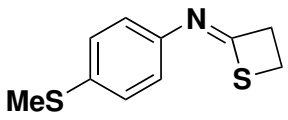
^{1}H NMR (400 MHz, C_6D_6) δ: 6.90 (d, ^4J = 2.0 Hz, 1H, bd H-4), 6.70 (dd, ^3J = 8.2 Hz, ^4J = 2.0 Hz, 1H, bd H-6), 6.63 (d, ^3J = 8.2 Hz, 1H, bd H-7), 5.25 (s, 2H, bd H-2), 3.24 (m, 2H, CH_2), 2.33 (m, 2H, SCH_2).

^{13}C NMR (100 MHz, C_6D_6) δ: 159.2 (C=N), 148.9 (bd C-3a), 145.5 (bd C-7a), 143.0 (bd C-5), 114.4 (bd C-6), 108.8 (bd C-7), 103.0 (bd C-4), 101.2 (bd C-2), 46.8 (CH_2), 20.4 (SCH_2).

^{15}N NMR (40 MHz, C_6D_6) δ: -81.4 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{10}NO_2S^+$: 208.0427 $[M + H]^+$; found: 208.0431.

4-(methylsulfanyl)-*N*-[(2Z)-2-thietanylidene]aniline (9)



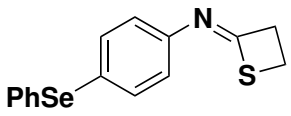
By following the general procedure, starting from 4-(methylthio)phenyl isothiocyanate (0.181 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **9** was obtained in 70% yield (0.147 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.12 (m, 2H, Ph H-3,5), 7.11 (m, 2H, Ph H-2,6), 3.27 (m, 2H, CH_2), 2.34 (m, 2H, SCH_2), 1.96 (s, 3H, SCH_3).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 160.1 (C=N), 145.8 (Ph C-1), 135.4 (Ph C-4), 128.4 (Ph C-3,5), 122.0 (Ph C-2,6), 46.9 (CH_2), 20.3 (SCH_2), 16.0 (SCH_3).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{12}NS_2^+$: 210.0406 $[M + H]^+$; found: 210.0405.

4-(phenylselanyl)-*N*-[(2Z)-2-thietanylidene]aniline (10)



Preparation of (4-isothiocyanatophenyl)(phenyl)selane:
4-(Phenylselanyl)aniline (0.500 g, 2.0 mmol, 1.0 equiv) was dissolved in DCM (20 mL). Thiophosgene (0.463 g, 0.31 mL, 4.0 mmol, 2.0 equiv) was added dropwise at 0 °C. After the addition was complete the reaction was allowed to reach room temperature and stirred for 3 hours. The reaction mixture was diluted with DCM, washed with sat. aqueous $NaHCO_3$, brine and dried over Na_2SO_4. Evaporation of the solvent gave (4-isothiocyanatophenyl)(phenyl)-selane as an orange oil in 96% yield (0.557 g) which was used without any further purification. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 7.51 (m, 2H), 7.39-7.31 (m, 5H), 7.09 (m, 2H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ: 134.0, 133.2, 131.5, 130.2, 130.0, 129.7, 128.8, 126.6.

By following the general procedure, starting from (4-isothiocyanatophenyl)-(phenyl)-selane (0.290 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **10** was obtained in 71% yield (0.226 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}H NMR (400 MHz, C_6D_6) δ: 7.43 (m, 2H, Ph 1 H-3,5), 7.39 (m, 2H, Ph 2 H-2,6), 7.04 (m, 2H, Ph 1 H-2,6) 6.91 (m, 3H, Ph 2 H-3,4,5), 3.21 (m, 2H, CH_2), 2.29 (m, 2H, SCH_2).

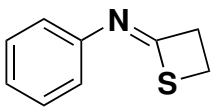
^{13}C NMR (100 MHz, C_6D_6) δ: 161.2 (C=N), 148.0 (Ph 1 C-1), 135.0 (Ph 1 C-3,5), 132.8 (Ph 2 C-2,6), 132.4 (Ph 2 C-1), 129.6 (Ph 2 C-3,5), 127.2 (Ph 1 C-4, Ph 2 C-4), 122.4 (Ph 1 C-2,6), 46.8 (CH_2), 20.1 (SCH_2).

^{15}N NMR (40 MHz, C_6D_6) δ: -81.7 (C=N).

^{77}Se NMR (76 MHz) δ: 410.5 (s).

HRMS (ESI), *m/z*: calcd. for $C_{15}H_{14}NSSe^+$: 320.0007 $[M + H]^+$; found: 320.0007.

***N*-[(2Z)-2-thietanylidene]aniline (11)**



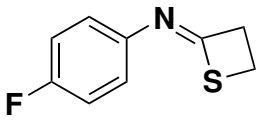
By following the general procedure, starting from phenyl isothiocyanate (0.135 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **11** was obtained in 76% yield (0.124 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.23 (m, 2H, Ph H-2,6), 7.17 (m, 2H, Ph H-3,5), 6.94 (m, 1H, Ph H-4), 3.26 (m, 2H, CH_2), 2.32 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 160.4 (C=N), 148.6 (Ph C-1), 129.6 (Ph C-3,5), 125.3 (Ph C-4) 121.3 (Ph C-2,6), 46.8 (CH_2), 20.0 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_9H_{10}NS^+$: 164.0528 $[M + H]^+$; found: 164.0530.

4-fluoro-*N*-[(2Z)-2-thietanylidene]aniline (12)



By following the general procedure, starting from 4-fluorophenyl isothiocyanate (0.153 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **12** was obtained in 80% yield (0.145 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.00 (m, 2H, Ph H-2,6), 6.78 (m, 2H, Ph H-3,5), 3.23 (m, 2H, CH_2), 2.32 (m, 2H, SCH_2).

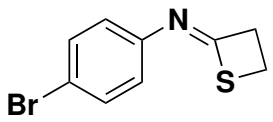
^{13}**C NMR** (100 MHz, C_6D_6) δ: 160.6 (d, $^{6}J_{C,F}$ = 1.8 Hz, C=N), 160.6 (d, $^{1}J_{C,F}$ = 243.4 Hz, Ph C-4), 122.8 (d, $^{3}J_{C,F}$ = 8.1 Hz, Ph C-2,6), 116.2 (d, $^{2}J_{C,F}$ = 22.5 Hz, Ph C-3,5), 46.8 (CH_2), 20.1 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -82.5 (C=N).

^{19}**F NMR** (376 MHz, C_6D_6) δ: -117.9 (m)

HRMS (ESI), *m/z*: calcd. for $C_9H_9FNS^+$: 182.0434 $[M + H]^+$; found: 182.0434.

4-bromo-*N*-[(2Z)-2-thietanylidene]aniline (13)



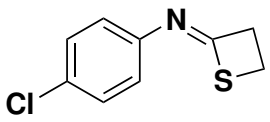
By following the general procedure, starting from 4-bromophenyl isothiocyanate (0.214 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **13** was obtained in 78% yield (0.189 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.22 (m, 2H, Ph H-3,5), 6.86 (m, 2H, Ph H-2,6), 3.19 (m, 2H, CH_2), 2.29 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 161.6 (C=N), 147.4 (Ph C-1), 132.7 (Ph C-3,5), 123.0 (Ph C-2,6) 118.4 (Ph C-4), 46.7 (CH_2), 20.1 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_9H_9BrNS^+$: 241.9634 $[M + H]^+$; found: 241.9632.

4-chloro-*N*-[(2Z)-2-thietanylidene]aniline (14)



By following the general procedure, starting from 4-chlorophenyl isothiocyanate (0.169 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **14** was obtained in 71% yield (0.140 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

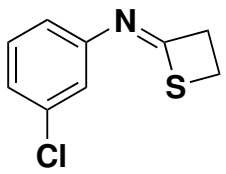
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.07 (m, 2H, Ph H-3,5), 6.93 (m, 2H, Ph H-2,6), 3.21 (m, 2H, CH_2), 2.29 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 161.6 (C=N), 146.9 (Ph C-1), 130.6 (Ph C-4), 129.7 (Ph C-3,5), 122.6 (Ph C-2,6), 46.7 (CH_2), 20.1 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -82.3 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_9H_9ClNS^+$: 198.0139 $[M + H]^+$; found: 198.0139.

3-chloro-*N*-[(2Z)-2-thietanylidene]aniline (15)



By following the general procedure, starting from 3-chlorophenyl isothiocyanate (0.169 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **15** was obtained in 74% yield (0.146 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

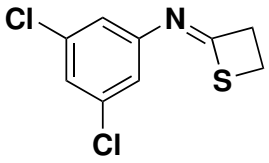
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.27 (t, J = 2.0 Hz, 1H, Ph H-2), 6.93 (m, 1H, Ph H-6), 6.90 (m, 1H, Ph H-4), 6.83 (m, 1H, Ph H-5), 3.16 (m, 2H, CH_2), 2.25 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 162.7 (C=N), 149.9 (Ph C-1), 135.3 (Ph C-3), 130.7 (Ph C-5), 125.2 (Ph C-4), 121.5 (Ph C-2), 119.4 (Ph C-6), 46.5 (CH_2), 20.0 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -81.7 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_9H_9ClNS^+$: 198.0139 $[M + H]^+$; found: 198.0137.

3,5-dichloro-*N*-[(2Z)-2-thietanylidene]aniline (16)



By following the general procedure, starting from 3,5-dichlorophenyl isothiocyanate (0.204 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **16** was obtained in 82% yield (0.190 g) as a yellow solid (mp: 55-58 °C) after purification by column chromatography on silica gel (*n*-hexane:DCM 3:7).

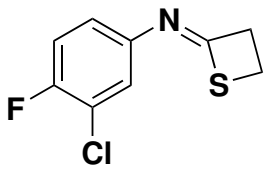
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.00 (d, ^{4}J = 1.9 Hz, 2H, Ph H-2,6), 6.90 (t, ^{4}J = 1.9 Hz, 1H, Ph H-4), 3.08 (m, 2H, CH_2), 2.19 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 164.6 (C=N), 150.5 (Ph C-1), 135.9 (Ph C-3,5), 125.1 (Ph C-4), 119.8 (Ph C-2,6), 46.3 (CH_2), 20.0 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -84.8 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_9H_8Cl_2NS^+$: 231.9749 $[M + H]^+$; found: 231.9739.

3-chloro-4-fluoro-*N*-[(2Z)-2-thietanylidene]aniline (17)



By following the general procedure, starting from 3-chloro-4-fluorophenyl isothiocyanate (0.188 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **17** was obtained in 75% yield (0.190 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

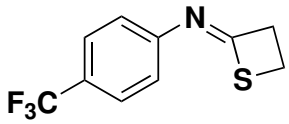
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.17 (m, 1H, Ph H-2), 6.73 (ddd, ^{3}J = 8.7 Hz, ^{4}J = 4.3 Hz, ^{4}J = 2.6 Hz, 1H, Ph H-6), 6.61 (t, ^{3}J = 8.7 Hz, 1H, Ph H-5) 3.16 (m, 2H, CH_2), 2.27 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 162.6 (C=N), 155.9 (d, $^{1}J_{C,F}$ = 246.3 Hz, Ph C-4), 145.1 (d, $^{4}J_{C,F}$ = 3.4 Hz, Ph C-1),123.2 (Ph C-2), 121.8 (d, $^{2}J_{C,F}$ = 18.7 Hz, Ph C-3), 120.9 (d, $^{3}J_{C,F}$ = 6.9 Hz, Ph C-6), 117.3 (d, $^{2}J_{C,F}$ = 22.0 Hz, PhC-5), 46.6 (CH_2), 20.1 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -120.3 (m).

HRMS (ESI), *m/z*: calcd. for $C_9H_8ClFNS^+$: 216.0045 $[M + H]^+$; found: 216.0046.

***N*-[(2Z)-2-thietanylidene]-4-(trifluoromethyl)aniline (18)**



By following the general procedure, starting from 4-trifluoromethylphenyl isothiocyanate (0.203 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **18** was obtained in 72% yield (0.166 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.31 (m, 2H, Ph H-3,5), 6.98 (m, 2H, Ph H-2,6), 3.18 (m, 2H, CH_2), 2.27 (m, 2H, SCH_2).

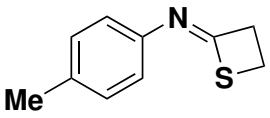
^{13}**C NMR** (100 MHz, C_6D_6) δ: 163.2 (C=N), 151.5 (Ph C-1), 128.3 (Ph C-4), 126.9 (q, $^{3}J_{C,F}$ = 3.8 Hz, Ph C-3,5), 125.1 (q, $^{1}J_{C,F}$ = 271.6 Hz, CF_3), 121.3 (Ph C-2,6), 46.6 (CH_2), 19.9 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -81.8 (C=N).

^{19}**F NMR** (376 MHz, C_6D_6) δ: -61.7 (s, CF_3).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_9F_3NS^+$: 232.0402 $[M + H]^+$; found: 232.0407.

4-methyl-*N*-[(2Z)-2-thietanylidene]aniline (19)



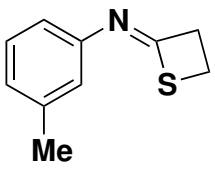
By following the general procedure, starting from p-tolyl isothiocyanate (0.149 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **19** was obtained in 76% yield (0.135 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.20 (m, 2H, Ph H-2,6), 6.99 (m, 2H, Ph H-3,5), 3.30 (m, 2H, CH_2), 2.35 (m, 2H, SCH_2), 2.07 (s, 3H, CH_3).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 159.4 (C=N), 146.1 (Ph C-1), 134.6 (Ph C-4), 130.2 (Ph C-3,5), 121.3 (Ph C-2,6), 46.9 (CH_2), 20.9 (CH_3), 20.2 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{12}NS^+$: 178.0685 $[M + H]^+$; found: 178.0688.

3-methyl-*N*-[(2Z)-2-thietanylidene]aniline (20)



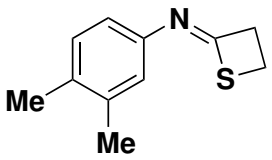
By following the general procedure, starting from 3-tolyl isothiocyanate (0.149 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **20** was obtained in 79% yield (0.140 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 9:1).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.13 (m, 1H, Ph H-5), 7.11 (m, 1H, Ph H-6), 7.08 (m, 1H, Ph H-2), 6.80 (m, 1H, Ph H-4), 3.30 (m, 2H, CH_2), 2.35 (m, 2H, SCH_2), 2.10 (s, 3H, CH_3).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 160.0 (C=N), 148.7 (Ph C-1), 139.3 (Ph C-3), 129.5 (Ph C-5), 126.1 (Ph C-4), 122.1 (Ph C-2), 118.2 (Ph C-6), 46.8 (CH_2), 21.4 (CH3), 20.0 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{12}NS^+$: 178.0685 $[M + H]^+$; found: 178.0692.

3,4-dimethyl-*N*-[(2Z)-2-thietanylidene]aniline (21)



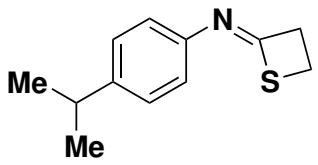
By following the general procedure, starting from 3,4-dimethylphenyl isothiocyanate (0.163 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **21** was obtained in 73% yield (0.140 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 9:1).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.11 (m, 1H, Ph H-2), 7.09 (m, 1H, Ph H-6), 7.00 (m, 1H, Ph H-5), 3.33 (m, 2H, CH_2) 2.38 (m, 2H, SCH_2) 2.00 (s, 3H, 3-CH_3), 1.97 (s, 3H, 4-CH_3).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 159.1 (C=N), 146.5 (Ph C-1), 137.6 (Ph C-3), 133.3 (Ph C-4), 130.7 (Ph C-5), 122.8 (Ph C-2), 118.6 (Ph C-6), 46.5 (CH_2), 20.2 (SCH_2), 19.9 (3-CH_3), 19.2 (4-CH_3).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{14}NS^+$: 192.0841 $[M + H]^+$; found: 192.0845.

4-isopropyl-*N*-[(2Z)-2-thietanylidene]aniline (22)



By following the general procedure, starting from 4-isopropylphenyl isothiocyanate (0.177 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **22** was obtained in 71% yield (0.146 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 9:1).

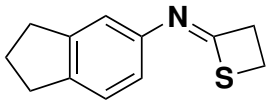
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.26 (m, 2H, Ph H-2,6), 7.09 (m, 2H, Ph H-3,5), 3.30 (m, 2H, CH_2), 2.67 (sept, ^{3}J = 6.9 Hz, 1H, CH), 2.36 (m, 2H, SCH_2), 1.10 (d, ^{3}J = 6.9 Hz, 6H, CH_3).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 159.3 (C=N), 146.4 (Ph C-1), 145.7 (Ph C-4), 127.6 (Ph C-3,5), 121.4 (Ph C-2,6), 46.9 (CH_2), 34.0 (CH), 24.2 (CH_3), 20.2 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -80.1 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{12}H_{16}NS^{+}$: 206.0998 $[M + H]^{+}$; found: 206.1005.

***N*-[(2Z)-2-thietanylidene]-5-indanamine (23)**



By following the general procedure, starting from 5-indanyl isothiocyanate (0.175 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **23** was obtained in 77% yield (0.157 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 9:1).

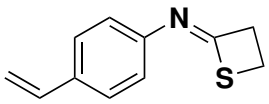
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.19 (s, 1H, indanyl H-4), 7.14 (m, 1H, indanyl H-6), 7.10 (m, 1H, indanyl H-7), 3.33 (m, 2H, CH2), 2.66 (m, 2H, indanyl H-3), 2.63 (m, 2H, indanyl H-1), 2.38 (m, 2H, SCH_2), 1.76 (m, 2H, indanyl H-2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 158.9 (C=N), 147.1 (indanyl C-5), 145.6 (indanyl C-3a), 141.0 (indanyl C-7a), 125.2 (indanyl C-7), 119.4 (indanyl C-6), 117.3 (indanyl C-4), 46.9 (CH2), 33.2 (indanyl C-3), 32.7 (indanyl C1), 25.9 (indanyl C-2), 20.2 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -79.1 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{12}H_{14}NS^{+}$: 204.0841 $[M + H]^{+}$; found: 204.0845.

***N*-[(2Z)-2-thietanylidene]-4-vinylaniline (24)**



By following the general procedure, starting from 4-vinylphenyl isothiocyanate[1] (0.161 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **24** was obtained in 70% yield (0.132 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}H NMR (400 MHz, C_6D_6) δ: 7.23 (m, 2H, Ph H-3,5), 7.17 (m, 2H, Ph H-2,6), 6.54 (dd, ^3J = 17.6, 10.9 Hz, 1H, CH=CH_2), 5.54 (dd, ^3J = 17.6 Hz, ^2J = 1.0 Hz, 1H, CH=CH_2 trans), 5.04 (dd, ^3J = 10.9 Hz, ^2J = 1.0 Hz, 1H, CH=CH_2 cis), 3.28 (m, 2H, CH_2), 2.34 (m, 2H, SCH_2).

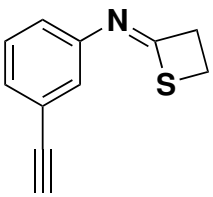
^{13}C NMR (100 MHz, C_6D_6) δ: 160.5 (C=N), 148.0 (Ph C-1), 136.9 (CH=CH_2), 134.9 (Ph C-4), 127.7 (Ph C-3,5), 121.5 (Ph C-2,6), 113.0 (CH=CH_2), 46.8 (CH_2), 20.2 (SCH_2).

^{15}N NMR (40 MHz, C_6D_6) δ: -80.6 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{12}NS^+$: 190.0685 $[M + H]^+$; found: 190.0684.

[1] P. J. Roth, P. Theato, in Non-Conventional Functional Block Copolymers, Vol. 1066, American Chemical Society, 2011, pp. 23-37.

3-ethynyl-*N*-[(2Z)-2-thietanylidene]aniline (25)



By following the general procedure, starting from 3-ethynyl-phenyl isothiocyanate[2] (0.159 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **25** was obtained in 74% yield (0.138 g) as a yellow oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 7:3).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.50 (m, 1H, Ph H-2), 7.20 (m, 1H, Ph H-4), 7.07 (m, 1H, Ph H-6), 6.93 (m, 1H, Ph H-5), 3.18 (m, 2H, CH_2), 2.70 (s, 1H, C≡CH), 2.26 (m, 2H, SCH_2).

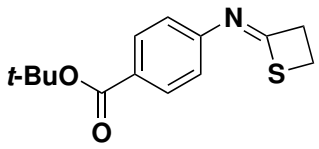
^{13}**C NMR** (100 MHz, C_6D_6) δ: 162.0 (C=N), 148.7 (Ph C-1), 129.7 (Ph C-5), 129.0 (Ph C-4), 124.8 (Ph C-2), 123.9 (Ph C-3), 121.9 (Ph C-6), 83.7 (C≡CH), 78.1 (C≡CH), 46.6 (CH_2), 20.0 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -81.8 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{10}NS^+$: 188.0528 $[M + H]^+$; found: 188.0525.

[2] Z. Fu, W. Yuan, N. Chen, Z. Yang, J. Xu, Green Chem. 2018, 20, 4484-4491.

2-methyl-2-propanyl-4-[(2Z)-2-thietanylideneamino]benzoate (26)



By following the general procedure, starting from tert-butyl 4-isothiocyanato-benzoate (0.235 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **26** was obtained in 80% yield (0.211 g) as a yellowish solid (mp: 52-55 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 6:4).

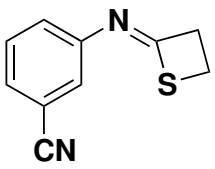
^{1}**H NMR** (400 MHz, C_6D_6) δ: 8.17 (m, 2H, Ph H-2,6), 7.12 (m, 2H, Ph H-3,5), 3.20 (m, 2H, CH_2), 2.27 (m, 2H, SCH_2), 1.47 (s, 9H, CCH_3).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 165.3 (C=O), 162.6 (C=N), 152.3 (Ph C-4), 131.5 (Ph C-2,6), 129.2 (Ph C-1), 120.8 (Ph C-3,5), 80.2 (CCH_3), 46.6 (CH_2), 28.2 (CCH_3), 19.9 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -80.4 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{14}H_{17}NNaO_2S^+$: 286.0872 $[M + H]^+$; found: 286.0868.

3-[(2Z)-2-thietanylideneamino]benzonitrile (27)



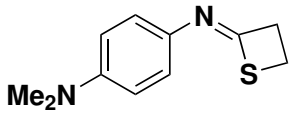
By following the general procedure, starting from 3-cyanophenyl isothiocyanate (0.160 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **27** was obtained in 69% yield (0.129 g) as a brown solid (mp: 122-125 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 7:3).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.16 (m, 1H, Ph H-2), 6.97 (m, 1H, Ph H-6), 6.78 (m, 1H, Ph H-4), 6.68 (m, 1H, Ph H-5), 3.13 (m, 2H, CH_2), 2.23 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 163.9 (C=N), 149.0 (Ph C-3), 130.2 (Ph C-5), 128.3 (Ph C-6), 125.0 (Ph C4), 124.3 (Ph C-2), 118.6 (C≡N), 114.0 (Ph C-1), 46.4 (CH_2), 19.9 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_9N_2S^+$: 189.0481 $[M + H]^+$; found: 189.0478.

***N,N*-dimethyl-*N´*-[(2Z)-2-thietanylidene]-1,4-benzenediamine (28)**



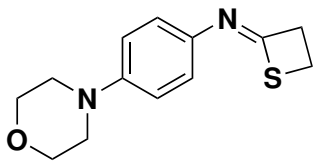
By following the general procedure, starting from 4-(*N,N*-dimethylamino)phenyl isothiocyanate (0.178 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **28** was obtained in 75% yield (0.155 g) as a brown solid (mp: 78-80 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.35 (m, 2H, Ph H-3,5), 6.58 (m, 2H, Ph H-2,6), 3.40 (m, 2H, CH_2), 2.47 (s, 6H, CH_3), 2.45 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 155.4 (C=N), 148.8 (Ph C-1), 138.1 (Ph C-4), 122.8 (Ph C-3,5), 113.6 (Ph C-2,6), 47.4 (CH_2), 40.4 (CH_3), 20.7 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{15}N_2S^+$: 207.0950 $[M + H]^+$; found: 207.0953.

4-(4-morpholinyl)-*N*-[(2Z)-2-thietanylidene]aniline (29)



By following the general procedure, starting from 4-morpholinophenyl isothiocyanate (0.220 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **29** was obtained in 82% yield (0.195 g) as a yellowish solid (mp: 115-117 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 6:4).

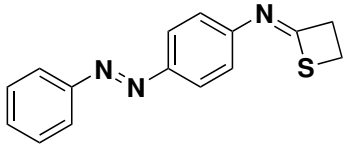
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.30 (m, 2H, Ph H-2,6), 6.66 (m, 2H, Ph H-3,5), 3.52 (m, 4H, morph H-2,6), 3.38 (m, 2H, CH_2), 2.69 (m, 4H, morph H-3,5), 2.43 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 157.4 (C=N), 149.4 (Ph C-4), 140.8 (Ph C-1), 122.5 (Ph C-2,6), 116.7 (Ph C-3,5), 66.9 (morph C-2,6), 49.6 (morph C-3,5), 47.2 (CH_2), 20.5 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -318.9 (morph), -81.9 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{13}H_{17}N_2OS^+$: 249.1056 $[M + H]^+$; found: 249.1064.

4-[(E)-phenyldiazenyl]-*N*-[(2Z)-2-thietanylidene]aniline (30)



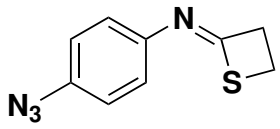
By following the general procedure, starting from 4-(phenylazo)phenyl isothiocyanate (0.239 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **30** was obtained in 67% yield (0.179 g) as an orange oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 8.07 (m, 2H, Ph 1 H-3,5), 8.03 (m, 2H, Ph 2 H-2,6), 7.25 (m, 2H, Ph 1 H-2,6), 7.19 (m, 2H, Ph 2 H-3,5), 7.10 (m, 1H, Ph 2 H-4), 3.23 (m, 2H, CH_2), 2.30 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 162.3 (C=N), 153.4 (Ph2 C-1), 151.0 (Ph 1 C-1), 150.6 (Ph 1 C-4), 130.9 (Ph2 C4), 129.3 (Ph 2 C-3,5), 124.9 (Ph 1 C-3,5), 123.3 (Ph2 C-2,6), 121.9 (Ph 1 C-2,6), 46.7 (CH_2), 20.1 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_{15}H_{14}N_3S^+$: 268.0903 $[M + H]^+$; found: 268.0902.

4-azido-*N*-[(2Z)-2-thietanylidene]aniline (31)



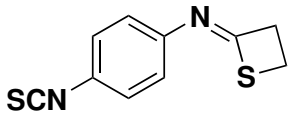
By following the general procedure, starting from 4-azidophenyl isothiocyanate (0.176 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **31** was obtained in 69% yield (0.141 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.02 (m, 2H, Ph H-2,6), 6.67 (m, 2H, Ph H-3,5), 3.25 (m, 2H, CH_2), 2.34 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 160.6 (C=N), 145.3 (Ph C-1), 137.0 (Ph C-4), 122.8 (Ph C-2,6) 120.2 (Ph C-3,5), 46.8 (CH_2), 20.3 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_9H_9N_4S^+$: 205.0542 $[M + H]^+$; found: 205.0541.

4-isothiocyanato-*N*-[(2Z)-2-thietanylidene]aniline (32)



By following the general procedure, starting from 1,4-phenylene diisothiocyanate (0.192 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **32** was obtained in 71% yield (0.156 g) as a white solid (mp: 102-104 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 9:1).

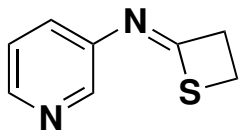
^{1}**H NMR** (400 MHz, C_6D_6) δ: 6.81 (m, 2H, Ph H-2,6), 6.55 (m, 2H, Ph H-3,5), 3.18 (m, 2H, CH_2), 2.29 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 162.1 (C=N), 147.1 (Ph C-1), 127.9 (Ph C-4), 126.9 (Ph C-3,5), 122.1 (Ph C-2,6), 46.7 (CH_2), 20.1 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -82.9 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{10}H_9N_2S_2^+$: 221.0202 $[M + H]^+$; found: 221.0198.

***N*-[(2Z)-2-thietanylidene]-3-pyridinammine (33)**



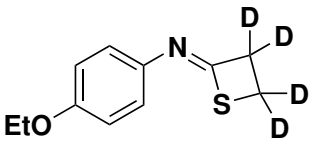
By following the general procedure, starting from pyridine-3-isothiocyanate (0.136 g, 1.0 mmol, 1.0 equiv), bromoiodomethane (0.662 g, 0.22 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **33** was obtained in 74% yield (0.122 g) as a brown oil after purification by column chromatography on silica gel (*n*-hexane:EtOAc 6:4).

^{1}**H NMR** (400 MHz, C_6D_6) δ: 8.76 (dd, ^4J = 2.6 Hz, ^5J = 0.8 Hz, 1H, Pyr H-2), 8.34 (dd, ^3J = 4.7 Hz, ^4J = 1.6 Hz, 1H, Pyr H-6), 7.18 (ddd, ^3J = 8.1 Hz, ^4J = 2.6 Hz, ^4J = 1.6 Hz, 1H, Pyr H-4), 6.72 (dd, ^3J = 8.1 Hz, ^3J = 4.7 Hz, ^5J = 0.8 Hz, 1H, Pyr H-5), 3.15 (m, 2H, CH_2), 2.24 (m, 2H, SCH_2).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 163.5 (C=N), 146.7 (Pyr C-6), 144.3 (Pyr C-3), 143.7 (Pyr C-2), 127.4 (Pyr C-4), 123.8 (Pyr C-5), 46.7 (CH_2), 19.9 (SCH_2).

HRMS (ESI), *m/z*: calcd. for $C_8H_9N_2S^+$: 165.0481 $[M + H]^+$; found: 165.0489.

4-ethoxy-*N*-[(2Z)-($^2H_4$)-2-thietanylidene]aniline (34)



By following the general procedure, starting from 4-ethoxyphenyl isothiocyanate (0.179 g, 1.0 mmol, 1.0 equiv), diiodomethane-d2 (0.810 g, 0.24 mL, 3.0 mmol, 3.0 equiv) and MeLi-LiBr (2.2 M in Et_2O, 1.27 mL, 2.8 mmol, 2.8 equiv) in dry THF (3 mL), compound **34** was obtained in 71% yield (0.150 g) as a brown solid (mp: 64-66 °C) after purification by column chromatography on silica gel (*n*-hexane:EtOAc 8:2).

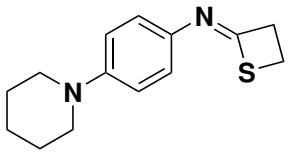
^{1}H NMR (400 MHz, C_6D_6) δ: 7.24 (m, 2H, Ph H-2,6), 6.81 (m, 2H, Ph H-3,5), 3.54 (q, ^3J = 7.0 Hz, 2H, OCH_2), 1.09 (t, ^3J = 7.0 Hz, 3H, CH_3).

^{13}C NMR (100 MHz, C_6D_6) δ: 157.9 (C=N), 157.1 (Ph C-4), 141.5 (Ph C-1), 122.7 (Ph C-2,6), 115.4 (Ph C-3,5), 63.4 (OCH_2), 46.3 (quint, $^1J_{C,D}$ = 21.0 Hz, CH_2), 19.6 (quint, $^1J_{C,D}$ = 19.6 Hz, SCH_2), 14.9 (CH_3).

^{15}N NMR (40 MHz, C_6D_6) δ: -81.4 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{10}D_4NOS^+$: 212.1042 $[M + H]^+$; found: 212.1036.

4-(1-piperidinyl)-*N*-[(2Z)-2-thietanylidene]aniline (35)



4-bromo-*N*-[(2Z)-2-thietanylidene]aniline (0.170 g, 0.7 mmol, 1.0 equiv), di-chlorobis-(tri-otolylphosphine)palladium(II) (0.028 g, 5 mol%), and piperidine (0.060 g, 0.07 mL, 0.7 mmol, 1.0 equiv) were dissolved in toluene. A solution of lithium bis-(trimethylsilyl)amide (1 M in THF, 0.84 mL, 0.8 mmol, 1.2 equiv) was added and the mixture was heated at 110 °C for 18 hours. The reaction mixture was filtered on celite. The filtrate was washed two times with water, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The residue was purified by column chromatography on silica gel (*n*-hexane:EtOAc 8:2) to give compound **35** in 79% yield (0.136 g) as a brown oil.

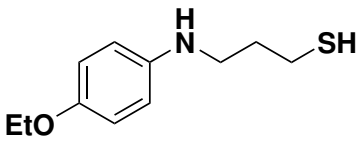
^{1}**H NMR** (400 MHz, C_6D_6) δ: 7.32 (m, 2H, Ph H-2,6), 6.80 (m, 2H, Ph H-3,5), 3.37 (m, 2H, CH_2), 2.86 (m, 4H, piperidine H-2,6), 2.43 (m, 2H, SCH_2), 1.43 (m, 4H, piperidine H-3,5), 1.28 (m, 2H, piperidine H-4).

^{13}**C NMR** (100 MHz, C_6D_6) δ: 156.6 (C=N), 150.4 (Ph C-4), 140.2 (Ph C-1), 122.5 (Ph C-2,6), 117.6 (Ph C-3,5), 50.9 (piperidine C-2,6), 47.2 (CH_2), 26.1 (piperidine C-3,5), 24.6 (piperidine C-4), 20.5 (SCH_2).

^{15}**N NMR** (40 MHz, C_6D_6) δ: -314.2 (piperidine), -81.6 (C=N).

HRMS (ESI), *m/z*: calcd. for $C_{14}H_{19}N_2S^+$: 247.1263 $[M + H]^+$; found: 247.1270.

3-[(4-ethoxyphenyl)amino]-1-propanethiol (36)



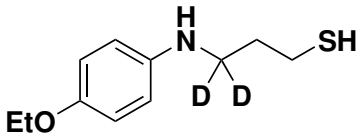
To a solution of 4-ethoxy-*N*-[(2Z)-2-thietanylidene]aniline (0.145 g, 0.7 mmol, 1.0 equiv) in dry THF (2 mL) a solution of $LiAlH_4$ (1M in THF, 0.7 mL, 0.7 mmol, 1.0 equiv) was added dropwise at 0 °C. The reaction mixture was allowed to reach room temperature and then stirred for 1.5 hours before being quenched with water. The reaction mixture was extracted exhaustively with Et_2O (3 x 10 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The residue was purified by column chromatography on silica gel (*n*-hexane:EtOAc 8:2) to give compound **36** in 95% yield (0.140 g) as a yellow oil.

^{1}H NMR (400 MHz, C_6D_6) δ: 6.78 (m, 2H, Ph H-3,5), 6.59 (m, 2H, Ph H-2,6), 3.96 (q, ^3J = 7.0 Hz, 2H, OCH_2CH_3), 3.22 (t, ^3J = 6.9 Hz, 2H, $CH_2CH_2CH_2SH$), 2.65 (t, ^3J = 7.0 Hz, 2H, $CH_2CH_2CH_2SH$), 1.91 (m, 2H, $CH_2CH_2CH_2SH$), 1.37 (t, ^3J = 7.0 Hz, 3H, OCH_2CH_3).

^{13}C NMR (100 MHz, C_6D_6) δ: 151.5 (Ph C-4), 142.2 (Ph C-1), 115.8 (Ph C-3,5), 114.2 (Ph C-2,6), 64.1 (OCH_2CH_3), 43.4 ($CH_2CH_2CH_2SH$), 33.5 ($CH_2CH_2CH_2SH$), 22.3 ($CH_2CH_2CH_2SH$), 15.0 (OCH_2CH_3).

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{16}NOS^+$: 212.1104 $[M + H]^+$; found: 212.1109.

3-[(4-ethoxyphenyl)amino](3,3-$^2H_2$)-1-propanethiol (37)



To a solution of 4-ethoxy-*N*-[(2Z)-2-thietanylidene]aniline (0.124 g, 0.7 mmol, 1.0 equiv) in dry THF (2 mL) a solution of $LiAlH_4$-d_4 (0.025 g, 0.6 mmol, 1.0 equiv) was added in one portion at 0 °C. The reaction mixture was allowed to reach room temperature and then stirred for 1.5 hours before being quenched with water. The reaction mixture was extracted exhaustively with Et_2O (3 x 10 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The residue was purified by column chromatography on silica gel (*n*-hexane:EtOAc 9:1) to give compound **37** in 96% yield (0.123 g) as a yellow oil.

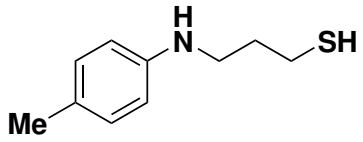
^{1}H NMR (400 MHz, C_6D_6) δ: 6.78 (m, 2H, Ph H-3,5), 6.58 (m, 2H, Ph H-2,6), 3.96 (q, ^3J = 7.0 Hz, 2H, OCH_2CH_3), 2.65 (t, ^3J = 7.0 Hz, 2H, $CD_2CH_2CH_2SH$), 1.90 (t, ^3J = 7.0 Hz, 2H, $CD_2CH_2CH_2SH$), 1.37 (t, ^3J = 7.0 Hz, 3H, OCH_2CH_3).

^{13}C NMR (100 MHz, C_6D_6) δ: 151.4 (Ph C-4), 142.3 (Ph C-1), 115.8 (Ph C-3,5), 114.2 (Ph C-2,6), 64.1 (OCH_2CH_3), 42.6 (q, $^1J_{C,D}$ = 20.5 Hz, $CD_2CH_2CH_2SH$), 33.3 ($CD_2CH_2CH_2SH$), 22.2 ($CD_2CH_2CH_2SH$), 15.0 (OCH_2CH_3).

^{15}N NMR (40 MHz, C_6D_6) δ: -320.9

HRMS (ESI), *m/z*: calcd. for $C_{11}H_{14}D_2NOS^+$: 214.1229 $[M + H]^+$; found: 214.1231.

3-[(4-methylphenyl)amino]-1-propanethiol (38)



To a solution of 4-methyl-*N*-[(2Z)-2-thietanylidene]aniline (0.124 g, 0.7 mmol, 1.0 equiv) in dry THF (2 mL) a solution of $LiAlH_4$ (1M in THF, 0.7 mL, 0.7 mmol, 1.0 equiv) was added dropwise at 0 °C. The reaction mixture was allowed to reach room temperature and then stirred for 1.5 hours before being quenched with water. The reaction mixture was extracted exhaustively with Et_2O (3 x 10 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The residue was purified by column chromatography on silica gel (*n*-hexane:EtOAc 8:2) to give compound **38** in 85% yield (0.108 g) as a yellow oil.

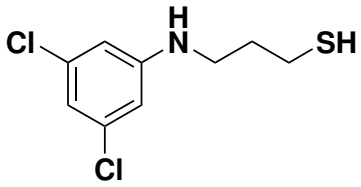
^{1}H NMR (400 MHz, C_6D_6) δ: 7.02 (m, 2H, Ph H-3,5), 6.67 (m, 2H, Ph H-2,6), 3.26 (t, ^3J = 6.8 Hz, 2H, $CH_2CH_2CH_2SH$), 2.64 (t, ^3J = 6.8 Hz, 2H, $CH_2CH_2CH_2SH$), 2.26 (s, 3H, CH_3), 1.95 (q, ^3J = 6.9 Hz, 2H, $CH_2CH_2CH_2SH$).

^{13}C NMR (100 MHz, C_6D_6) δ: 144.1 (Ph C-1), 129.9 (Ph C-3,5), 128.3 (Ph C-4), 114.2 (Ph C-2,6), 43.7 ($CH_2CH_2CH_2SH$), 32.9 ($CH_2CH_2CH_2SH$), 22.1 ($CH_2CH_2CH_2SH$), 20.4 (CH_3).

^{15}N NMR (40 MHz, C_6D_6) δ: -318.2.

HRMS (ESI), *m/z*: calcd. for $C_{10}H_{16}NS^+$: 182.0998 $[M + H]^+$; found: 182.0999.

3-[(3,5-dichlorophenyl)amino]-1-propanethiol (39)



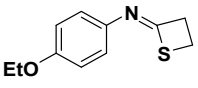
To a solution of 3,5-dichloro-*N*-[(2Z)-2-thietanylidene]aniline (0.126 g, 0.7 mmol, 1.0 equiv) in dry THF (2 mL) a solution of $LiAlH_4$ (1M in THF, 0.7 mL, 0.7 mmol, 1.0 equiv) was added dropwise at 0 °C. The reaction mixture was allowed to reach room temperature and then stirred for 1.5 hours before being quenched with water. The reaction mixture was extracted exhaustively with Et_2O (3 x 10 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The residue was purified by column chromatography on silica gel (*n*-hexane:EtOAc 8:2) to give compound **39** in 92% yield (0.152 g) as a yellow oil.

^{1}H NMR (400 MHz, C_6D_6) δ: 6.66 (t, $^4J = 1.8$ Hz, 1H, Ph H-4), 6.46 (d, $^4J = 1.8$ Hz, 2H, Ph H-2,6), 3.89 (brs, 1H, NH), 3.24 (t, $^3J = 6.8$ Hz, 2H, $CH_2CH_2CH_2SH$), 2.64 (m, 2H, $CH_2CH_2CH_2SH$), 1.91 (q, $^3J = 6.8$ Hz, 2H, $CH_2CH_2CH_2SH$), 1.41 (t, $^3J = 7.9$ Hz, 1H, SH).

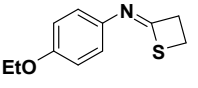
^{13}C NMR (100 MHz, C_6D_6) δ: 149.6 (Ph C-1), 135.5 (Ph C-3,5), 117.1 (Ph C-4), 110.9 (Ph C-2,6), 42.0 ($CH_2CH_2CH_2SH$), 32.9 ($CH_2CH_2CH_2SH$), 22.0 ($CH_2CH_2CH_2SH$).

HRMS (ESI), *m/z*: calcd. for $C_9H_{12}CL_2NS^+$: 236.0062 $[M + H]^+$; found: 236.0064.

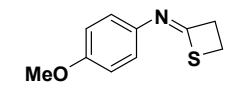
5.3.2 Copies of ^{1}H- and ^{13}C-NMR Spectra



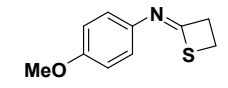
(2) (^{1}H-NMR, 400 MHz, C_6D_6)



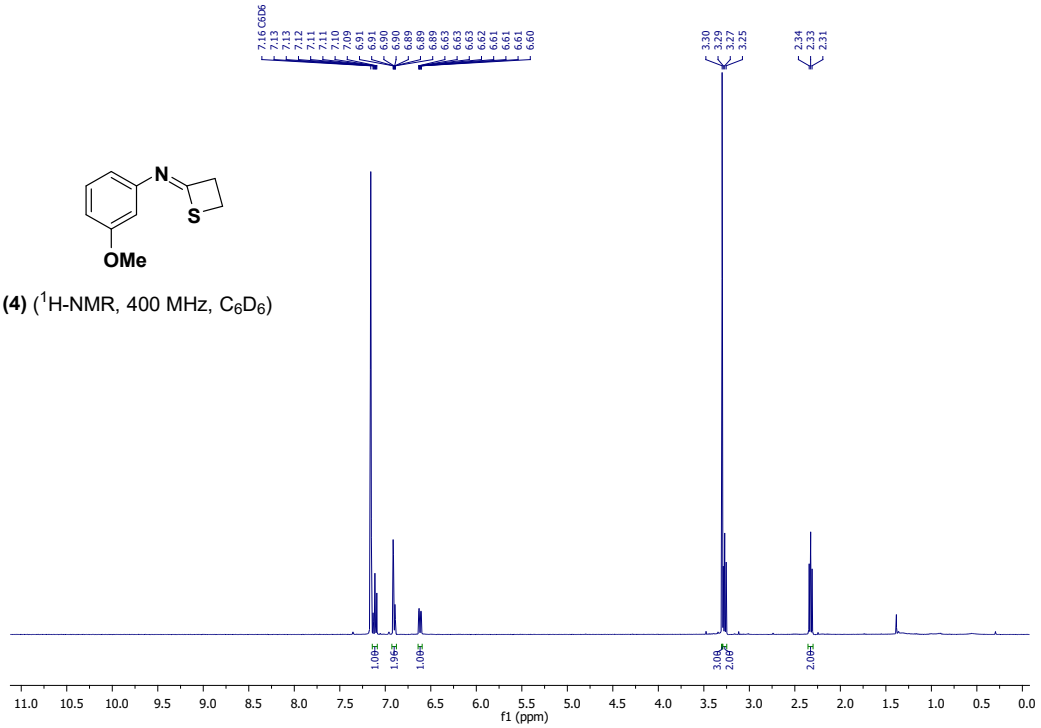
(2) (^{13}C-NMR, 100 MHz, C_6D_6)



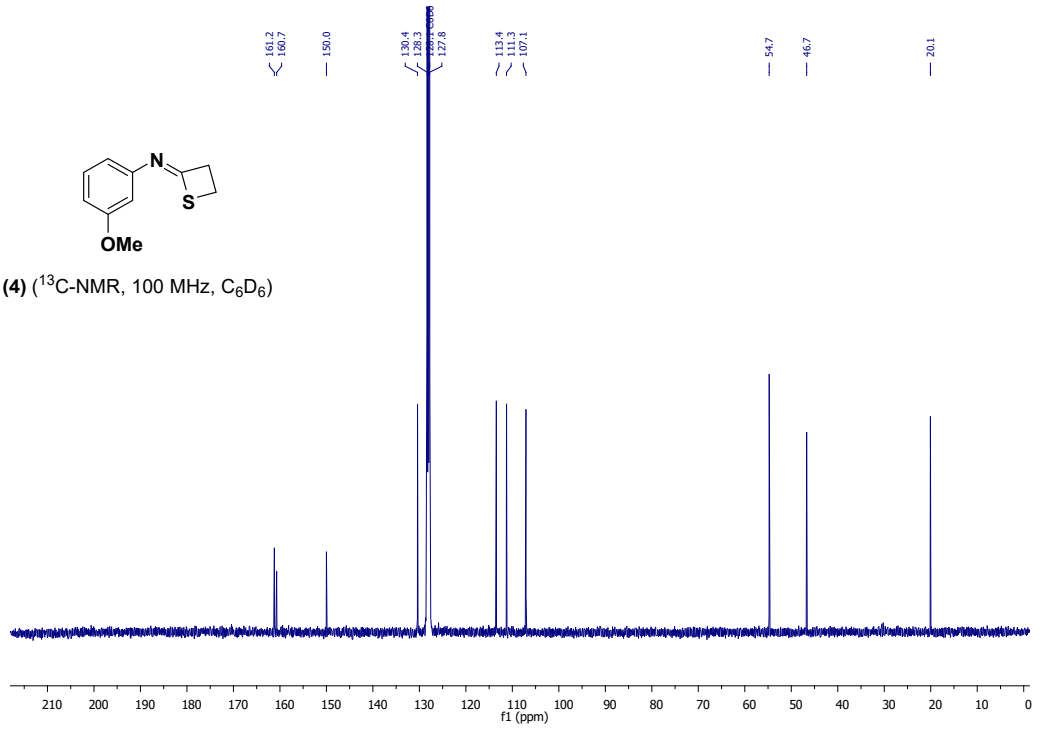
(3) (^{1}H-NMR, 400 MHz, C_6D_6)



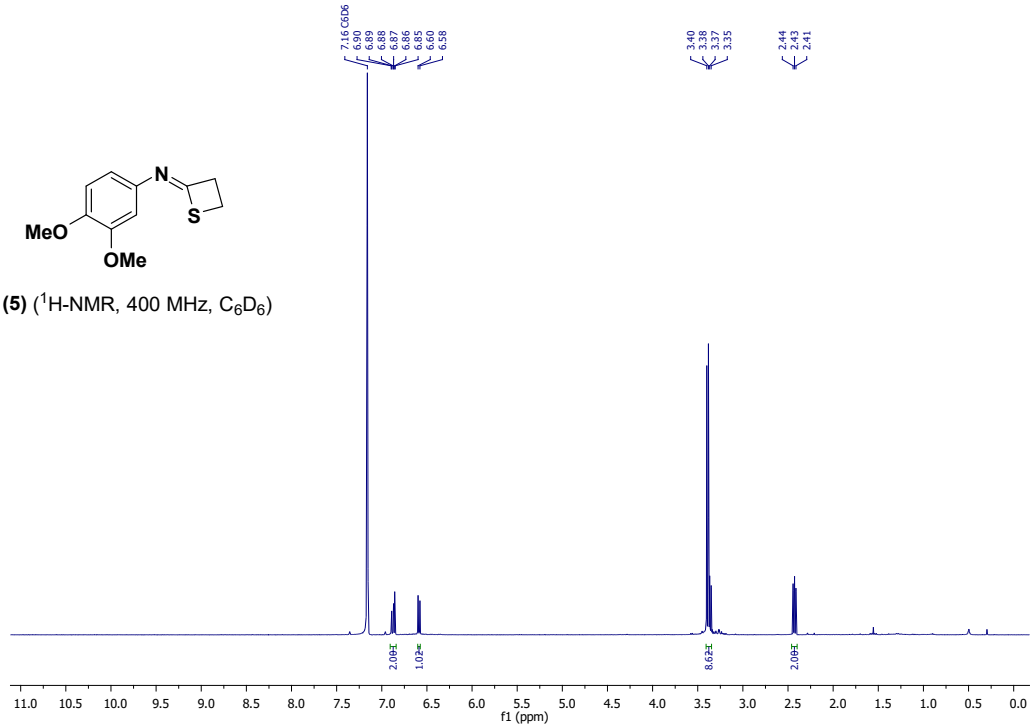
(3) (^{13}C-NMR, 100 MHz, C_6D_6)

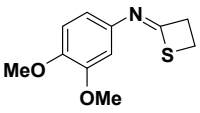


(4) (^{1}H-NMR, 400 MHz, C_6D_6)



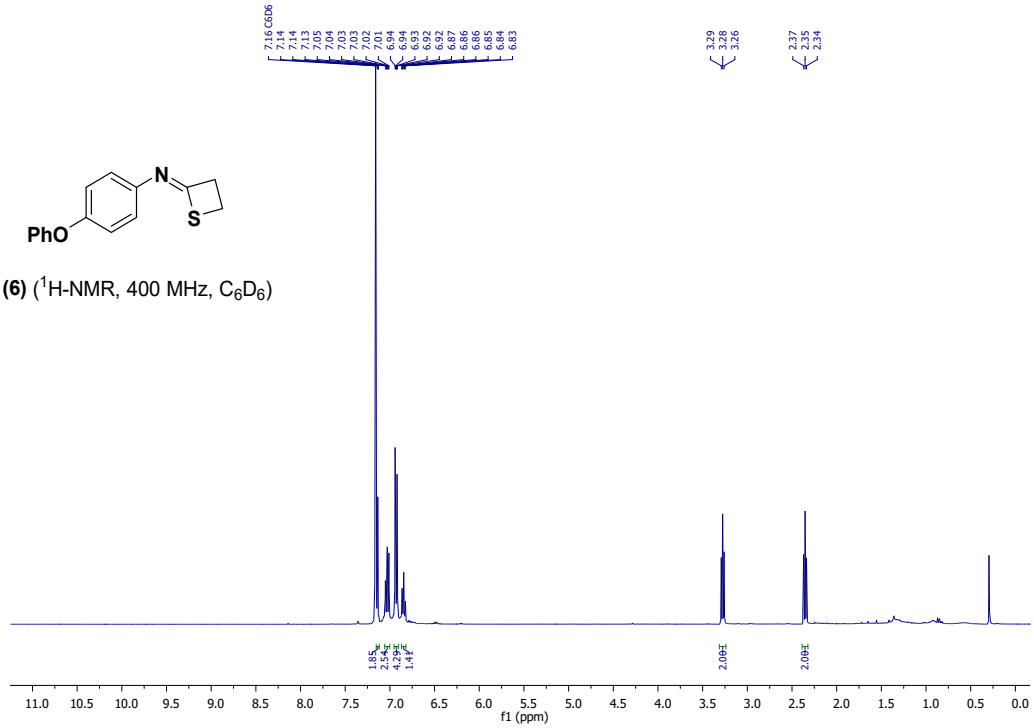
(4) (^{13}C-NMR, 100 MHz, C_6D_6)



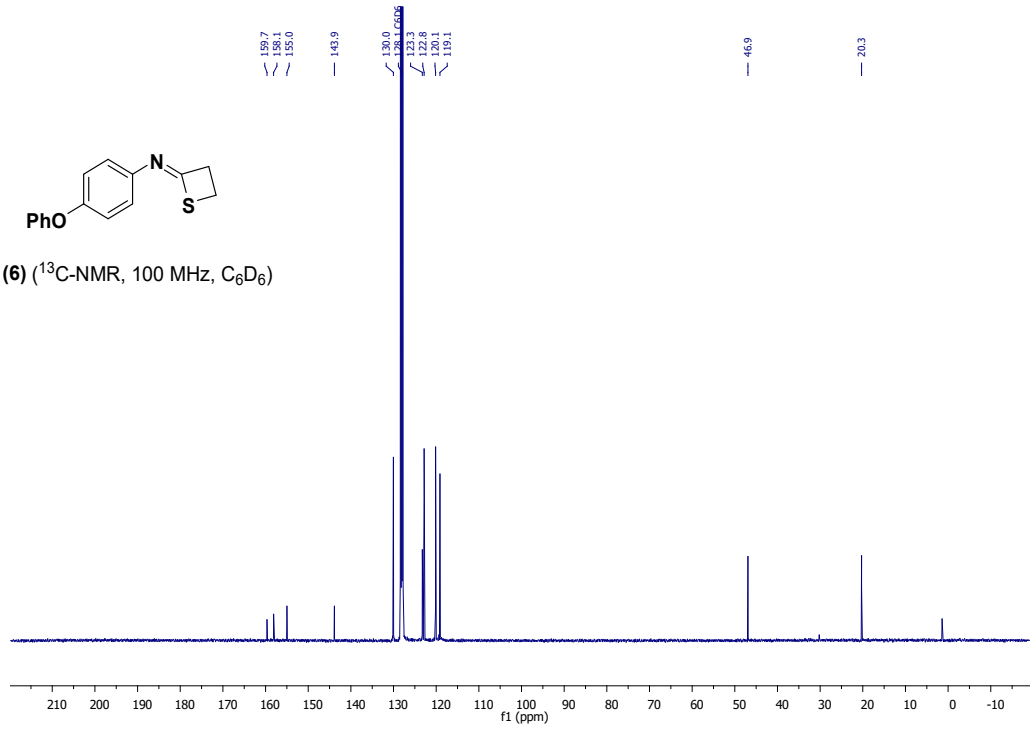


(5) (^{1}H-NMR, 400 MHz, C_6D_6)

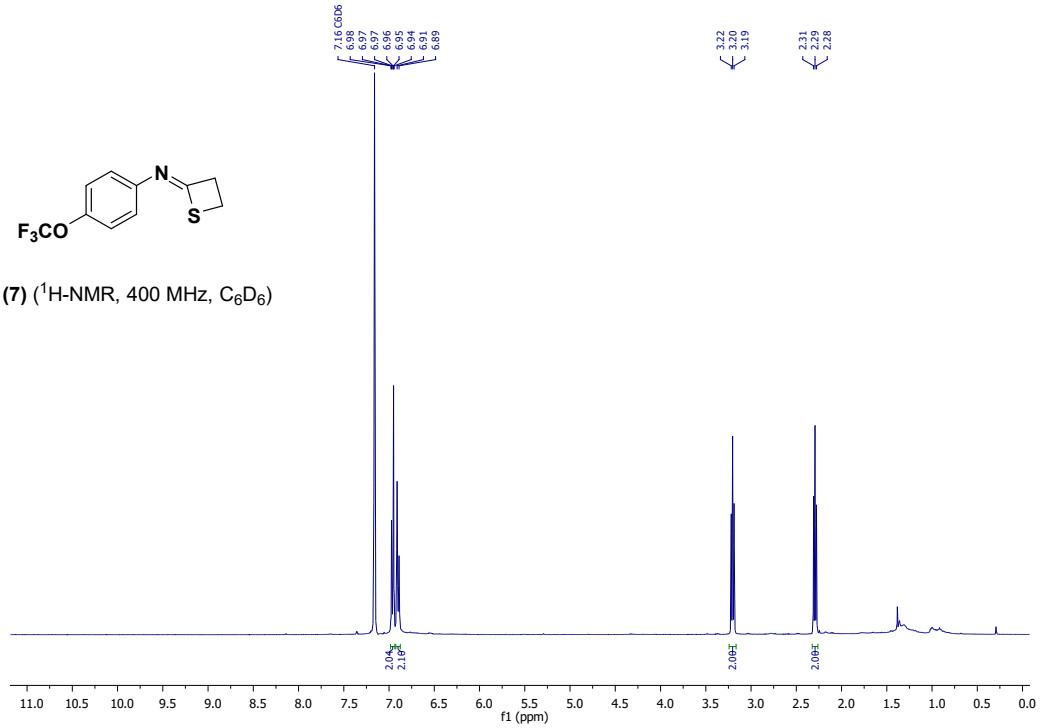
(5) (^{13}C-NMR, 100 MHz, C_6D_6)



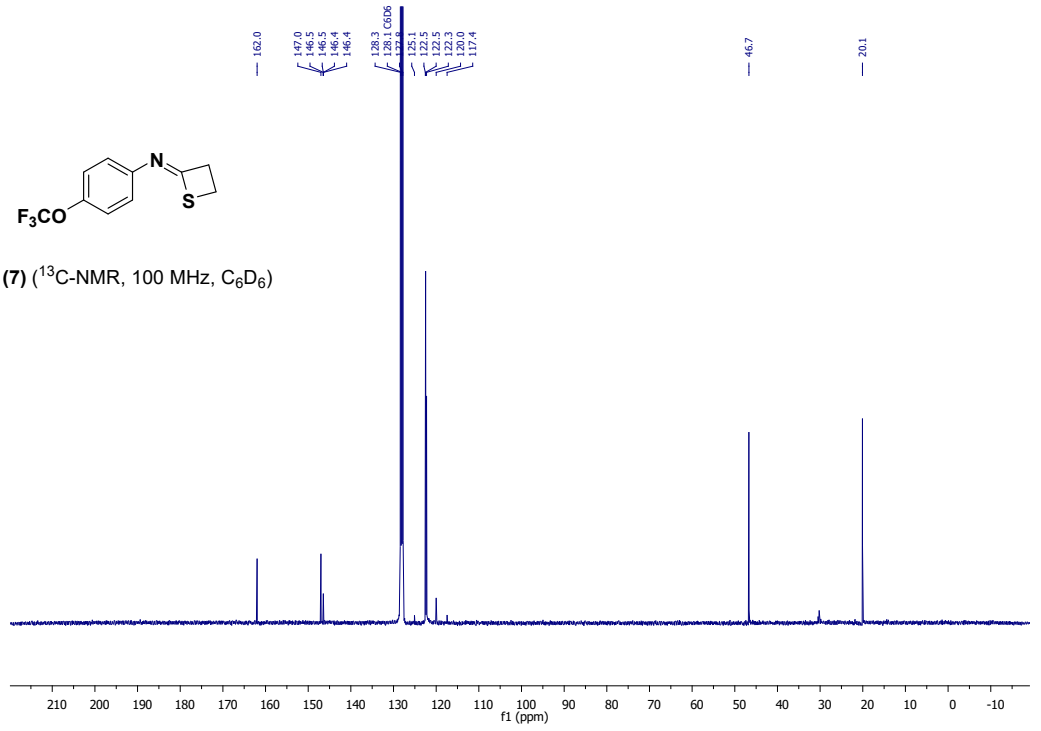
(6) (^{1}H-NMR, 400 MHz, C_6D_6)



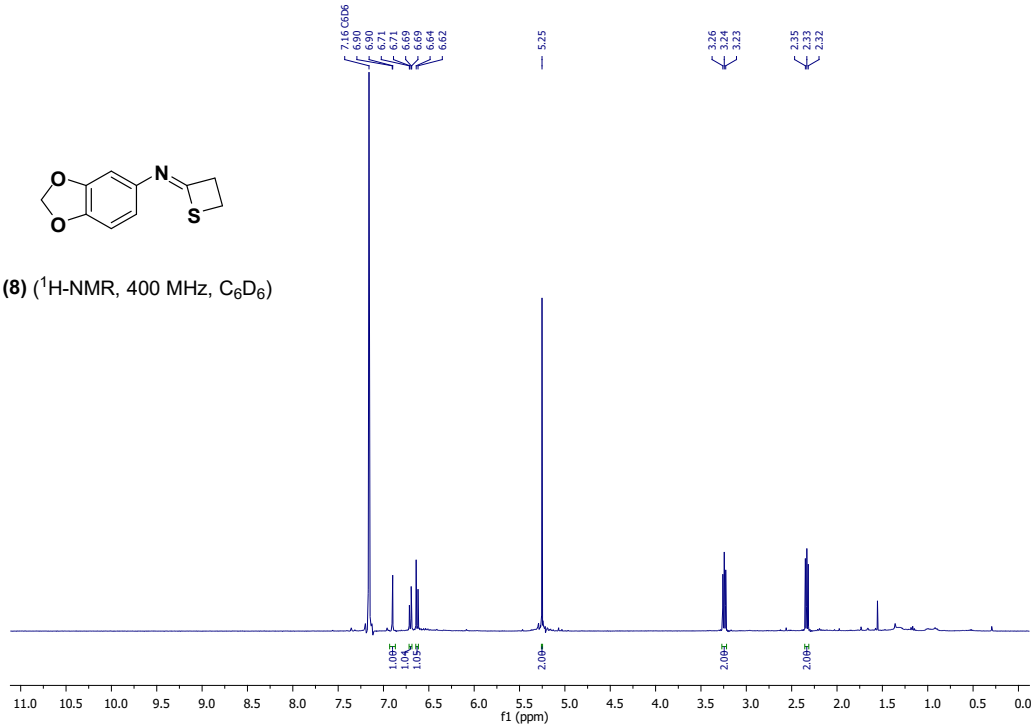
(6) (^{13}C-NMR, 100 MHz, C_6D_6)



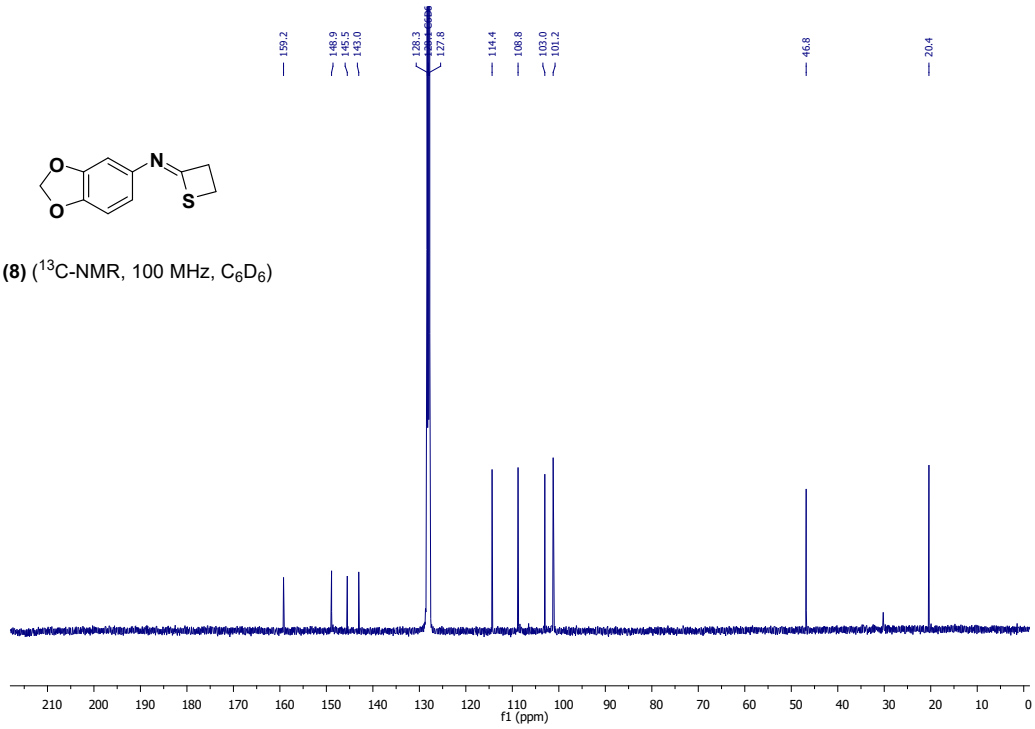
(7) (^{1}H-NMR, 400 MHz, C_6D_6)



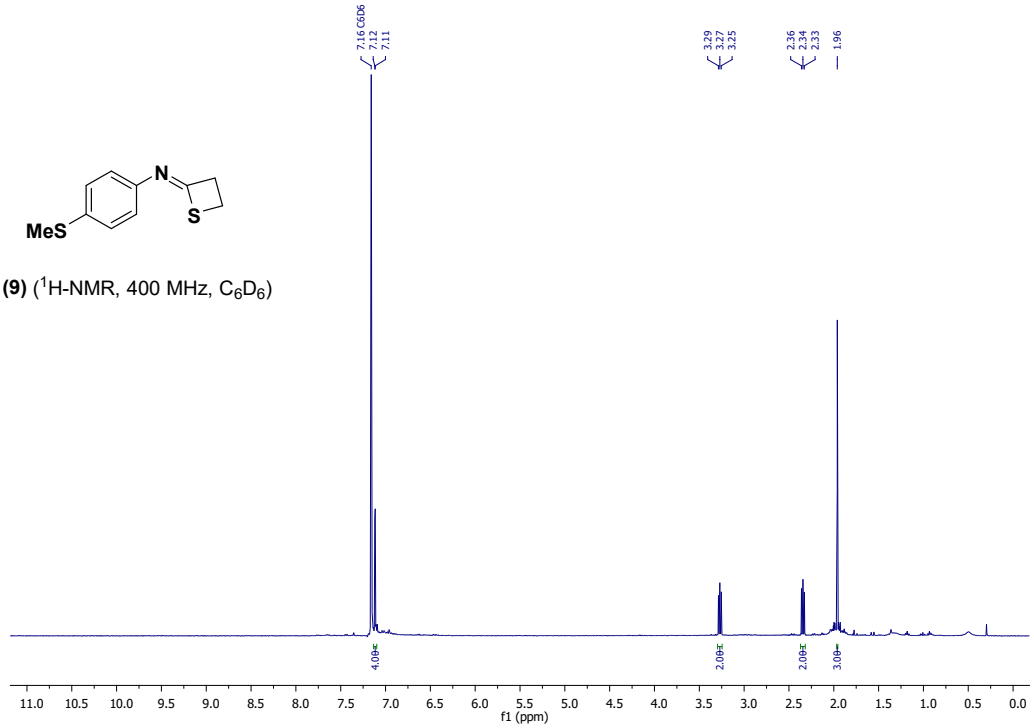
(7) (^{13}C-NMR, 100 MHz, C_6D_6)



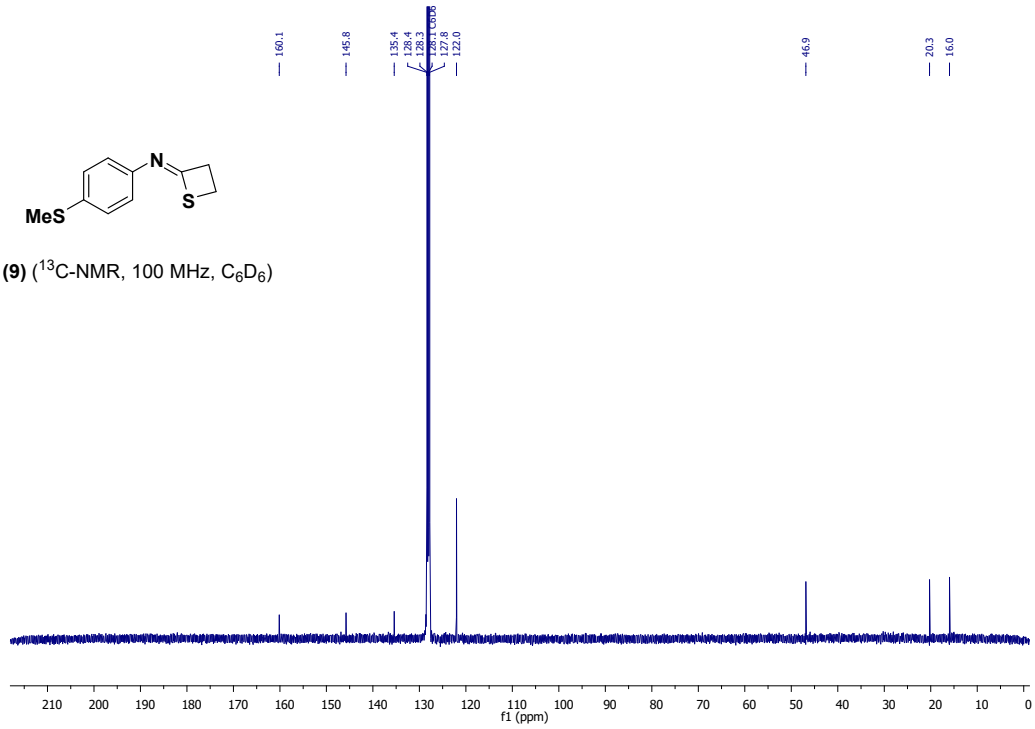
(8) (^{1}H-NMR, 400 MHz, C_6D_6)



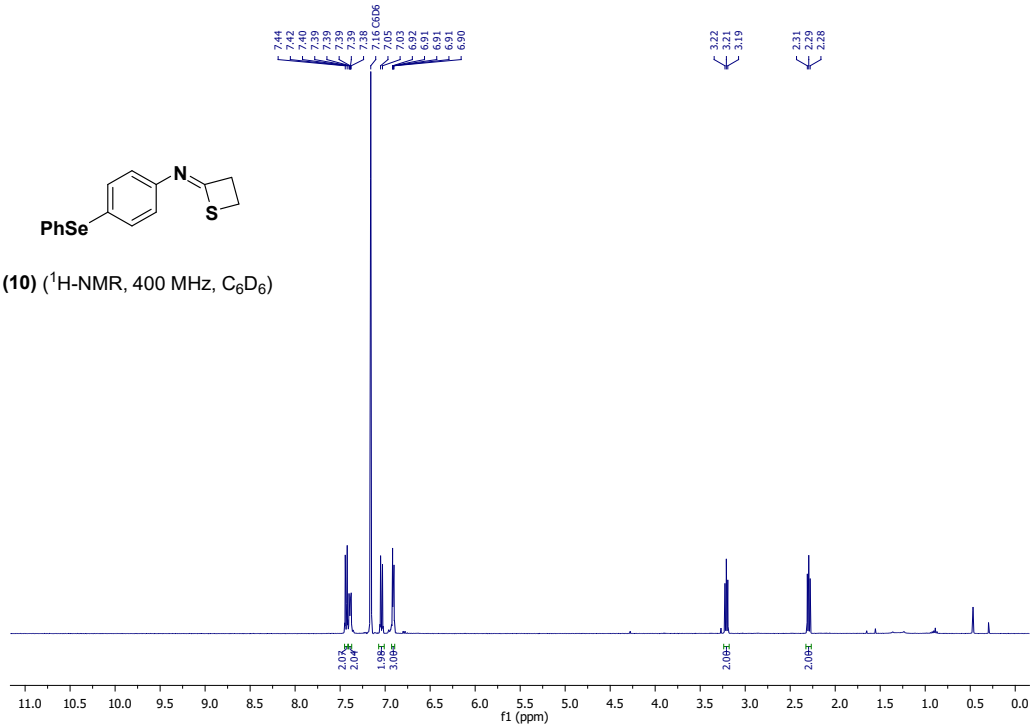
(8) (^{13}C-NMR, 100 MHz, C_6D_6)



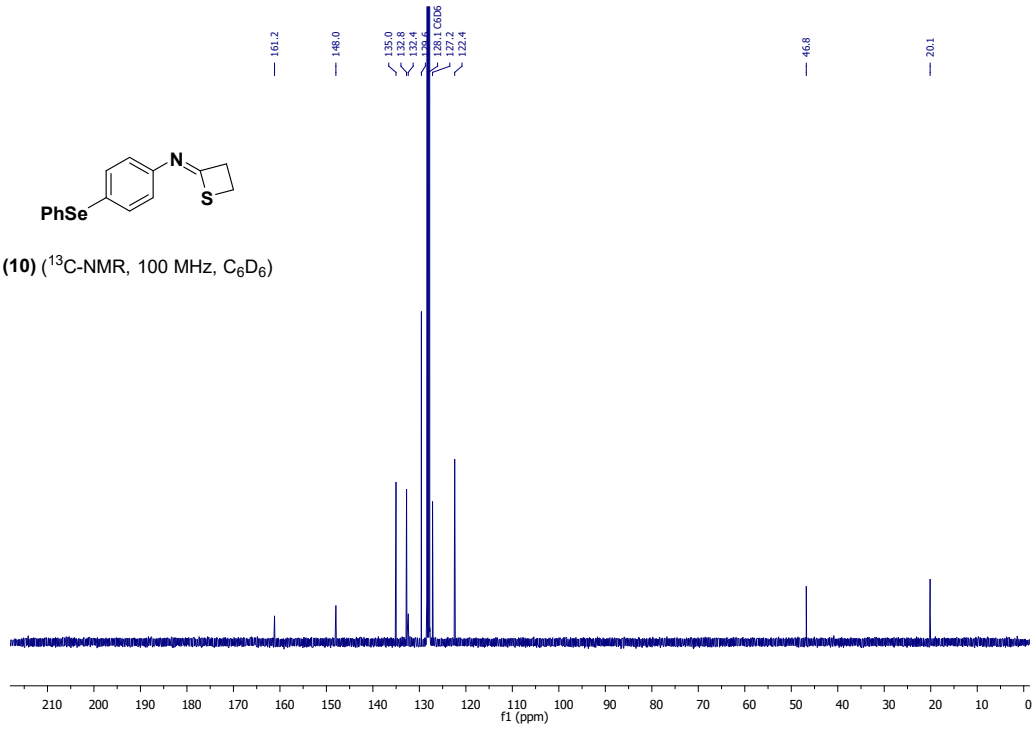
(9) (^{1}H-NMR, 400 MHz, C_6D_6)



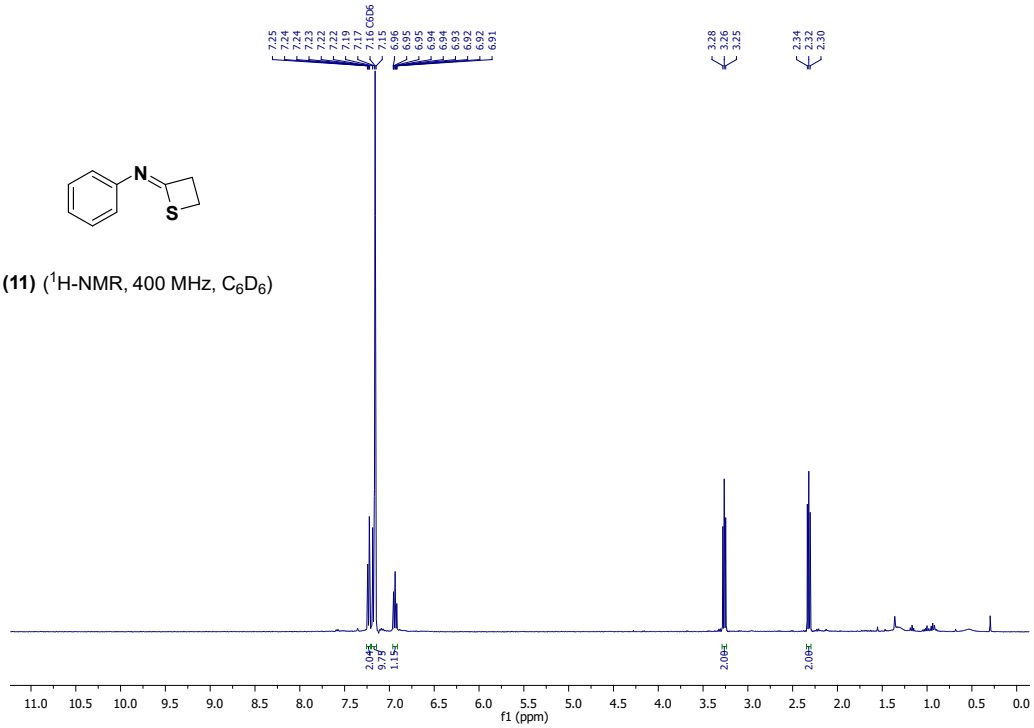
(9) (^{13}C-NMR, 100 MHz, C_6D_6)



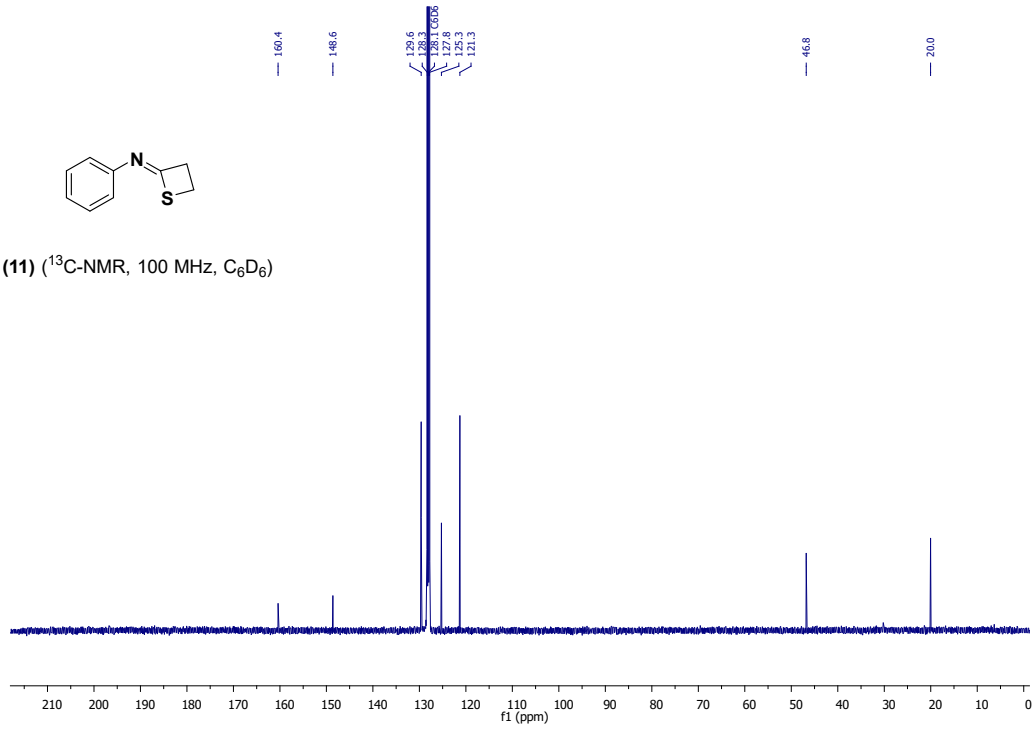
(10) (^{1}H-NMR, 400 MHz, C_6D_6)



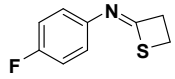
(10) (^{13}C-NMR, 100 MHz, C_6D_6)



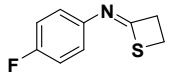
(11) (^{1}H-NMR, 400 MHz, C_6D_6)



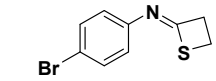
(11) (^{13}C-NMR, 100 MHz, C_6D_6)



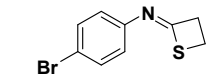
(12) (^{1}H-NMR, 400 MHz, C_6D_6)



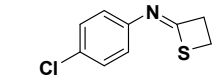
(12) (^{13}C-NMR, 100 MHz, C_6D_6)



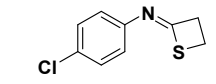
(13) (^{1}H-NMR, 400 MHz, C_6D_6)



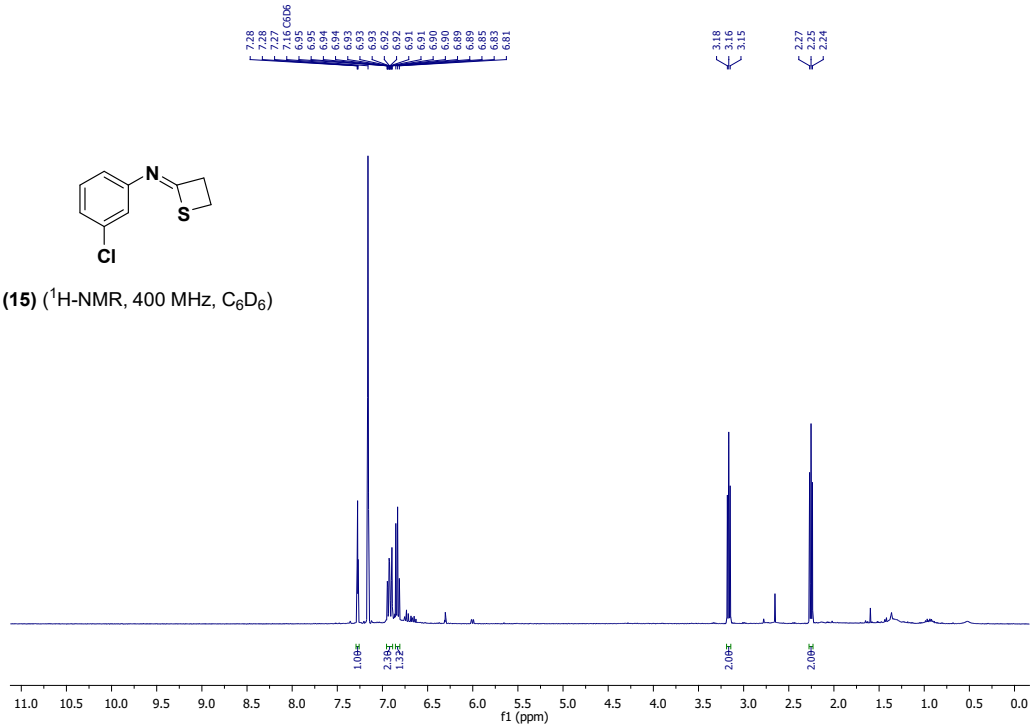
(13) (^{13}C-NMR, 100 MHz, C_6D_6)



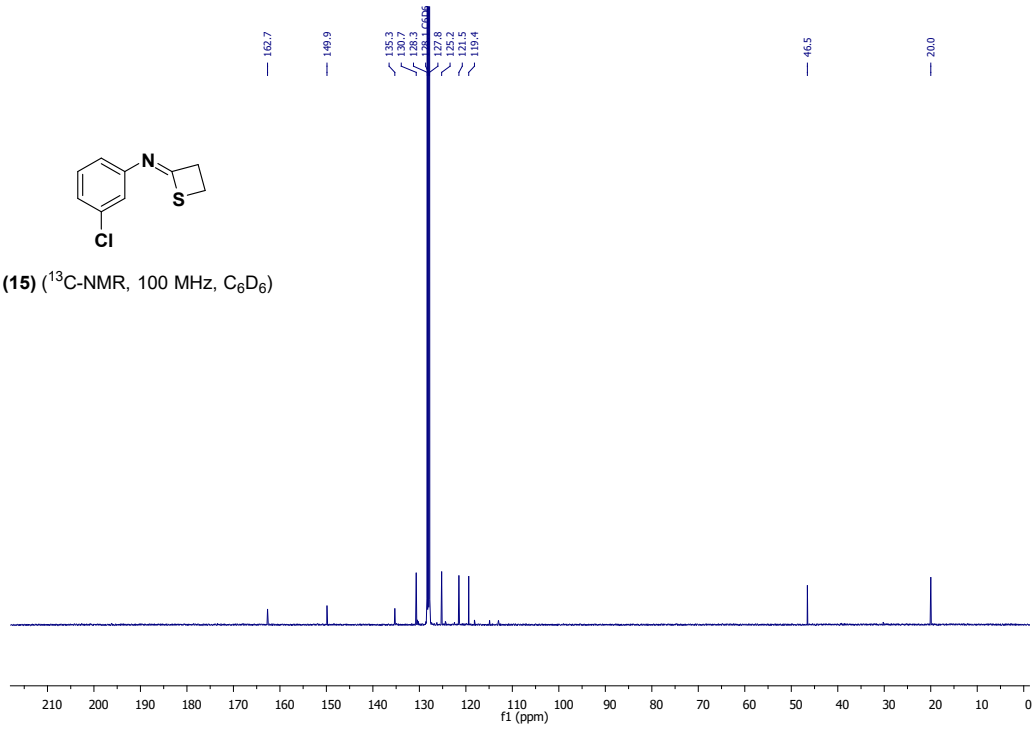
(14) (^{1}H-NMR, 400 MHz, C_6D_6)



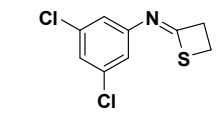
(14) (^{13}C-NMR, 100 MHz, C_6D_6)



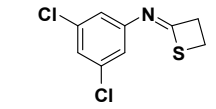
(15) (^{1}H-NMR, 400 MHz, C_6D_6)



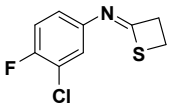
(15) (^{13}C-NMR, 100 MHz, C_6D_6)



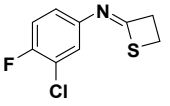
(16) (^{1}H-NMR, 400 MHz, C_6D_6)



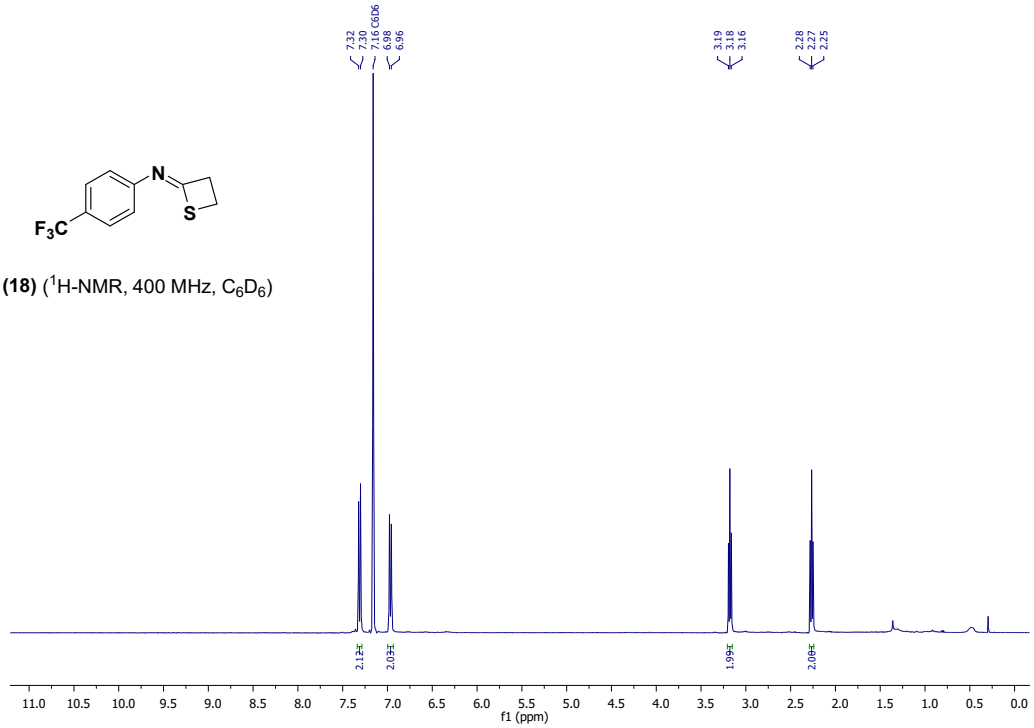
(16) (^{13}C-NMR, 100 MHz, C_6D_6)



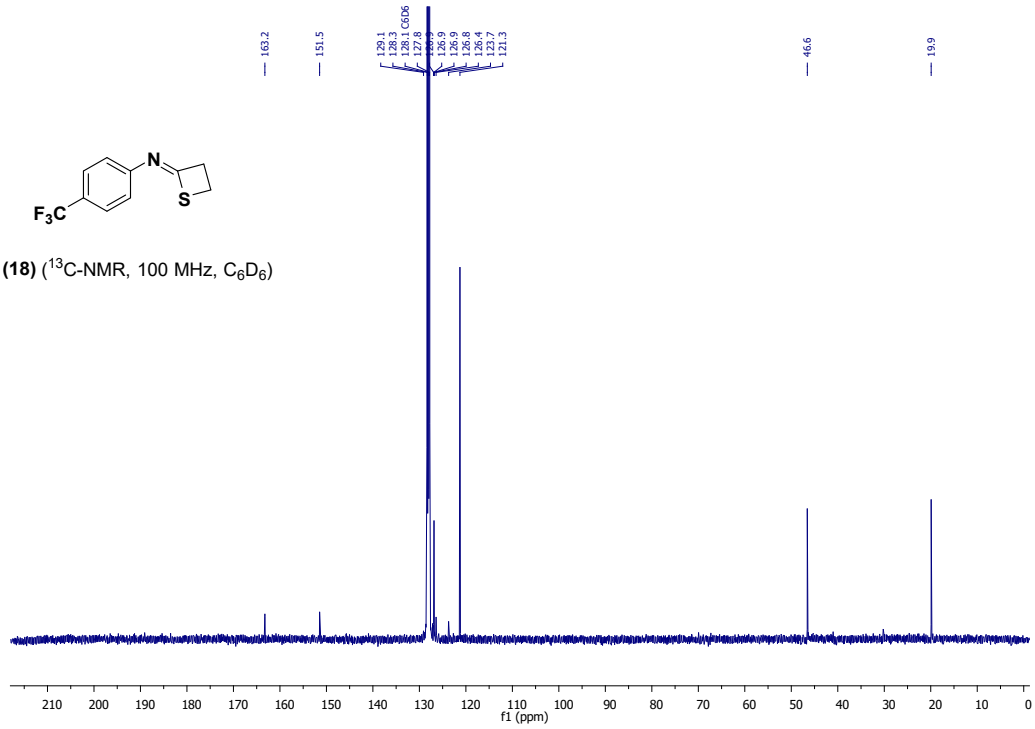
(17) (^{1}H-NMR, 400 MHz, C_6D_6)



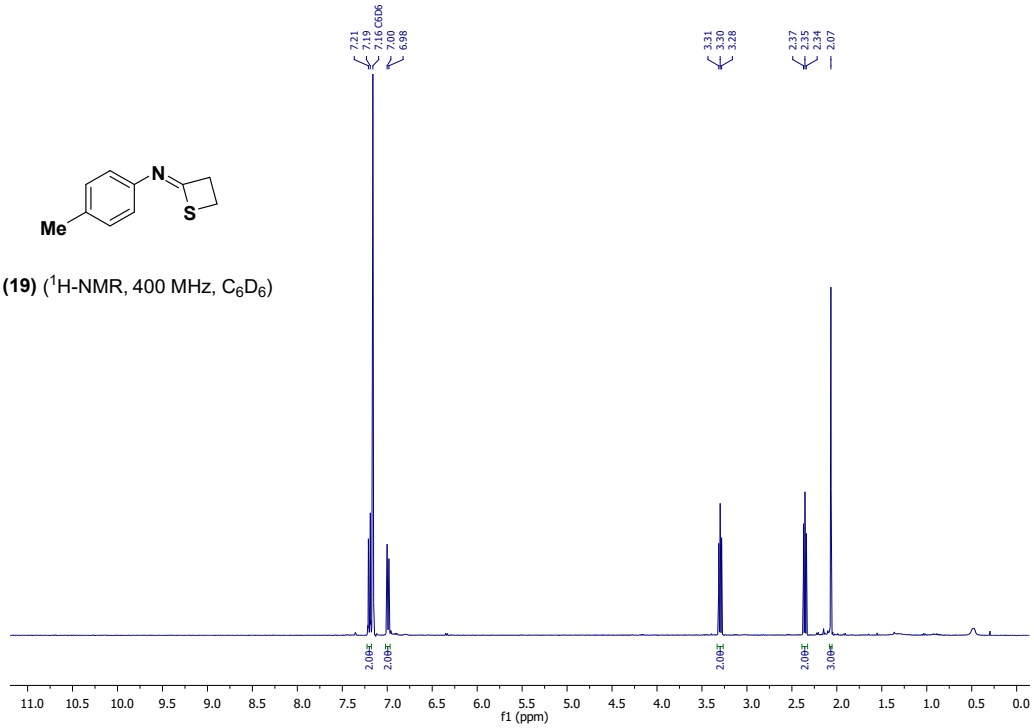
(17) (^{13}C-NMR, 100 MHz, C_6D_6)



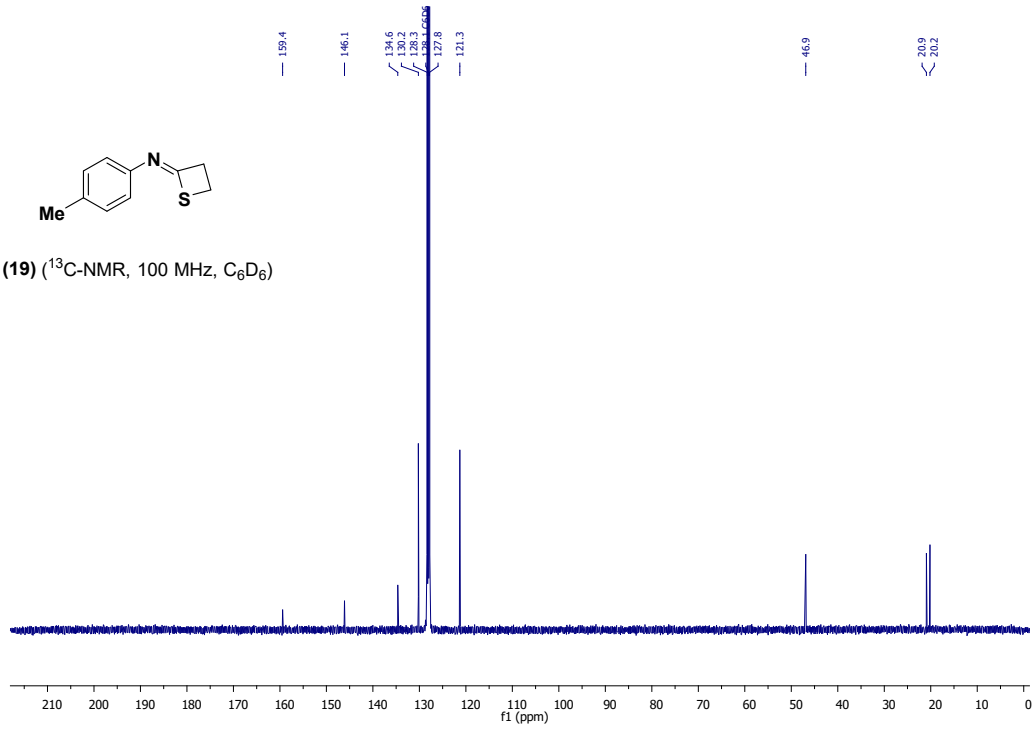
(18) (^{1}H-NMR, 400 MHz, C_6D_6)



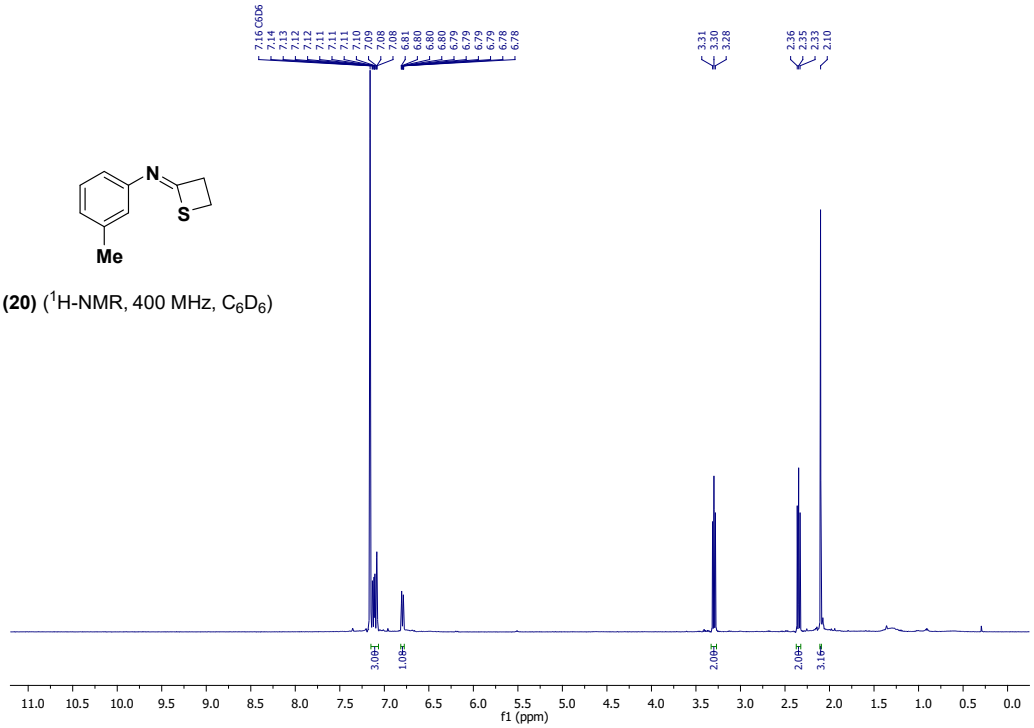
(18) (^{13}C-NMR, 100 MHz, C_6D_6)



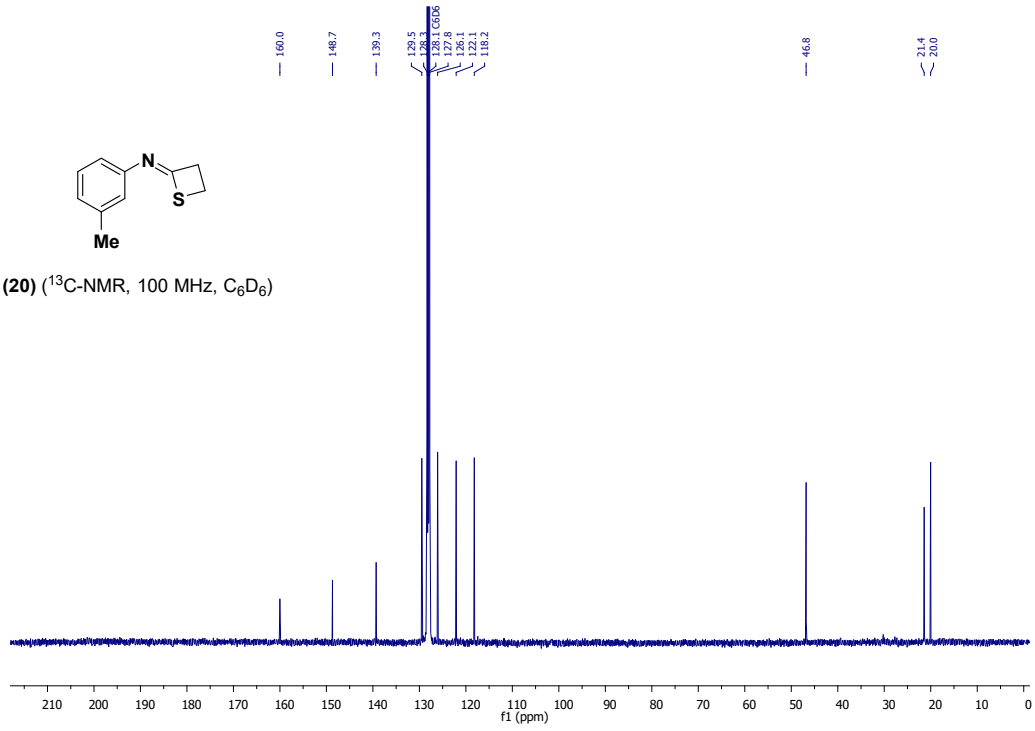
(19) (^{1}H-NMR, 400 MHz, C_6D_6)



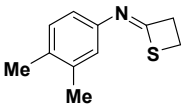
(19) (^{13}C-NMR, 100 MHz, C_6D_6)



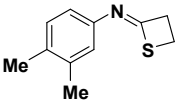
(20) (^{1}H-NMR, 400 MHz, C_6D_6)



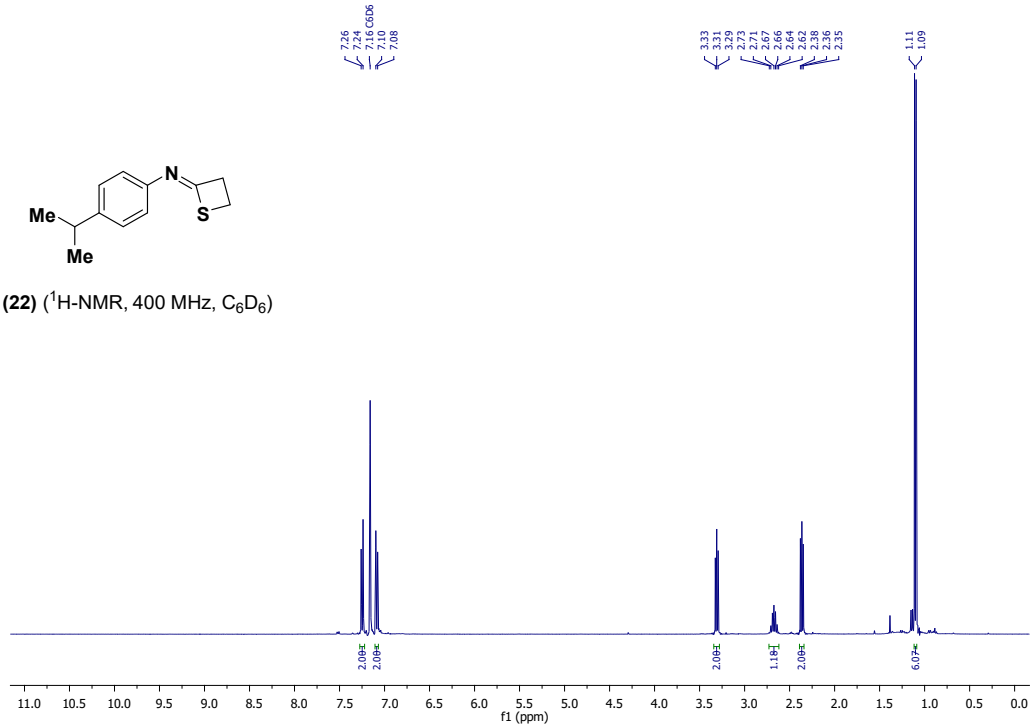
(20) (^{13}C-NMR, 100 MHz, C_6D_6)



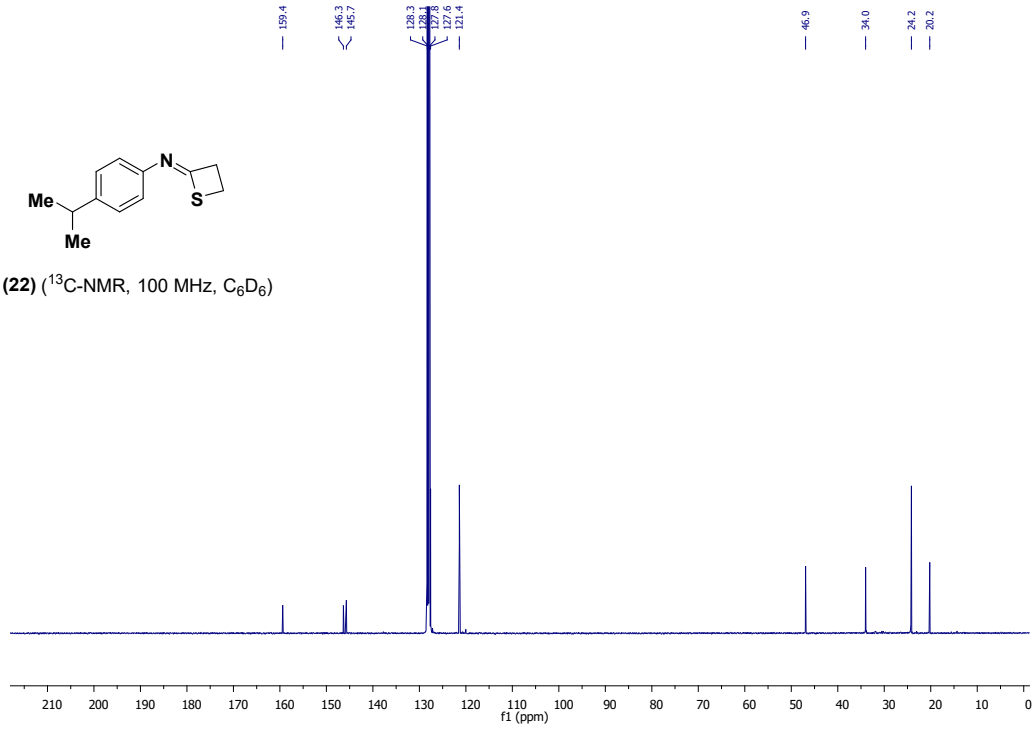
(21) (^{1}H-NMR, 400 MHz, C_6D_6)



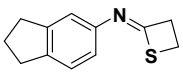
(21) (^{13}C-NMR, 100 MHz, C_6D_6)



(22) (^{1}H-NMR, 400 MHz, C_6D_6)



(22) (^{13}C-NMR, 100 MHz, C_6D_6)



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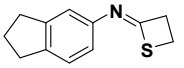
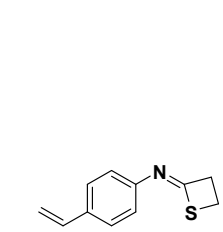


(23) (^{13}C-NMR, 100 MHz, C_6D_6)



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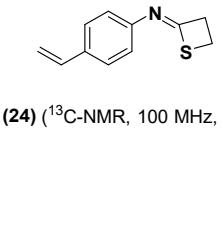
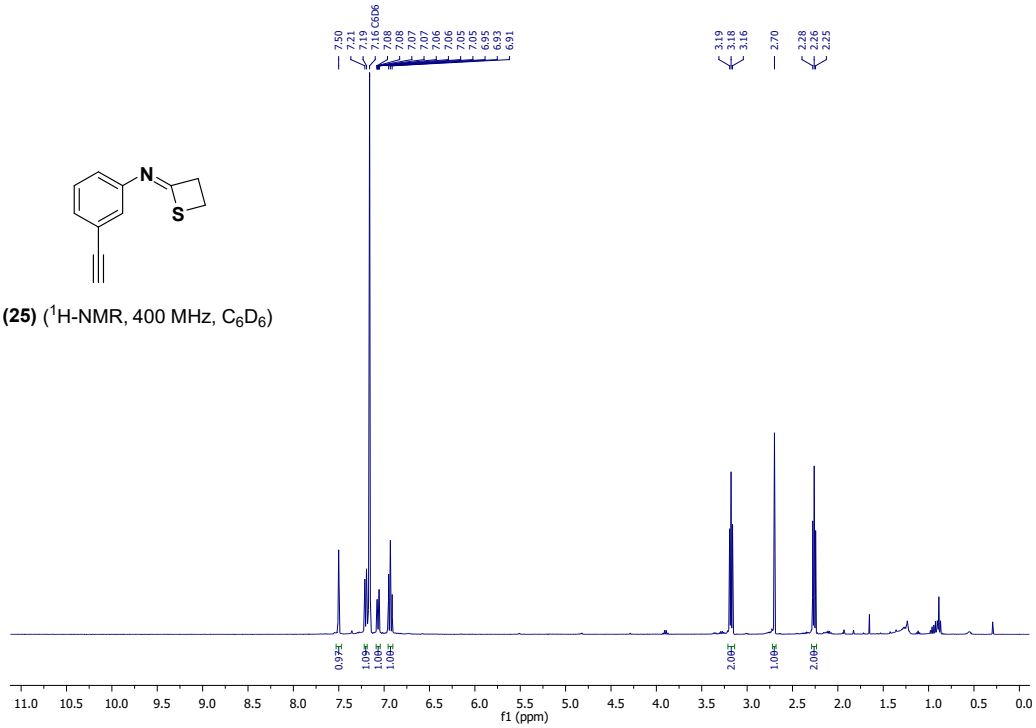


(24) (^{13}C-NMR, 100 MHz, C_6D_6)



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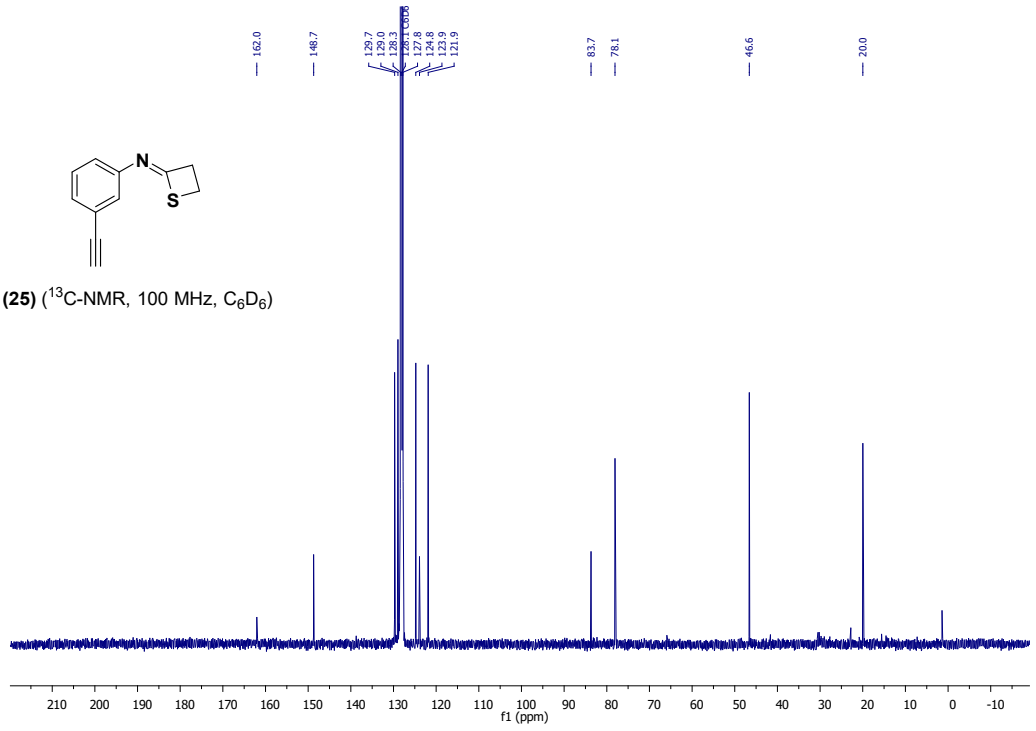

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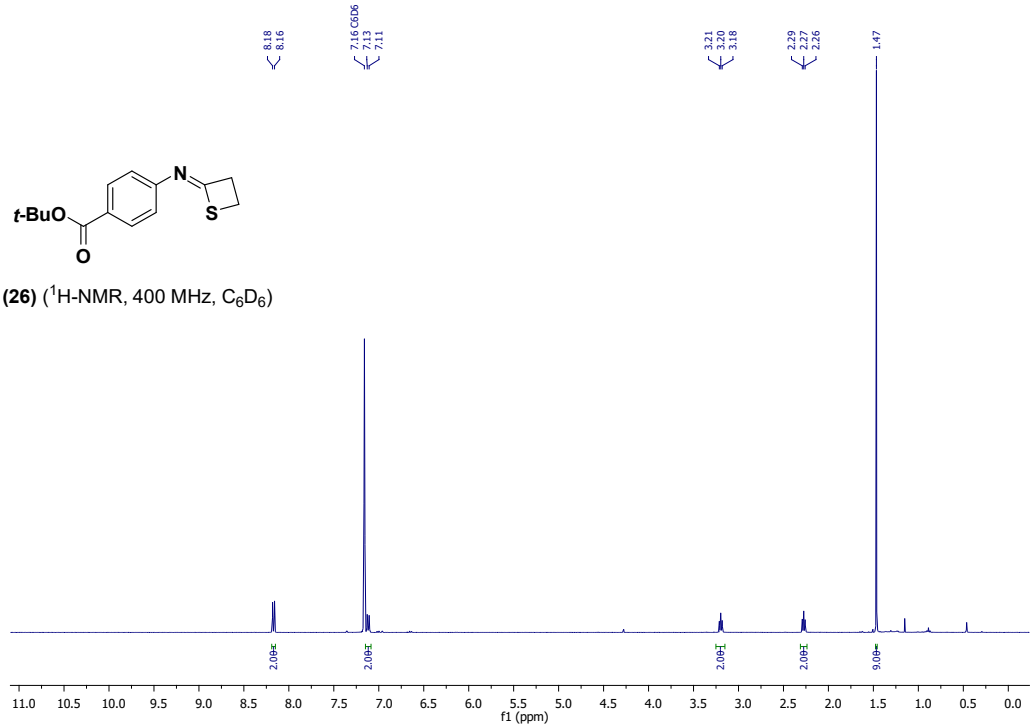

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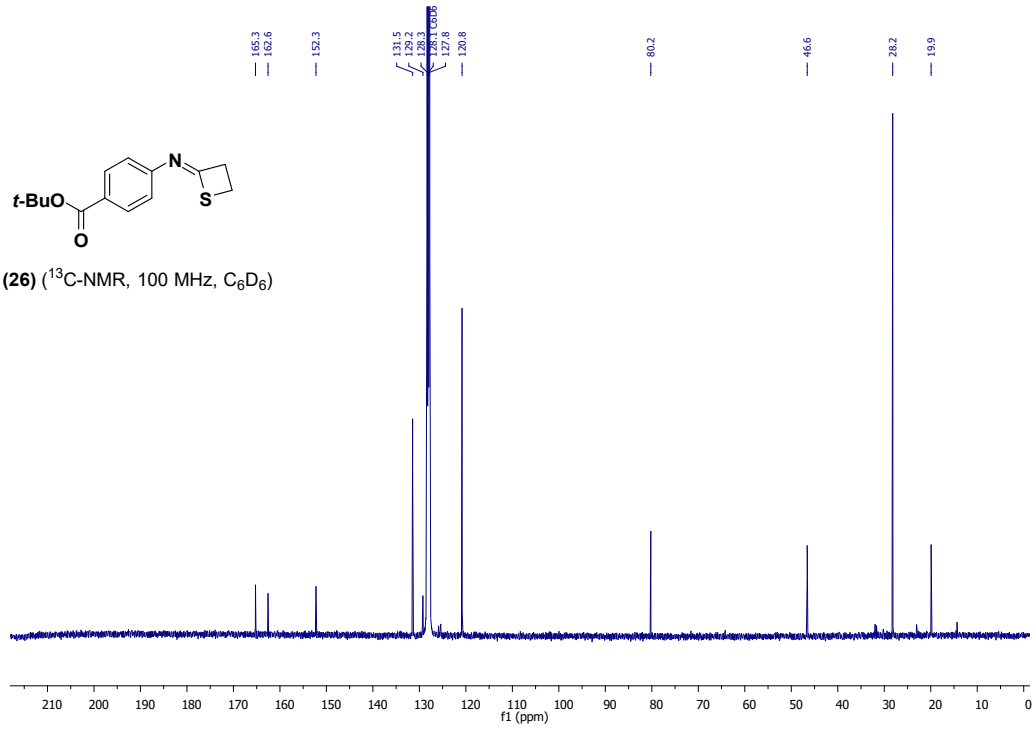

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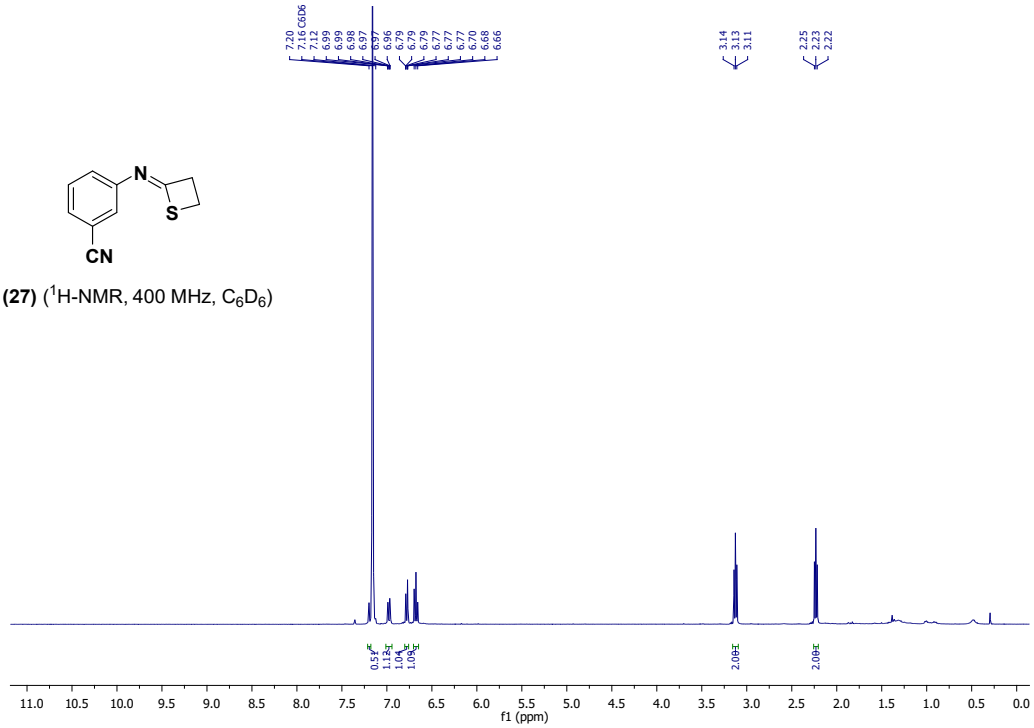
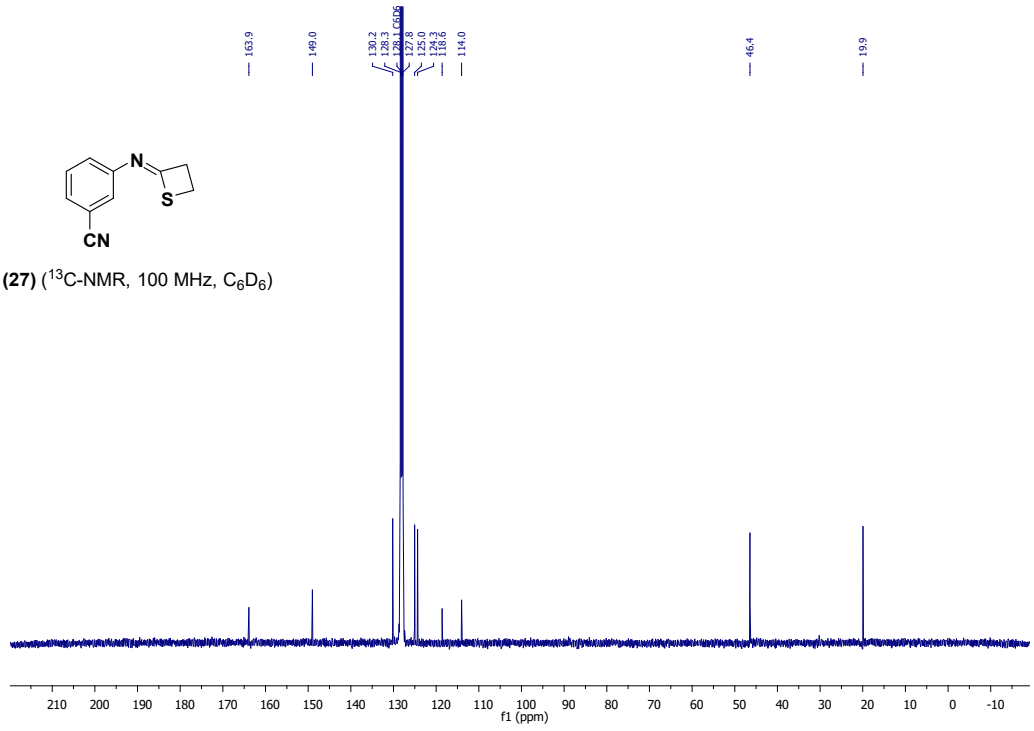
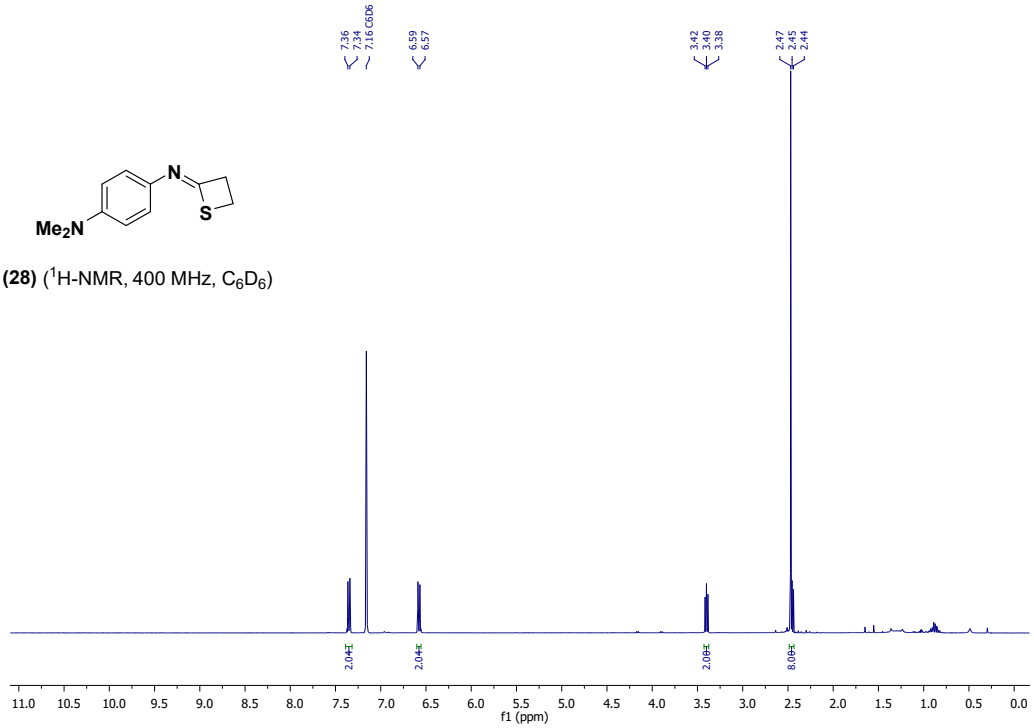


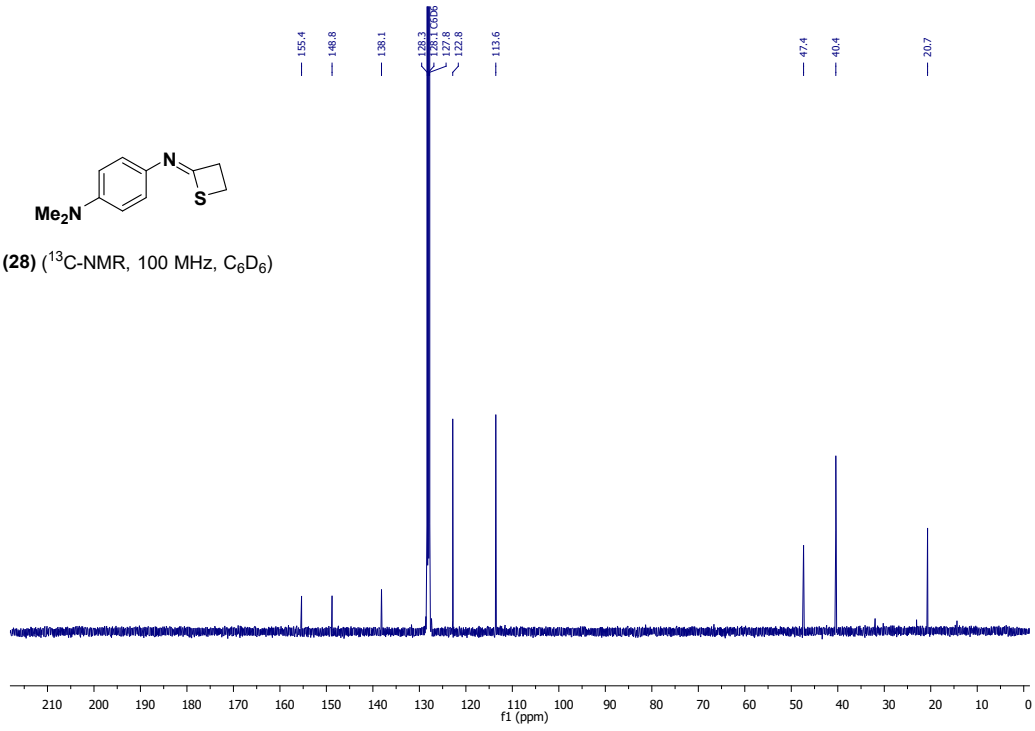
(27) (^{1}H-NMR, 400 MHz, C_6D_6)



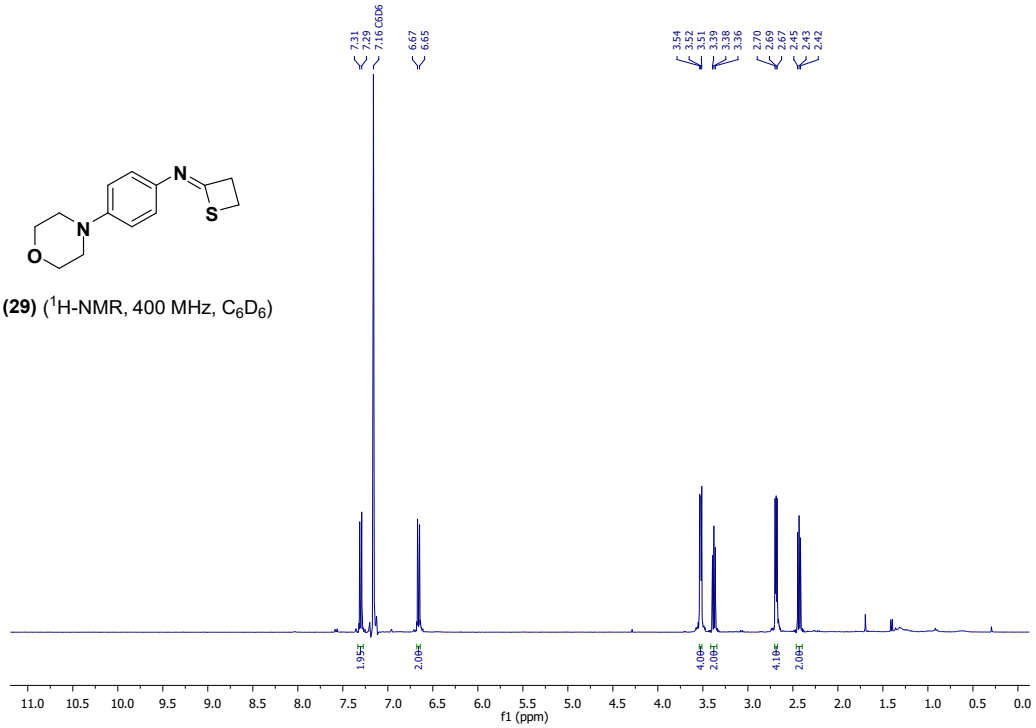
(27) (^{13}C-NMR, 100 MHz, C_6D_6)



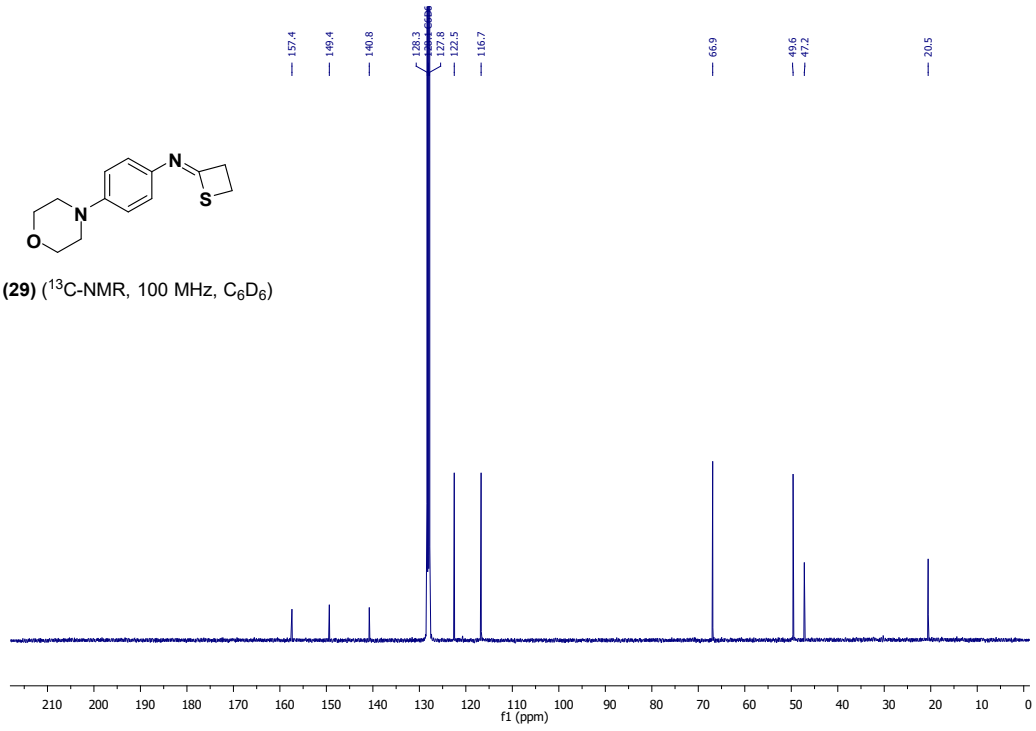
(28) (^{1}H-NMR, 400 MHz, C_6D_6)



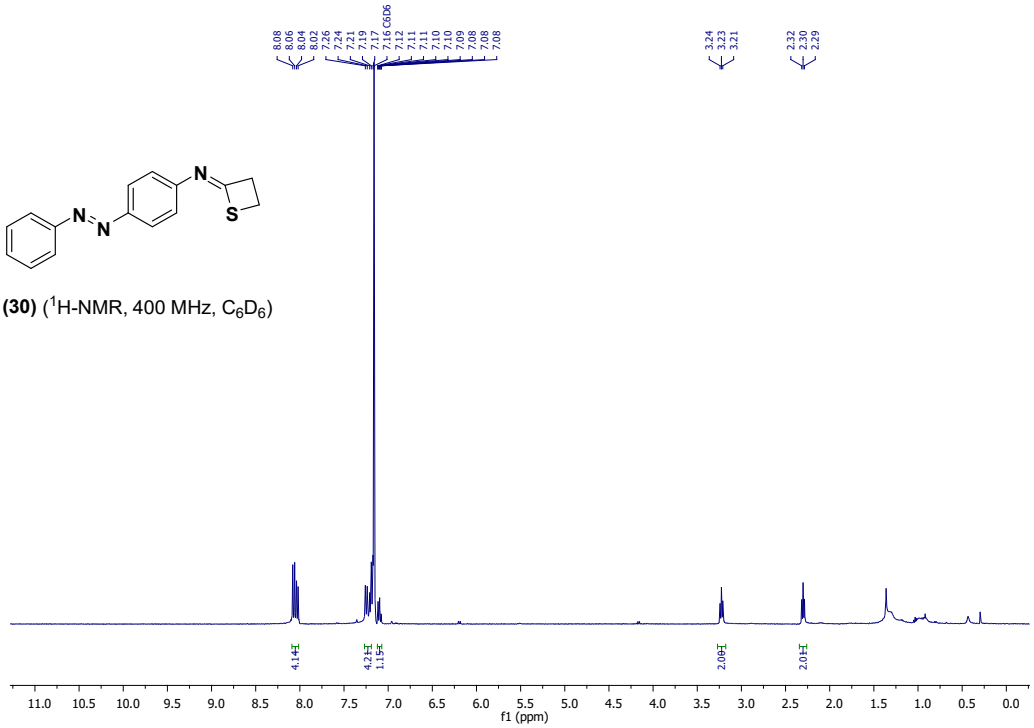
(28) (^{13}C-NMR, 100 MHz, C_6D_6)



(29) (^{1}H-NMR, 400 MHz, C_6D_6)



(29) (^{13}C-NMR, 100 MHz, C_6D_6)



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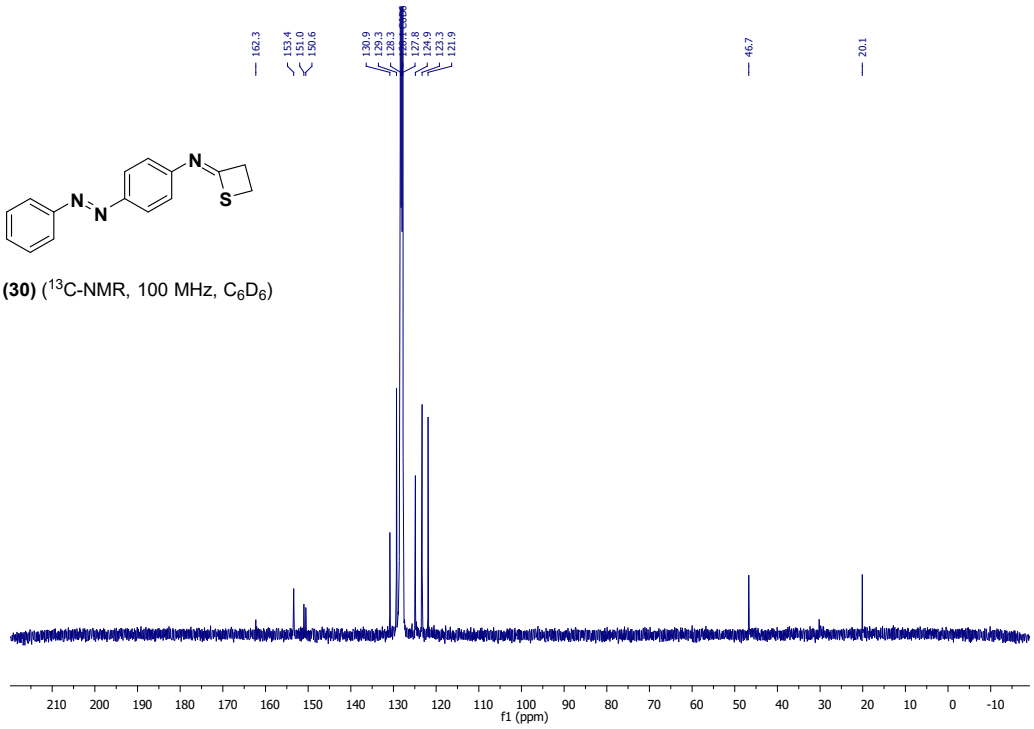

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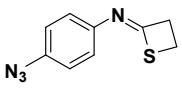

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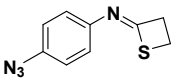
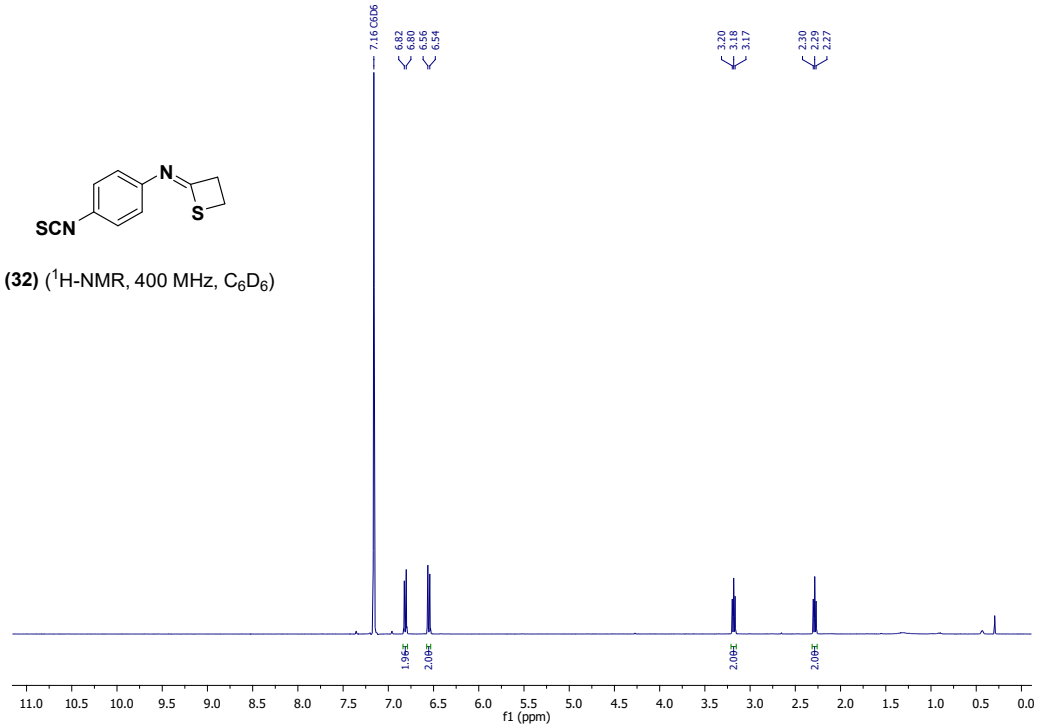
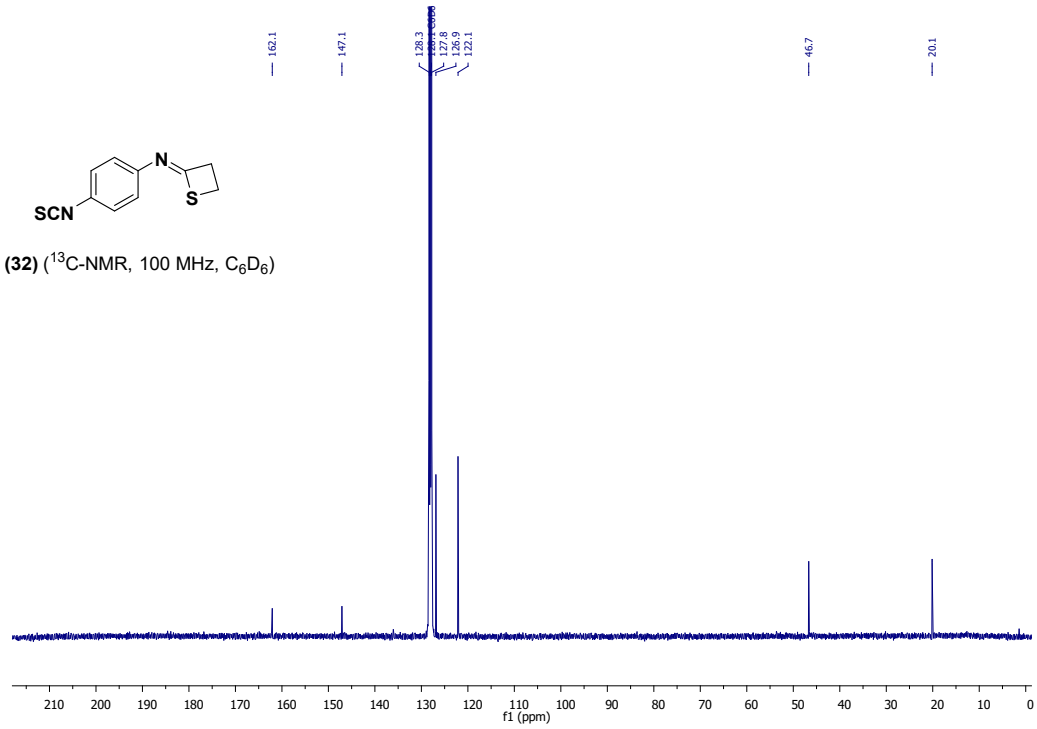


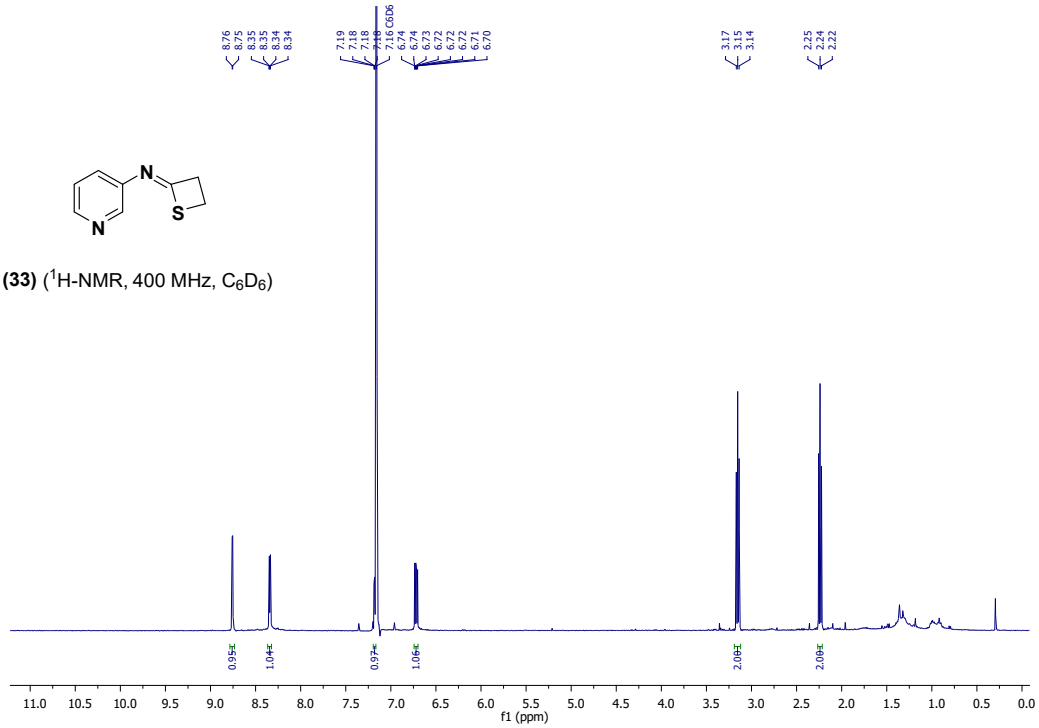
(31) (^{13}C-NMR, 100 MHz, C_6D_6)



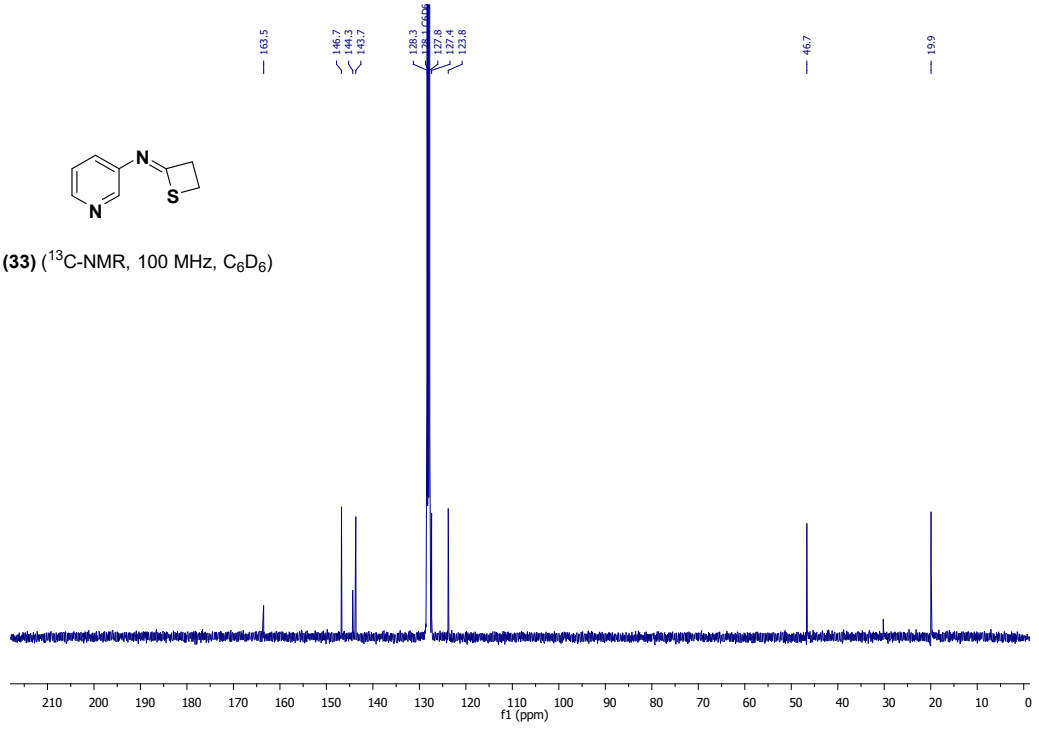
(32) (^{1}H-NMR, 400 MHz, C_6D_6)



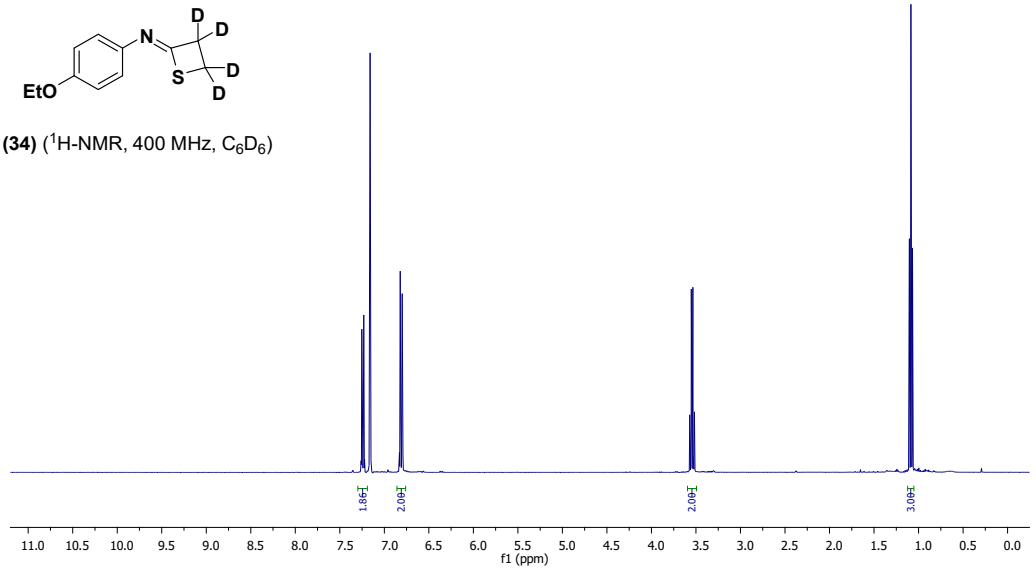
(32) (^{13}C-NMR, 100 MHz, C_6D_6)



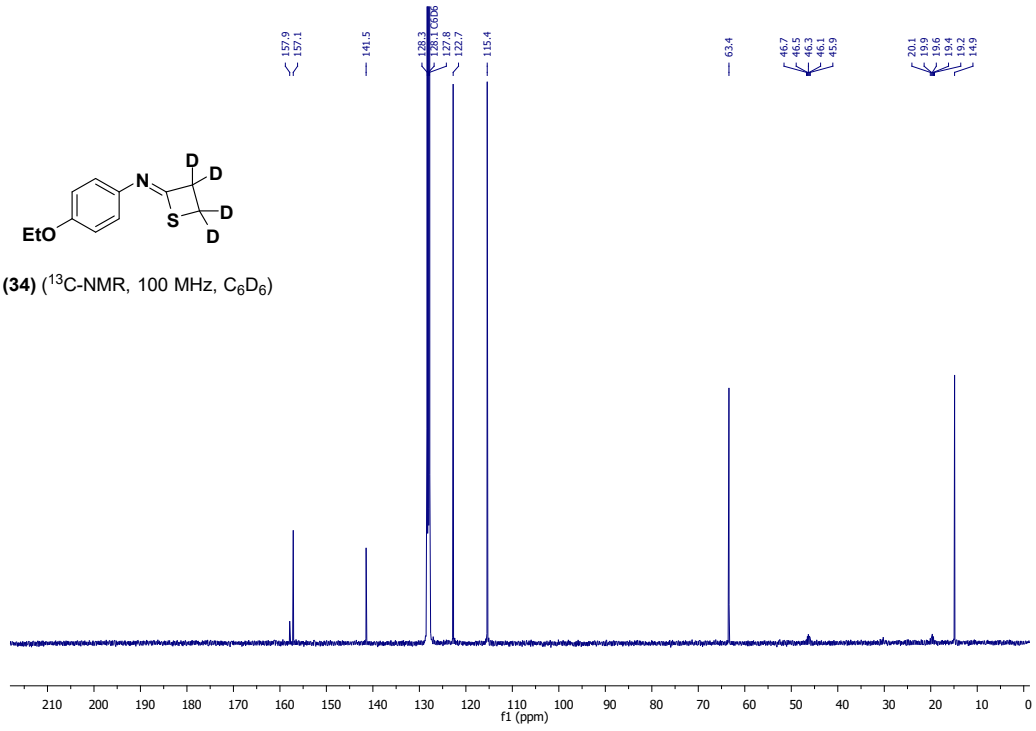
(33) (^{1}H-NMR, 400 MHz, C_6D_6)



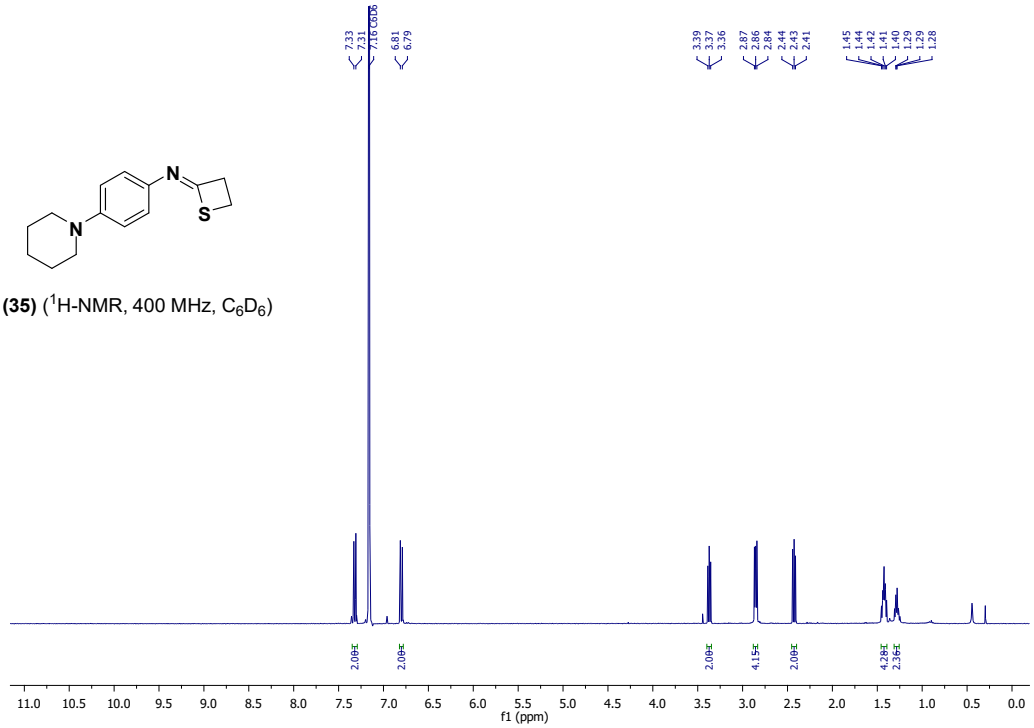
(33) (^{13}C-NMR, 100 MHz, C_6D_6)



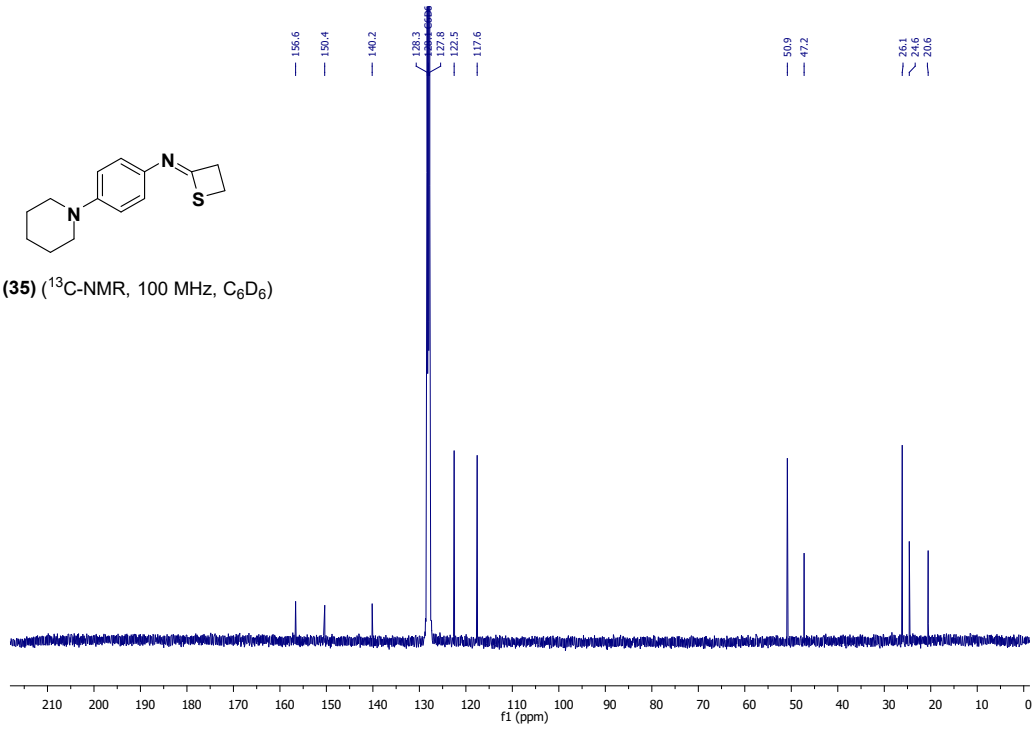
(34) (^{1}H-NMR, 400 MHz, C_6D_6)



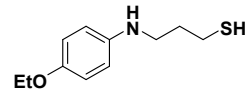
(34) (^{13}C-NMR, 100 MHz, C_6D_6)



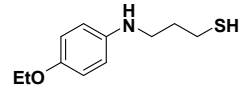
(35) (^{1}H-NMR, 400 MHz, C_6D_6)



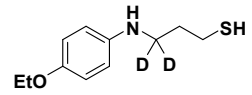
(35) (^{13}C-NMR, 100 MHz, C_6D_6)



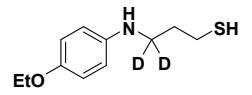
(36) (^{1}H-NMR, 400 MHz, $CDCl_3$)



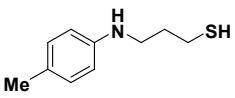
(36) (^{13}C-NMR, 100 MHz, $CDCl_3$)



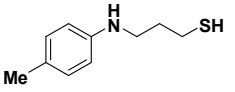
(37) (^{1}H-NMR, 400 MHz, $CDCl_3$)



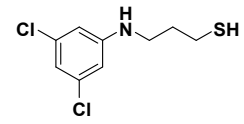
(37) (^{13}C-NMR, 100 MHz, $CDCl_3$)



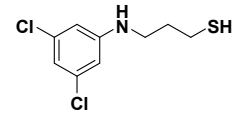
(38) (^{1}H-NMR, 400 MHz, $CDCl_3$)



(38) (^{13}C-NMR, 100 MHz, $CDCl_3$)

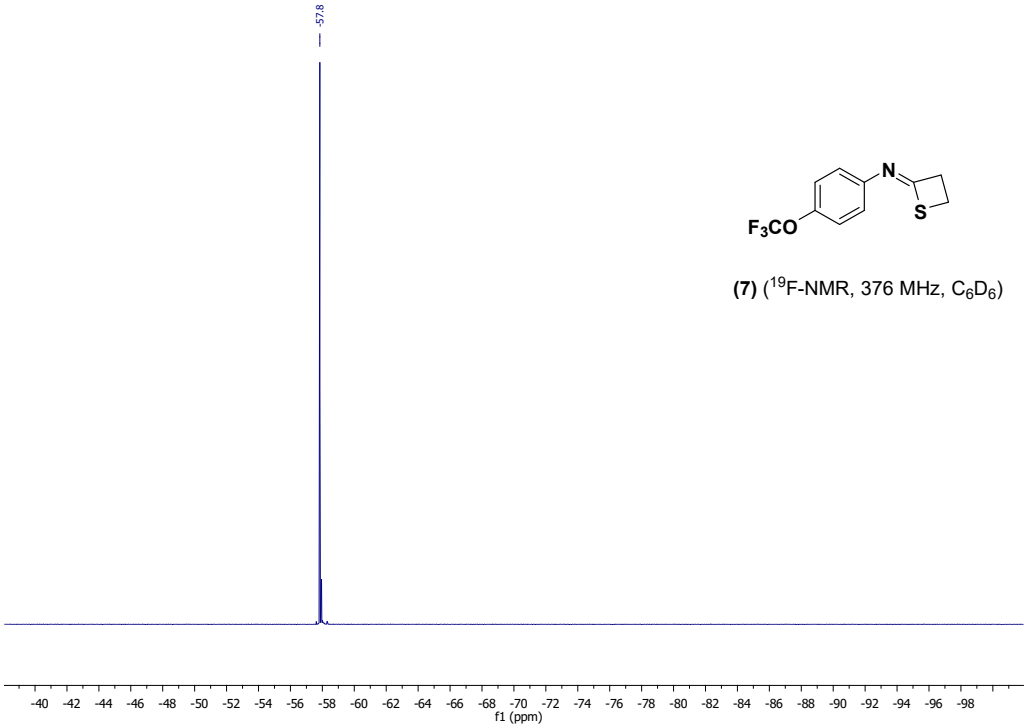


(39) (^{1}H-NMR, 400 MHz, $CDCl_3$)

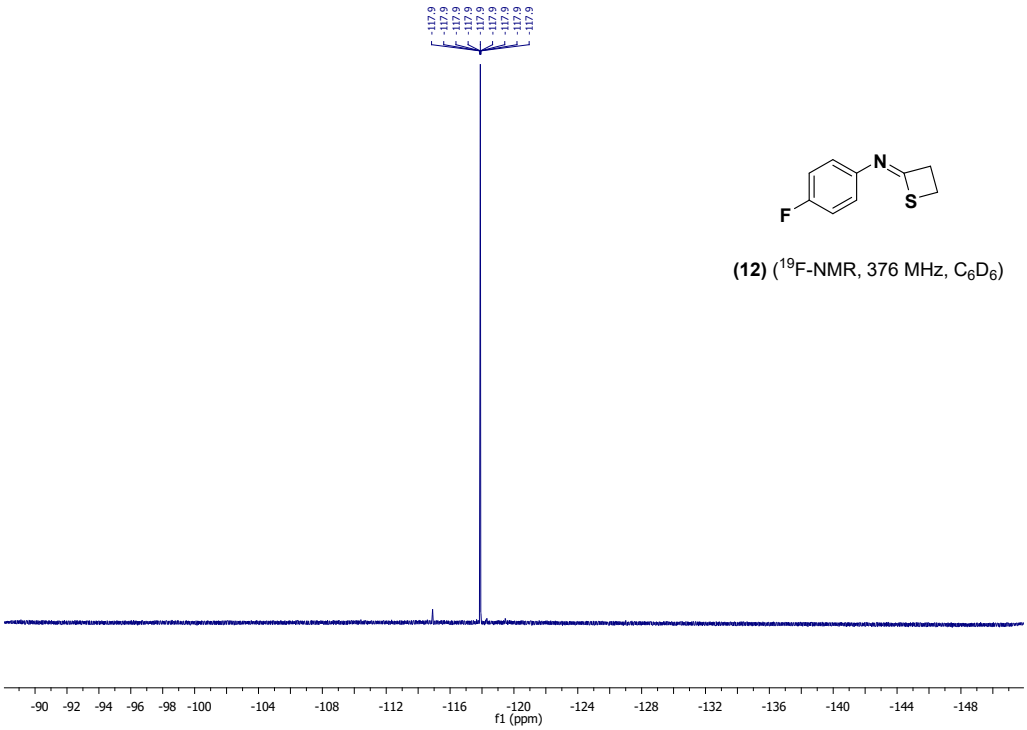


(39) (^{13}C-NMR, 100 MHz, $CDCl_3$)

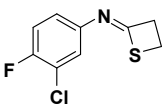
5.3.3 Copies of ^{19}F- and ^{77}Se-NMR Spectra



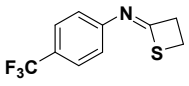
(7) (^{19}F-NMR, 376 MHz, C_6D_6)



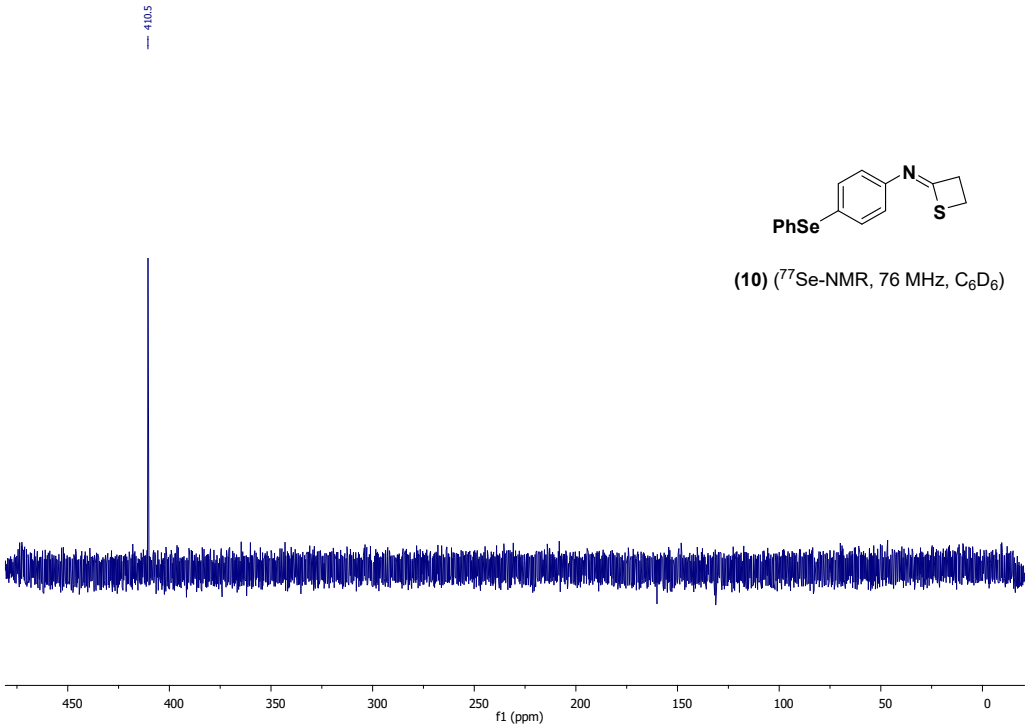
(12) (^{19}F-NMR, 376 MHz, C_6D_6)



(17) (^{19}F-NMR, 376 MHz, C_6D_6)



(18) (^{19}F-NMR, 376 MHz, C_6D_6)



(10) (^{77}Se-NMR, 76 MHz, C_6D_6)

5.3.4 X-ray Analysis for Compound 2

Sample	Machine	Source	Temp.	Detector Distance	Time/Frame	#Frames	Frame width	CCDC
	Bruker		[K]	[mm]	[s]		[°]	
Compound **2**	D8	Mo	150	40	60	1511	0.500	**2081745**

Table 2: Experimental parameter and CCDC-Code.

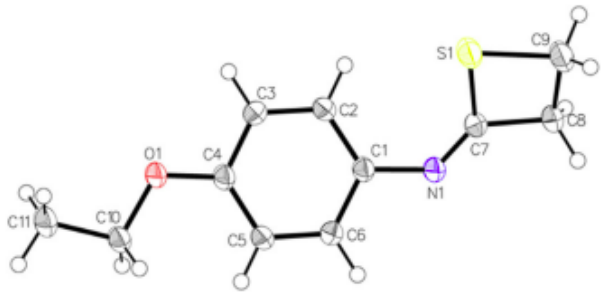


Figure 37: X-ray structure.

Radiation [Å]	MoKα (λ = 0.71073)	Z	2	Measurement method	\f and \w scans
Crystal habit	clear colourless block	a [Å]	6.7458(9)		
Crystal size [mm^3]	0.6 × 0.04 × 0.03	b [Å]	7.2758(10)	Abs. correction type	multiscan
Empirical formula	C11H13NOS	b [Å]	82.878(6)	Abs. correction Tmin	0.5985
Formula weight [g/mol]	207.28	α [°]	82.878(6)	Abs. correction Tmax	0.7460
Temperature [K]	150.0	β [°]	80.158(5)	Density (calculated) [g/cm^3]	1.344
Crystal system	Triclinic	γ [°]	78.337(6)	Absorption coefficient [mm^{-1}]	0.281
Space group	P-1	Volume [Å^3]	512.30(12)	F (000) [e$^-$]	220.0

Table 3: Sample and crystal data.

2θ range for data collection [°]	5.742 to 60.16		Index ranges	Goodness-of-fit on F^2	1.035
Reflections collected	12143	h	$-9 \leq h \leq 9$	Diff. peak and hole [e^{-}Å^{-3}]	0.29/-0.26
Data / restraints / parameters	2868/0/128	k	$-10 \leq k \leq 9$		
Refinement method	Direct Methods	l	$-15 \leq l \leq 15$	Function minimized	Σ w (F_o^2 - F_c^2)^2
		all data	R1 = 0.0680, wR2 = 0.1038	Weighting scheme	where
		I>2σ(I)	R1 = 0.0437, wR2 = 0.0929	w=1/[$\sigma^2(F_o^2)$ + (0.0364P)^2 + 0.2642P]	P=(F_o^2+2F_c^2)/3

Table 4: Data collection and structure refinement.

The X-ray intensity data were measured on Bruker D8 Venture diffractometer equipped with multilayer monochromator, Mo K/α INCOATEC micro focus sealed tube and Oxford cooling system. The structure was solved by *Direct Methods*. Non-hydrogen atoms were refined with *anisotropic displacement parameters*. Hydrogen atoms were inserted at calculated positions and refined with riding model. The following software was used: *Bruker SAINT software package*[3] using a narrow-frame algorithm for frame integration, *SADABS*[4] for absorption correction, *OLEX*[5] for structure solution, refinement, molecular diagrams and graphical user-interface, *Shelxle*[6] for refinement and graphical user-interface *SHELXS-2015*[7] for structure solution and refinement, *Platon*[8] for symmetry check. Experimental data and CCDC-Codes (Available online: `http://www.ccdc.cam.ac.uk/conts/retrieving.html`) can be found in Table 2. Crystal data, data collection parameters, and structure refinement details are given in Tables 3 and 4. Asymmetric Unit visualized in Figure 37.

[3] **Bruker SAINT V8.38B Copyright © 2005-2019 Bruker AXS.**
[4] **G. M. Sheldrick, 1996, SHELXS. University of Göttingen, Germany.**
[5] **O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard, H. Puschmann, J. Appl. Crystallogr. 2009, 42, 339-341.**
[6] **C. B. Hübschle, G. M. Sheldricka, B. Dittricha, J. Appl. Cryst. 2011, 44, 1281-1284.**
[7] **G. M. Sheldrick, Acta Cryst. 2015, C71, 3-8.**
[8] **A. Spek, Acta Cryst. D 2009, 65, 148-155.**

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