Thesis for the Master's Degree in Chemistry

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C-C Bond formation in the purine 8-position by addition of allylmetals

60 study points

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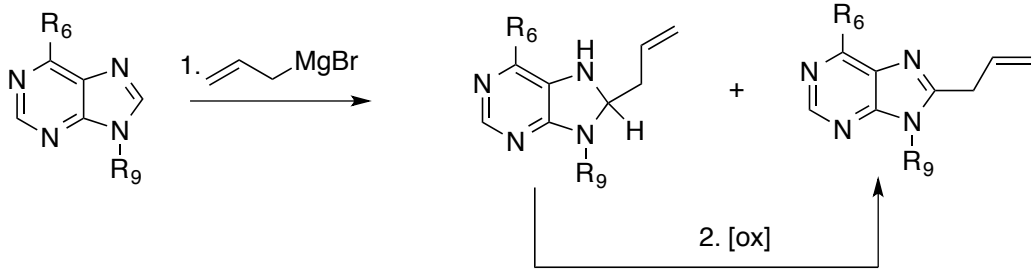
Abstract

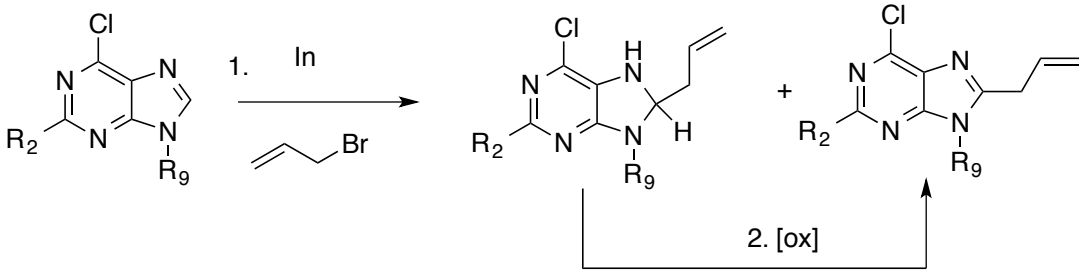
8-Substituted purines have been extensively studied as for example anticancer or antiviral drugs. C-C Bond formation at the purine 8-position has been most commonly done via 8-halopurines, *e.g.* Pd-catalyzed coupling reactions. Meanwhile, direct conversion of purines not substituted at C-8 to 8-alkylpurines seems to be promising but there are few reports in the literature. In this thesis, addition of an allylmetallic reagent to 8-unsustituted purines followed by oxidation of the adduct to form 8-allylated purines will be discussed.

A Grignard reagent, *i.e.* allylmagnesium bromide, and the allylindium reagent were employed in this study. The general reactions with respect to each reagent are sketched in **Scheme A** and **Scheme B**.



R_6 = Cl, OMe, or piperidinyl, R_9 = allyl or benzyl

Scheme A



R_2 = H, R_9 = allyl or Boc
R_2 = Cl, R_9 = allyl

Scheme B

Abbreviations

Ac	Acetyl
Bn	Benzyl
Bu	Butyl
BuLi	Butyllithium
Boc	*tert*-butyloxycarbonyl
COSY	Correlation Spectroscopy (NMR)
DCM	Dichloromethane
DDQ	Dichloro dicyano quinone
DEAD	Diethyl azodicarboxylate
DMF	N,N-dimethylformamide
DNA	Deoxyribonucleic acid
EI	Electron impact (MS)
ESI	Electronsprayionisation (MS)
EtOAc	Ethyl acetate
EtOH	Ethanol
equivs.	equivalent
HMBC	Heteronuclear Multiple Bond Coherence
HMQC	Heteronuclear Multiple Quantum Coherence
HRMS	High Resolution Mass Spectra
HSQC	Heteronuclear Single Quantum Correlation (NMR)
J	Coupling constant (NMR)
LDA	Lithium diisopropylaminde
Me	Methyl

MeOH	Methanol
MS	Mass Spectrometry
NMR	Nuclear Magnetic Resonance Spectroscopy
Ph	Phenyl
ppm	Parts per million
RNA	Ribonucleic acid
r.t.	Room temperature
S_NAr	Aromatic Nucleophilic Substitution
***t*-BuOK**	Potassium-tert-butoxide
***n*-BuOH**	1-Butanol
THF	Tetrahydronfuran

Table of contents

1 Introduction

Purines are common in nature and many of them have been extensively studied as potential drugs in treating viral diseases and cancers. These researches foster the development of an efficient methodology for functionalization in all purine positions. This thesis focused on the C-C bond formation at the C-8 position. In this chapter, purines will first be discussed in terms of their chemical structures, biological importance, and pharmaceutical applications as antivirus and anticancer drugs. The subsequent sections will attempt to picture the whole view of the project and define the scope of this work. Finally, the organization of the thesis is summarized according to topics that have done within the scope.

1.1 Purines

The German chemist Emil Fischer named a compound that he first synthesized from uric acid purine,[1] which practically means pure urine, in 1899. Purine **3** is a heterocyclic compound whose structure consists of two different heteroaromatic rings, pyrimidine **1** and imidazole **2**, fused into one another.[2] **Figure 1.1** presents the structures of pyrimidine **1**, imidazole **2**, and purine itself **3** with its numbering convention.[2]

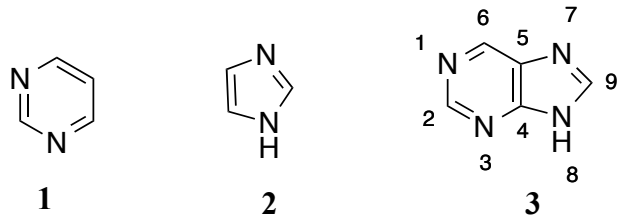


Figure 1.1

Purine can only be synthesized in the laboratory because it can hardly be found in nature. Instead, purine-based derivatives are abundantly present in living things with various biologically crucial functions.[3-5] Adenine **4** and guanine **8** shown in **Figure 1.2** are two most important purines because they are DNA and RNA bases. Aside from those, adenine is a building block for adenosine diphosphate (ADP) and adenosine 5'-triphosphate **5** (ATP), energy storage units in living cells, and for 3'-5'-cyclic adenosine monophosphate **6** (cAMP),

a second messenger in many biological processes, and for nicotinamide adenine dinucleotide **7** (NAD^+/NADH), a metabolic coenzyme, while guanine is the substrate for the synthesis of both DNA during its replication process and RNA in its transcription procedure.

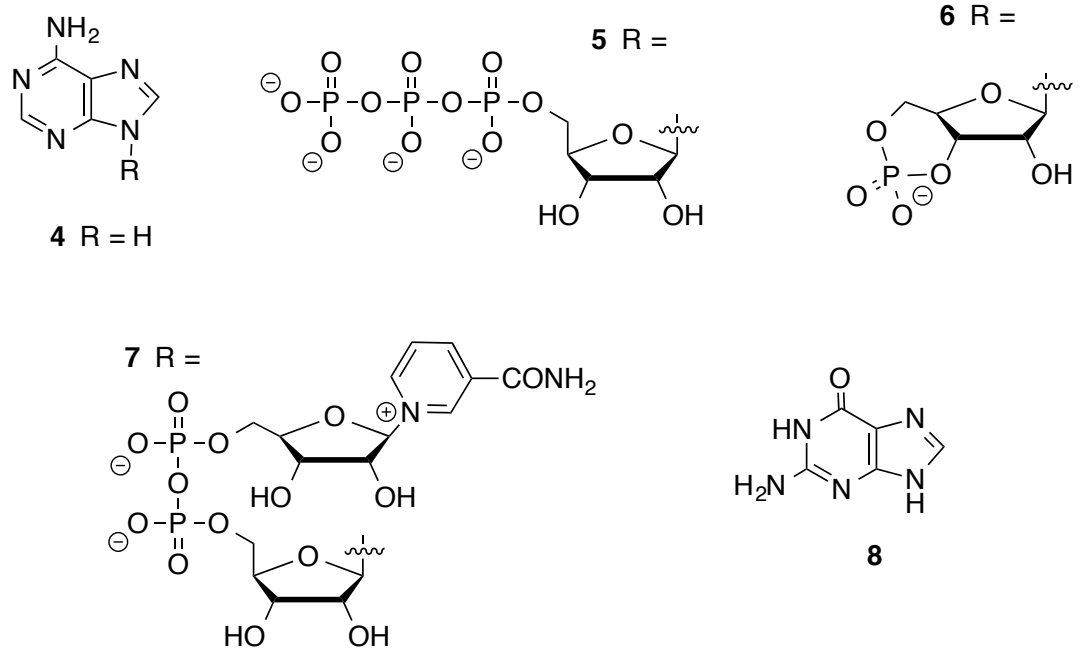


Figure 1.2

Since many purine-containing compounds have essential biological roles, analogs have been pharmaceutically studied as potential drugs for the treatment of viral diseases and cancers. Acyclovir **9** and didanosine (ddI) **10** are two well-known examples of antiviral drugs (**Figure 1.3**).[6-8] Acyclovir, which is used for the treatment of herpes virus infections, is a guanosine analog while didanosine, which is used to treat HIV, is an adenosine analog after being metabolized. Both play false substrates for the viral DNA replication process that subsequently stop the proliferation of the virus. In the cancer therapy, purine-based antimetabolites have been also employed as false substrates in order to restrain the development of cancer tissues, which unfortunately grow much faster than their surrounding healthy tissues.[9] 6-Mercaptopurine[10-11] **11** and fludarabine phosphate[12-13] **12** are two exemplary anticancer drugs in this category (**Figure 1.3**). Both are prodrugs that necessarily undergo appropriate metabolic activation to exert their cytotoxic capability. Apart from the aforementioned metabolites, several pyrido[1,2-*e*]purines **13** have been studied as potential anticancer drugs due to their cytotoxic activities towards breast cancer cells.[14-18] These

compounds can suppress the fast growth of cancer tissues by intercalating themselves into DNA of malignant cells, further causing damage and finally killing them.

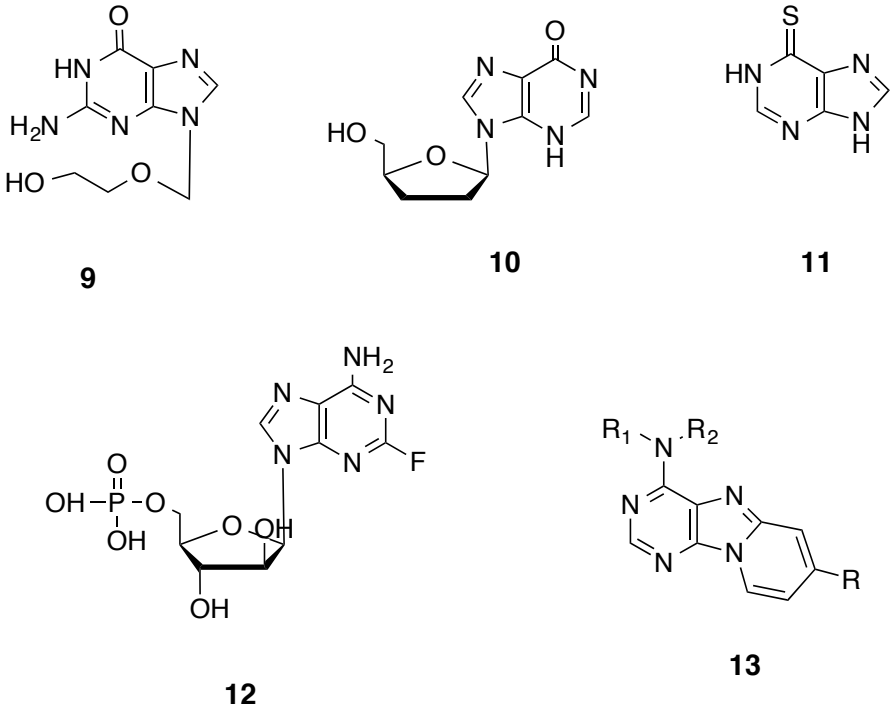


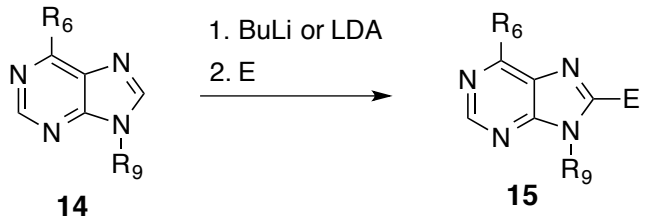
Figure 1.3

The significance of purine derivatives as bioactive compounds in general and as potential drugs in particular has attracted much attention of researchers in organic chemistry. The need of synthesizing novel purines with various biological activities requires efficient methodologies of making C-C bonds and C-N bonds in purine chemistry. This work discuses the C-C bond formation at the C-8 position of 8-unsubstituted purines.

1.2 Aim of the project

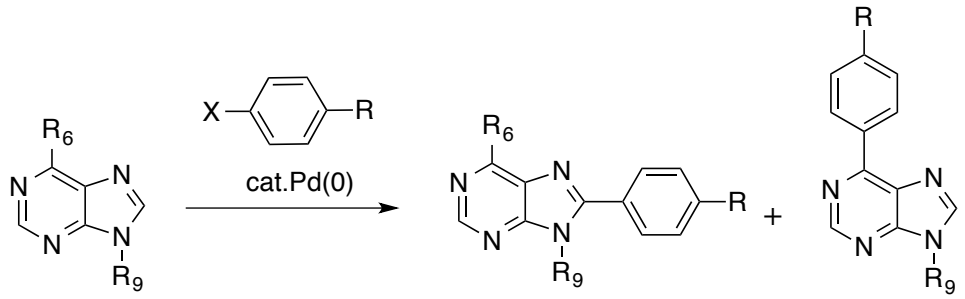
Functionalization at the C-8 position of purines can be done *via* metal-mediated reactions.[4] Pd-catalyzed coupling reactions, *e.g.* Suzuki coupling[19-21] and Stille coupling,[22-23] between 8-halopurines and an organometal are the most common method to form the C-C bond at the purine 8-position. These methods, however, require the halogenation of purines at the C-8 position before the couplings can take place. Direct transformation of purines not substituted at C-8 to 8-alkyl and 8-arylpurines were reported with limitations. 8-Unsubstituted purines **14**

can be lithiated by butyllithium (BuLi)[24-25] or lithium diisopropylamide (LDA)[26-27] and then trapped with desired organic electrophiles (**Scheme 1.1**) to give 8-substituted purines **15** but these organolithium reagents are strong bases and can not be compatible with diverse functional groups. A number of examples of direct C-8 arylation of purines[28] and purine nucleosides[29] **16** were carried out but in all these cases the C-6 coupling **18** took place as well (**Scheme 1.2**). Another approach is addition of an organometal followed by oxidation of the adduct with few examples in the literature. PhLi added to 6-chloro-9-methylpurine[30] and Grignard reagents added to highly activated 2-oxopurines but the yields were not satisfactory towards the target products.[31-32] The details of these reactions will be discussed in depth in **Section 2.3**. This project aims to inspect the C-C bond formation in the purine 8-position by addition of allylmetals.



14 **15**

Scheme 1.1: Purines were lithiated at the C-8 position and trapped with an electrophile[24-27]

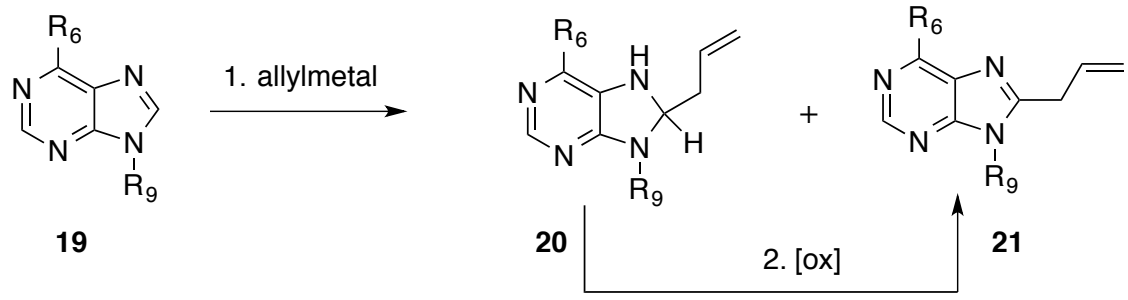


16 X = Br, I **17** **18**

Scheme 1.2 Direct coupling at the C-8 position of purines **16** gave the mixture 8-arylated purines **17** and 6-arylated purines **18**[28-29]

Former Master student Victor Marzouk attempted to add allylmagnesium bromide to 9-allylated purines **19** and 7-allylated purines **22**.[33-34] In both cases, the adducts **20** and **23** were formed and subsequently were oxidized to rearomatized products **21** and **24**, respectively. Those reactions are sketched in **Scheme 1.3** and **Scheme 1.4**. Depending on the specific

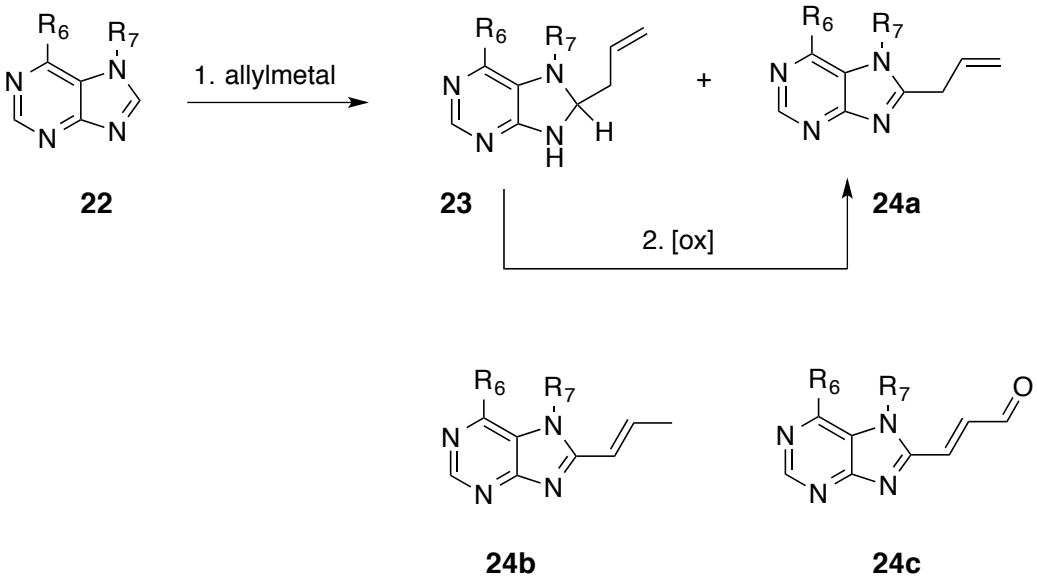
purine adduct, the oxidation step can be done with the oxygen in the air or *via* another oxidative agent such as manganese dioxide (MnO_2). The details of these reactions and their yields are summarized in **Table 1.1** and **Table 1.2**. Additionally, Victor Marzouk made one attempt to add allylindium to a purine **19a** (**Table 1.1**, entry **3**). The conversion was 90%, but the isolated yield was not satisfactory due to difficulties during work-up.



Scheme 1.3 Addition of an allylmetal to 8-unsubstituted purines **19** followed by an oxidation process gave 8-allylated purines **21**

Table 1.1

Entry	Substrate	R_2	R_6	R_9	Reagents	Yield (%) **21**
1	**19a**	H	1-piperidinyl	allyl	allylMgBr	89
2	**19b**	H	Cl	allyl	1. allylMgBr 2. MnO_2	70
3	**19a**	H	Cl	allyl	1. In, allylBr 2. MnO_2	48



Scheme 1.4: Addition of an allylmetal to 8-unsubstituted purines **22** followed by the oxidation of the adduct **23** gave a mixture of 8-allylated purines **24a**, **24b**, and **24c**

Table 1.2

Entry	Substrate	R_2	R_6	R_7	Reagents	Yield (%) **24**
1	**22a**	H	1-piperidinyl	allyl	1. allylMgBr 2. MnO_2	85
2	**22b**	H	Cl	allyl	1. allylMgBr 2. MnO_2	80[a]
3	**22c**	H	Cl	Me	1. allylMgBr 2. MnO_2	90[b]

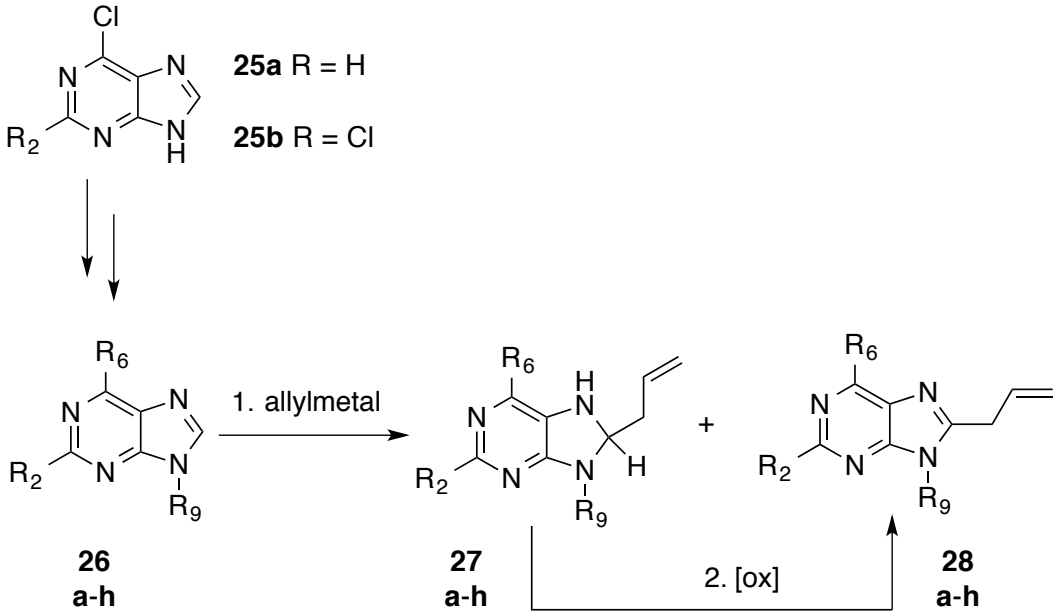
(a) 80:13:7 mixture of **24a**, **24b**, and **24c**

(b) 82:11:7 mixture of **24a**, **24b**, and **24c**

1.3 Scope of the thesis

The addition of an allylic group to the C-8 position of 9-allyl-6-(piperidin-1-yl)purine (**19a**) and 9-allyl-6-chloropurine (**19b**) was performed by using the Grignard reagent, *i.e.* allylmagnesium bromide. In this thesis, it was first attempted to reproduce the two reactions with the procedures recorded in the thesis of Victor Marzouk.[34] The thesis then continued

with the addition of the Grignard reagent to other purine substrates. Finally, allylmagnesium bromide was replaced with the allylindium reagent as an alternative. The general synthesis route carried out in the entire thesis is shown in **Scheme 1.5**. All the needed substrates **26** were synthesized from either 6-chloropurine (**25a**, R_2 = H) or 2,6-dichloropurine (**25b**, R_2 = Cl).



26a-c, **27a-c**, **28a-c**	R_2 = H, R_6 = Cl, 1-piperidinyl, or OMe, R_9 = allyl
26d-f, **27d-f**, **28d-f**	R_2 = H, R_6 = Cl, 1-piperidinyl, or OMe, R_9 = benzyl
26g, **27g**, **28g**	R_2 = Cl, R_6 = Cl, R_9 = allyl
26h, **27h**, **28h**	R_2 = H, R_6 = Cl, R_9 = Boc

Scheme 1.5

The addition of allylmagnesium bromide was first conducted with three 9-allyl-6-substituted purines **26a-c** where the substituents at the C-6 position were chloride, piperidinyl, and methoxide. Each addition reaction had two steps. First, the allylic group from the Grignard reagent added to the C-8 position in the purines **26a-c**, forming the adduct **27a-c**, respectively. Next, the adducts were converted to 8-allylated purines **28a-c** through an oxidation process.

9-Benzyl-6-substituted purines **26d-f** were selected as additional substrates to further study the stability of the C-8 addition of the Grignard reagent due to their structural similarity with 9-allyl-6-substituted purines **26a-c**, respectively. As previously discussed, each reaction of

the substrate **26d-f** included two successive steps. The first step formed the adduct **27d-f**, which was oxidized in the second step to produce 8-allylated purines **28d-f**.

Allylindium reagents were applied to three purine substrates: 9-allyl-6-chloropurine (**26a**), 9-allyl-2,6-dichloropurine (**26g**), and 9-Boc-6-chloropurine (**26h**). These reactions were expected to work as they did with the Grignard reagent in the previous reactions. The adducts **27a** and **27g-h** are formed in the first step. Subsequently, the oxidation would convert all the adducts to the target products **28a** and **28g-h**, respectively. All the addition reactions with organometals conducted in the thesis are summarized in **Table 1.3.**

Table 1.3: Substrates and reagents were employed for the syntheses shown in **Scheme 1.5**

Entry	Substrate	R_2	R_6	R_9	Reagents
1	**26a**	H	Cl	allyl	1. allylMgBr 2. Oxidizing agent
2	**26b**	H	1-piperidinyl	allyl	1. allylMgBr 2. Oxidizing agent
3	**26c**	H	OMe	allyl	1. allylMgBr 2. Oxidizing agent
4	**26d**	H	Cl	benzyl	1. allylMgBr 2. Oxidizing agent
5	**26e**	H	1-piperidinyl	benzyl	1. allylMgBr 2. Oxidizing agent
6	**26f**	H	OMe	benzyl	1. allylMgBr 2. Oxidizing agent
7	**26a**	H	Cl	allyl	1. In, allylBr 2. Oxidizing agent
8	**26g**	Cl	Cl	allyl	1. In, allylBr 2. Oxidizing agent
9	**26h**	H	Cl	Boc	1. In, allylBr 2. Oxidizing agent

1.4 Thesis organization

The thesis is further structured into four more chapters. Chapter 2 reviews key reaction types that lay fundamentals for preparing the needed purine substrates and the addition of organometals to various purine derivatives. Chapter 3 describes and discusses all reactions that have been done and all the compounds that have been obtained. In the Chapter 4, a conclusion for the whole thesis and relevant future work are presented. Finally, Chapter 5 is dedicated for procedures of the conducted reactions and spectra of the obtained compounds, *i.e.* ^{1}H NMR, ^{13}C NMR, COSY NMR, HSQC NMR, HMBC NMR, MS (EI), HRMS.

2 Background

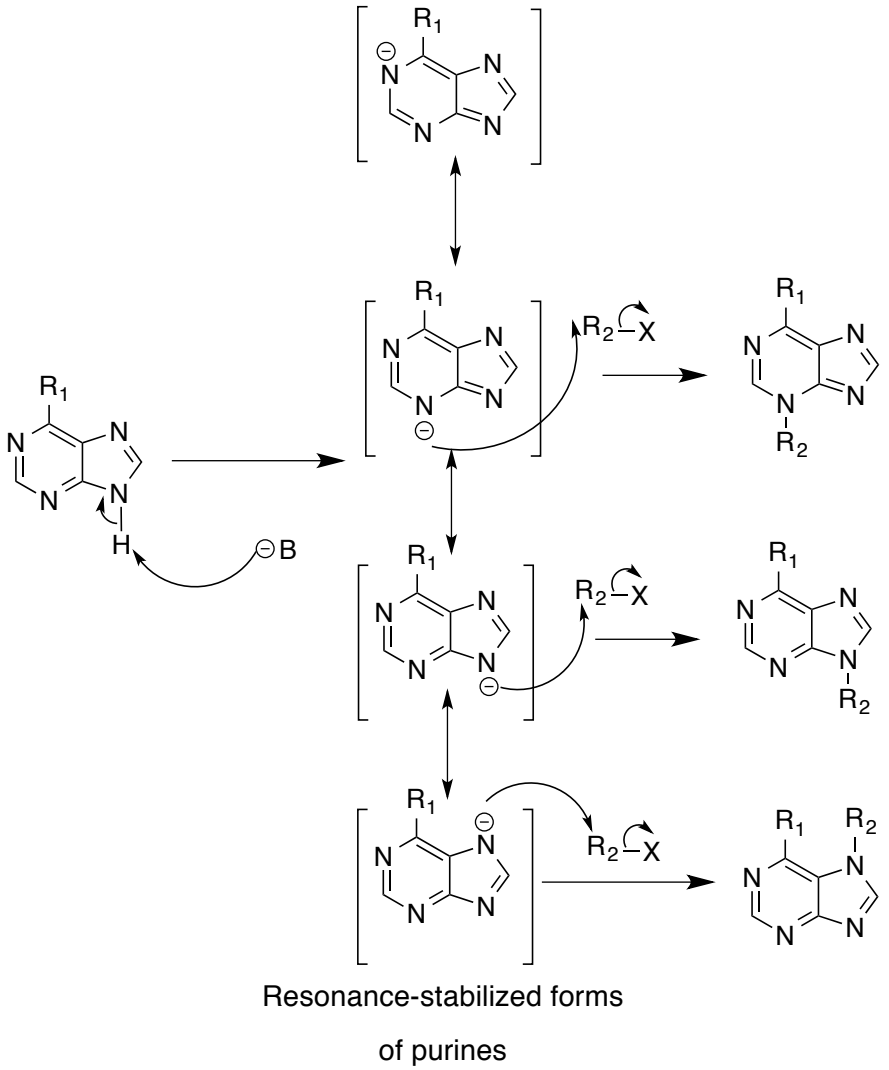
Purine includes pyrimidine and imidazole fused together, and consequently owns properties of both an electron-deficient six-membered ring and an electron-rich five-membered ring.[2] Specifically, purines can undergo nucleophilic attacks at carbon in the pyrimidine moiety and either electrophilic or nucleophilic attacks at carbon and nitrogen in the imidazole moiety. This chapter begins with N-alkylation, a reaction between purines and electrophilic species. Then, the aromatic nucleophilic substitution of purines will be discussed in terms of amination and alkoxidation. Finally, last sections of this chapter is dedicated to addition of organometals to purines, overview of organoindium chemistry, and further review on the oxidation reaction to rearomatize the adducts.

2.1 N-alkylation

Two major methods to alkylate purines at nitrogen positions are base-induced alkylation (**Section 2.1.1**) and the Mitsunobu reaction (**Section 2.1.2**). The former needs an *alkyl halide* reagent while the latter works with an *alcohol*.

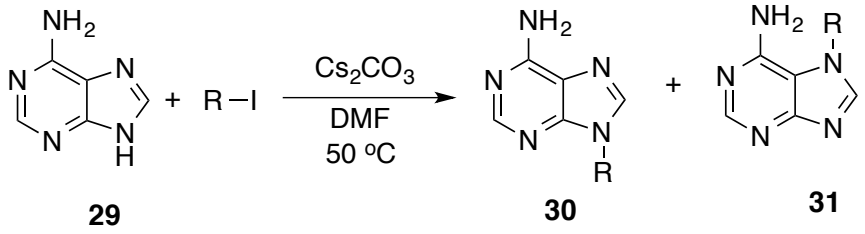
2.1.1 Base-induced alkylation

The idea of the base-induced alkylation is resorting to a base to deprotonate purines and trapping the resulting anion with an alkyl halide. One of the challenges in this reaction is the existence of four resonance-stabilized anions of purines in basic condition. As the result, several N-alkylated products are being produced in a single alkylation reaction.[2] The general mechanism of the base-induced alkylation of purines to produce N-3, N-7, and N-9 alkylated isomers is sketched in **Scheme 2.1**.[35] The N-1 alkylated isomer has not seen reported to be formed through the base-induced alkylation.



Scheme 2.1

Various bases, *i.e.* NaH, K_2CO_3, and Cs_2CO_3, alongside with a couple of solvents, *i.e.* DMSO and DMF, were employed in these reactions that mostly gave good yields.[34, 36-39] For instance, the alkylation of adenine **29** using a wide range of alkyl iodides, Cs_2CO_3 as the base in DMF resulted in the yields not lower than 79% for 9-alkylated purines **30** (**Scheme 2.2** and **Table 2.1**) and insignificant amount of N-7 isomers **31**.[38]



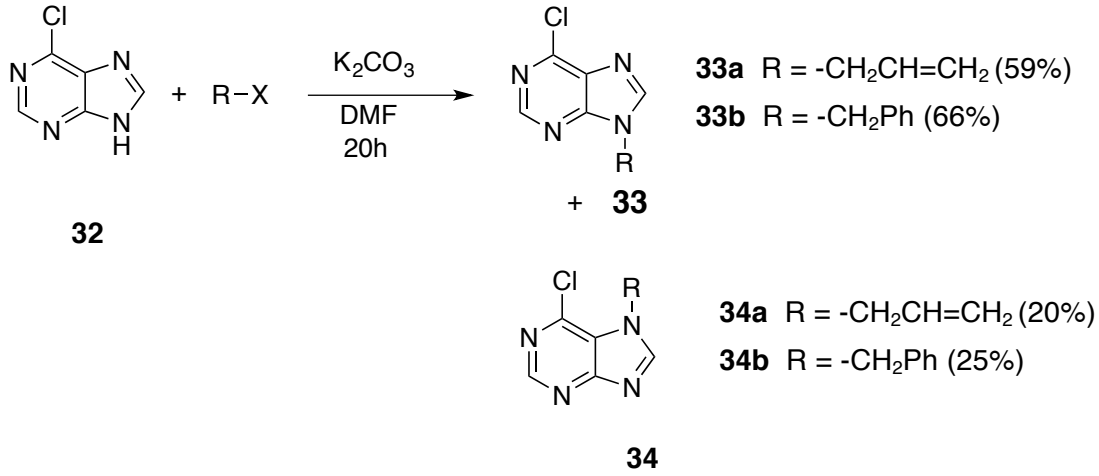
29 **30** **31**

Scheme 2.2

Table 2.1: Alkyl groups examined in the reactions of shown **Scheme 2.1** and the reactions' yields[38]

R	Yield (%) **30**	R	Yield (%) **30**
$-CH_2CH_3$	91	$-(CH_2)_2OC(O)CH_3$	91
$-(CH_2)_2CH_3$	93	$-(CH_2)_3OC(O)CH_3$	89
$-(CH_2)_3CH_3$	95	$-(CH_2)_4OC(O)CH_3$	88
$-(CH_2)_4CH_3$	91	$-(CH_2)_4CN$	89
$-(CH_2)_2PO(OCH_2CH_3)_2$	79		

The allylation and benzylation of 6-chloropurines **32** in the presence of K_2CO_3 in DMF gave mixtures of N-9 and N-7 isomers with similar ratios: 59% 9-allylated isomer **33a** and 20% 7-allylated isomer **34a**[40] relative to 66% 9-benzylated isomer **33b** and 25% 7-benzylated isomer **34b**[41] (**Scheme 2.3**).



32

34

Scheme 2.3

The ratio of N-9 to N-7 alkylation may be affected by the steric hindrance of substituents at the C-6 position in purines. A bulky 6-substituent may substantially impede the formation of N-7 isomer and concurrently increase the proportion of N-9 counterpart. The increased N-9 to N-7 ratios with decreasing the defined distance from the 6-substituents to the N-7 position, d(H,N-7) shown in **Figure 2.1**, is an example of the steric effect (**Table 2.2**).[42] Unsubstituted imidazole (**Table 2.2**, entry **4**) and 2-butylimidazole (**Table 2.2**, entry **5**) are very effective to hinder the N-7 isomer.

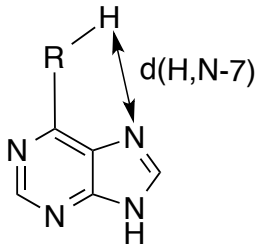


Figure 2.1: The defined distance from the 6-substituents to the N-7 position, d(H,N-7), is roughly the shortest distance between N-7 and the closest hydrogen atom in the 6-substituents

Table 2.2: The steric hindrance caused by various 6-substituents affects the N-9 to N-7 ratios

Entry	6-substituent	d(H,N-7) in Å[42]	N-9 to N-7 ratio[42]
1	Me	2.902	9:1
2	Et	2.762	16:1
3	*i*-Pr	2.701	25:1
4	Imidazol-1-yl	2.436	1:0
5	2-Butylimidazol-1-yl	2.430	1:0

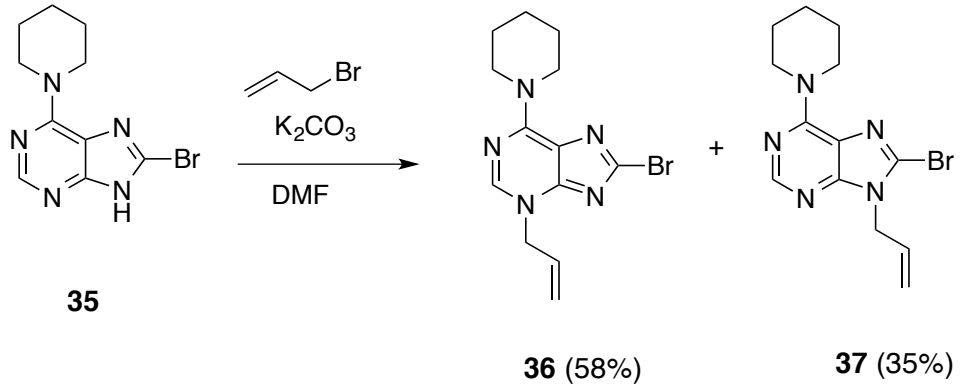
Besides the steric effect, electronic characteristic of the 6-substituents also contributes to the variation of the isomer ratios. The N-9 to N-7 isomer ratios varying with different 6-halopurines is a good example of the combination of the electronic effect and the steric effect (**Table 2.3**).[43] For all halogens, the increasing of their atom sizes leads to the increasing of

the isomer ratios. However, hydrogen has a smaller atom size but gives a higher ratio compared to the fluoride (**Table 2.3**, entry **1** and **2**).

Table 2.3

Entry	6-substituent	Atom radii Å[44]	N-9 to N-7 ratio[45]
1	H	1.20	4.0:1
2	F	1.47	3.4:1
3	Cl	1.75	5.5:1
4	Br	1.85	7.3:1
5	I	1.98	9.0:1

The steric effect may also promote the formation of the N-3 isomer. The allylation of compound **35** gave 58% N-3 allylated isomer **36** and 35% N-9 allylated isomer **37** (**Scheme 2.4**).[46] Both C-6 and C-8 substituents, *i.e.* bromide and piperidinyl, respectively, sterically hindered the formation of the N-7 isomer. The similar results have been observed with the arylation of 8-bromoadenine.[47-48]



35

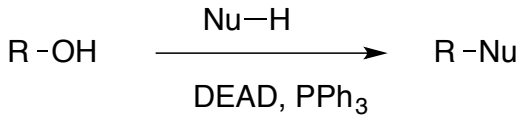
36 (58%) **37** (35%)

Scheme 2.4

2.1.2 The Mitsunobu reaction

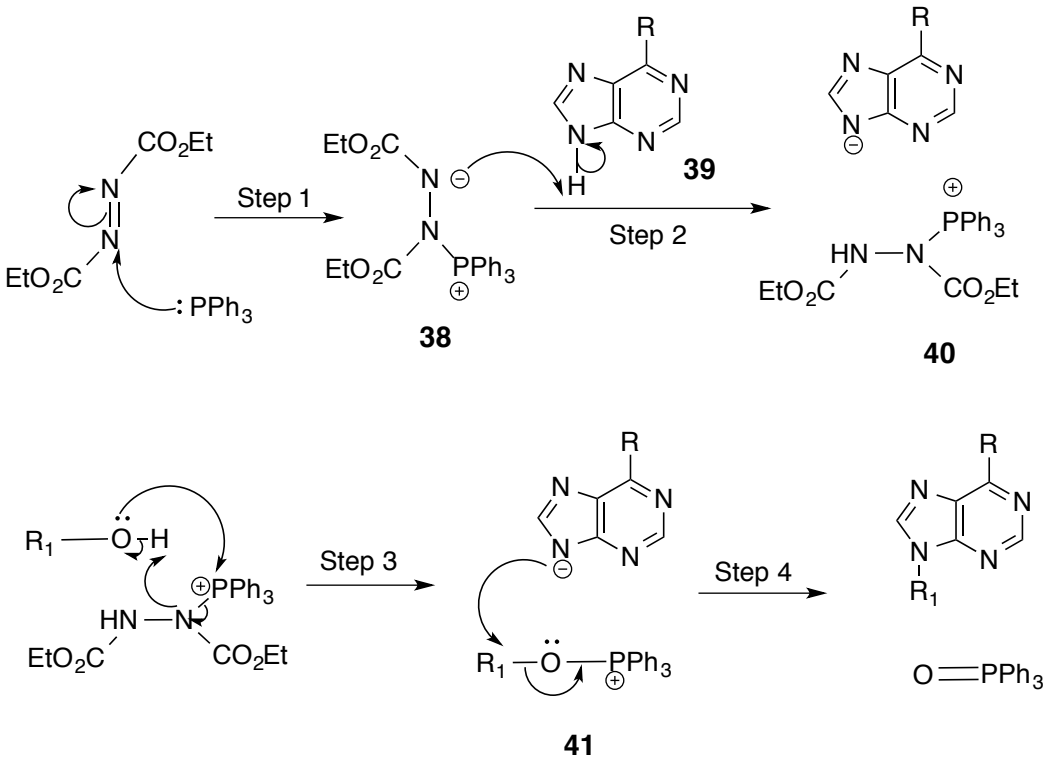
The Mitsunobu reaction can also be employed to alkylate purines. The key idea of this reaction is converting a hydroxyl group to a strong leaving group that is readily attacked by a

nucleophile. The general Mitsunobu reaction with triphenylphosphine (PPh_3) and diethyl azodicarboxylate (DEAD) is shown in **Scheme 2.5.**[49]



Scheme 2.5

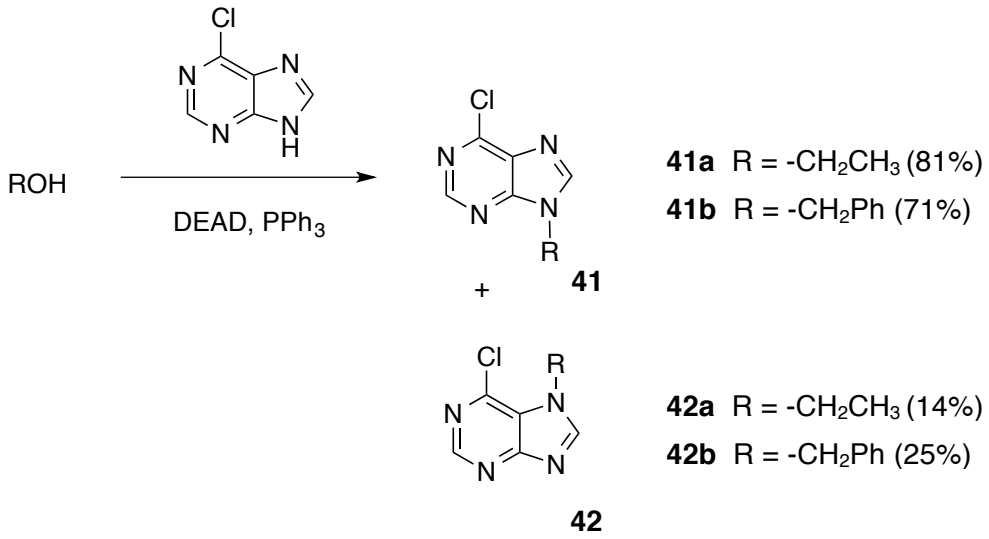
The mechanism[35] of the Mitsunobu reaction of purines has four steps, which are described in **Scheme 2.6**. First, PPh_3 attacks DEAD, forming zwitterionic adduct **38**. Next, compound **38** deprotonates the purine derivatives **39**, turning them to negative charged nucleophiles. The resulting phosphonium ion **40** then reacts with the alcohol and results in an oxyphosphonium ion **41**, which undergoes S_N2 displacement by the negative-charged purine nucleophile formed in the second step. The alkylation of purines with the Mitsunobu reaction also produces mixtures of N-alkylated isomers.



Scheme 2.6: [35]The mechanism of Mitsunobu reaction with DEAD and PPh_3

The Mitsunobu reaction of 6-chloropurine and ethanol (**Scheme 2.7**) produced 81% 9-ethylated isomer **41a** and 14% 7-ethylated isomer **42a**.[50] Similar reaction with benzyl alcohol

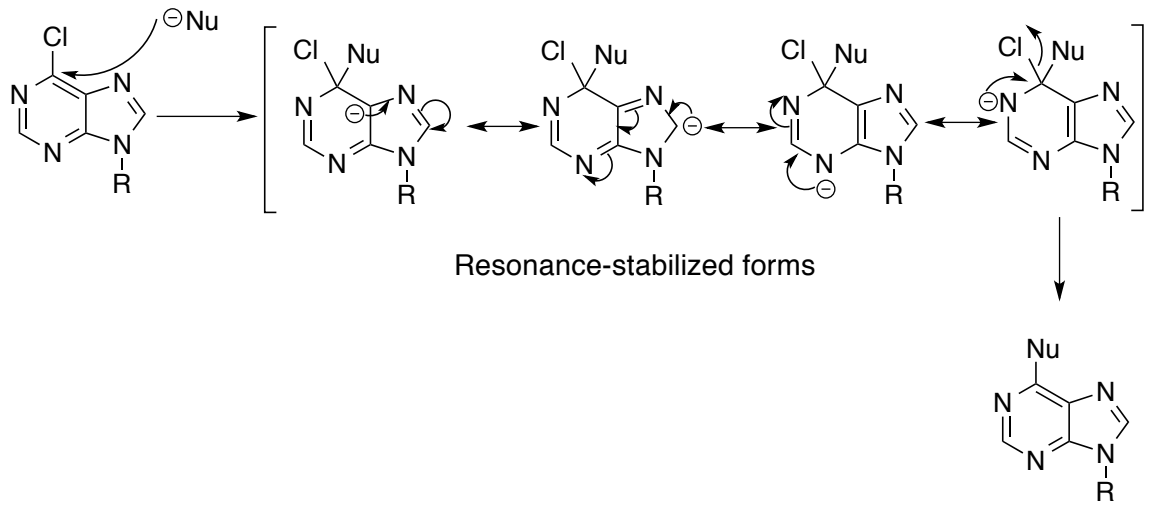
yielded 71% 9-benzylated isomer **41b** and 25% 7-benzylated isomer **42b**.[50] The major disadvantage of the Mitsunobu reactions is the difficulty of removing hydrazine and phosphine oxide from the target products, making it not favored in the large-scaled synthesis.[51]



Scheme 2.7

2.2 Aromatic nucleophilic substitution (S_NAr)

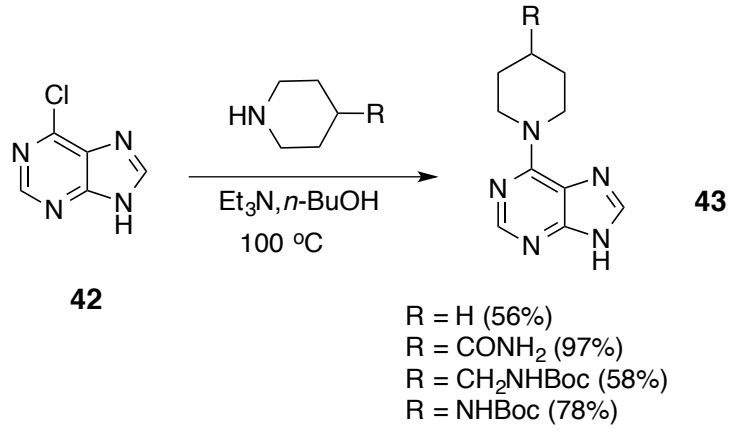
The aromatic nucleophilic substitution (S_NAr) of 6-chloropurines involves addition of the nucleophile followed by elimination of the chloride. This type of reaction is also called addition-elimination.[52] The general mechanism of the S_NAr of 6-chloropurines is described in **Scheme 2.8**.[53]



Scheme 2.8: The addition of a nucleophile to 6-chloropurines first forms several resonance stabilized intermediates and is followed by the elimination of chloride

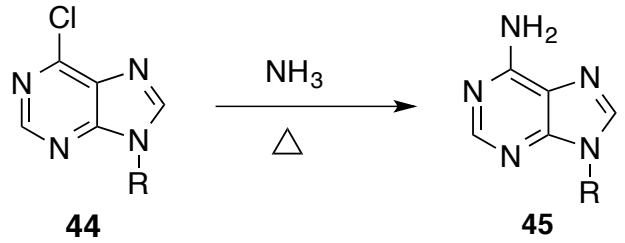
2.2.1 Amination of 6-chloropurines

Amination of 6-chloropurines follows the preceding S_NAr mechanism in which the nucleophile is an appropriate amine. Heating is widely employed in this reaction and can give good yields.[54-56] 6-Chloropurine **42** underwent aromatic substitution with piperidinyl derivatives in triethyl amine and *n*-BuOH as solvent, producing compounds **43** (**Scheme 2.9**).[54]



Scheme 2.9

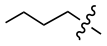
Adenine derivatives **45** were formed by reacting the corresponding 6-chloropurines **44** with ammonia, heating the mixture above 100 °C, obtaining good yields (**Scheme 2.10** and **Table 2.4**).[55-56]



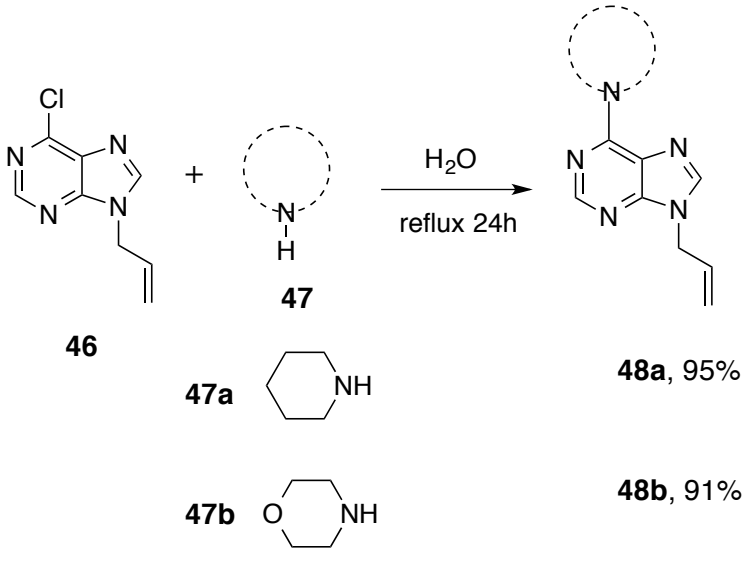
44 **45**

Scheme 2.10

Table 2.4: Yields of the reactions shown in **Scheme 2.10**

R	Conditions	Yield (%) **45**
H	MeOH, 120 °C, 15 h	87
HO 	1,4-dioxane, 110 °C, 16 h	91

The amination of 6-chloropurines **46** by refluxing in water was reported to give good yields.[57] Compounds **48** were resulted from the substitution of the piperidinyl and morpholinyl groups **47** on compound **46** by refluxing in water. Both gave yields of over 90% (**Scheme 2.11**).

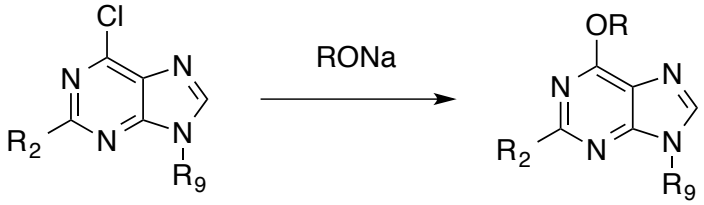


46 **47** **47a** **47b** **48a**, 95% **48b**, 91%

Scheme 2.11

2.2.2 Alkoxylation of 6-chloropurines

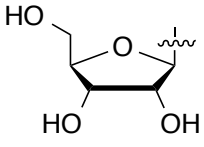
Alkoxylation of 6-chloropurines also follows S_NAr mechanism in which the nucleophiles are alkoxide anions of sodium alkoxide or potassium alkoxide. Like the discussed amination, the alkoxylation of 6-chloropurines can be conducted with heating. 6-Chloropurines **49** were substituted at the 6-position with various sodium alkoxides to give 6-alkoxylated purines **50** by refluxing (**Scheme 2.12** and **Table 2.5**).[58-61]



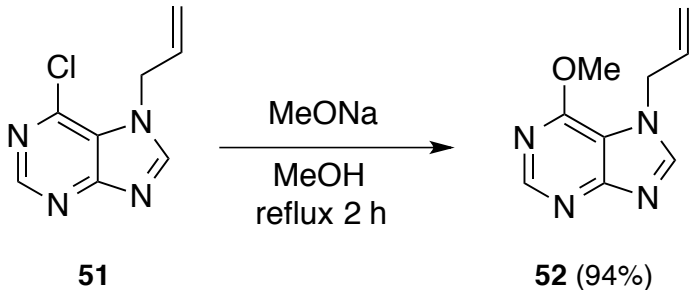
49 **50**

Scheme 2.12

Table 2.5: Yields of the reactions shown in **Scheme 2.12**

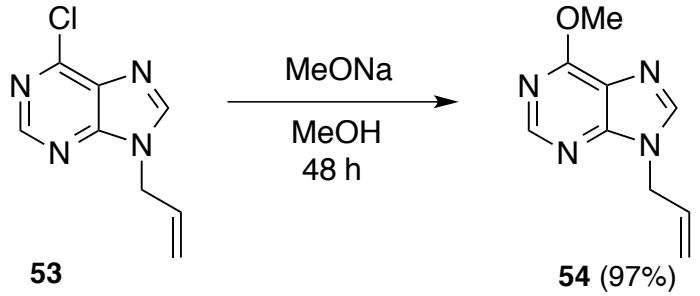
R_2	R_9	Reagent and Conditions	Yield (%) **50**
NH_2	H	NaOBu, reflux, 18 h	83[58]
NH_2	H	NaOMe, reflux, 3 h	85[59]
H	Bn	$NaOCH_2CH{=}CH_2$, reflux, 15 h	72[60]
NH_2		NaOBn, 115 ^oC, 10 min.	47[61]

Compound **51** reacting with MeONa by refluxing with MeOH gave a good yield of compound **52** (94%, **Scheme 2.13**). In the same condition but at room temperature, methoxylation of compound **53** needed much more time to give 97% yield of compound **54** (**Scheme 2.14**).[62]



51 **52** (94%)

Scheme 2.13



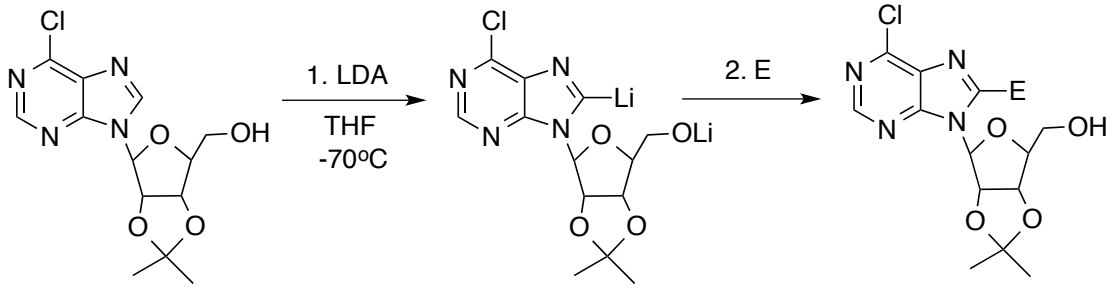
53 **54** (97%)

Scheme 2.14

2.3 C-C Bond formation in the purine 8-position *via* organometals

The formation of C-C bond at the C-8 position of purines can be done through 8-halopurines in metal-halogen exchange reactions[63] or coupling reactions such as the Stille coupling[22-23] and Suzuki coupling[19-21] with a paladium(0) catalyst. However, such reactions require the preparation of 8-halopurines from 8-unsubstiuted purines beforehand. Direct conversion of 8-unsubstituted to 8-alkyl or arylpurines is more challenging and is reviewed in this section.

A number of purines and purine nucleosides not substituted at C-8 may be lithiated by BuLi[24-25] or LDA[26-27] and trapped with an organic electrophile. 6-Chloropurine nucleoside **55** was lithiated by LDA in THF to form 8-lithiated product **56**, then being trapped with a number of electrophiles, resulting 8-substituted purine **57**. **Table 2.6** lists all electrophiles, C-8 substituents, and the yields of the reactions shown in **Scheme 2.15**.[26]

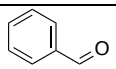
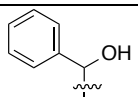
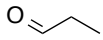
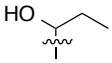
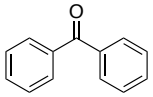
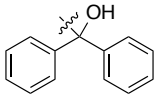
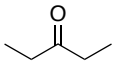
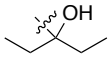


55 **56** **57**

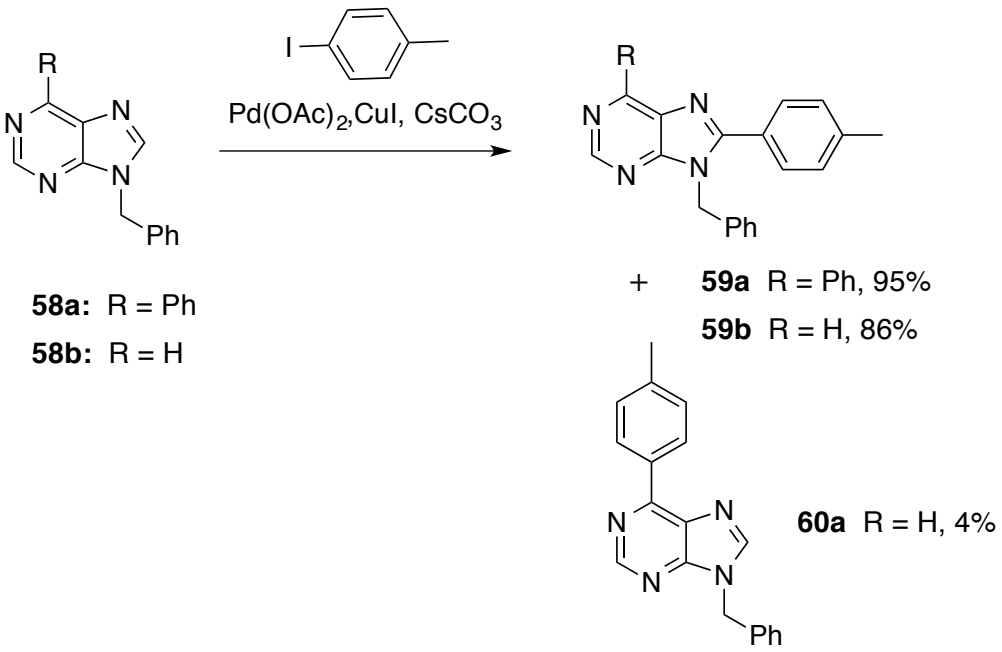
Scheme 2.15

However, the employment of the organolithium reagent has a couple of disadvantages. The reagent is a strong base that makes it incompatible with many functional groups[4] and its sensitivity with the moisture poses difficulties in handling the reactions.

Table 2.6: Electrophiles and corresponding yields of the reactions shown in **Scheme 2.15**

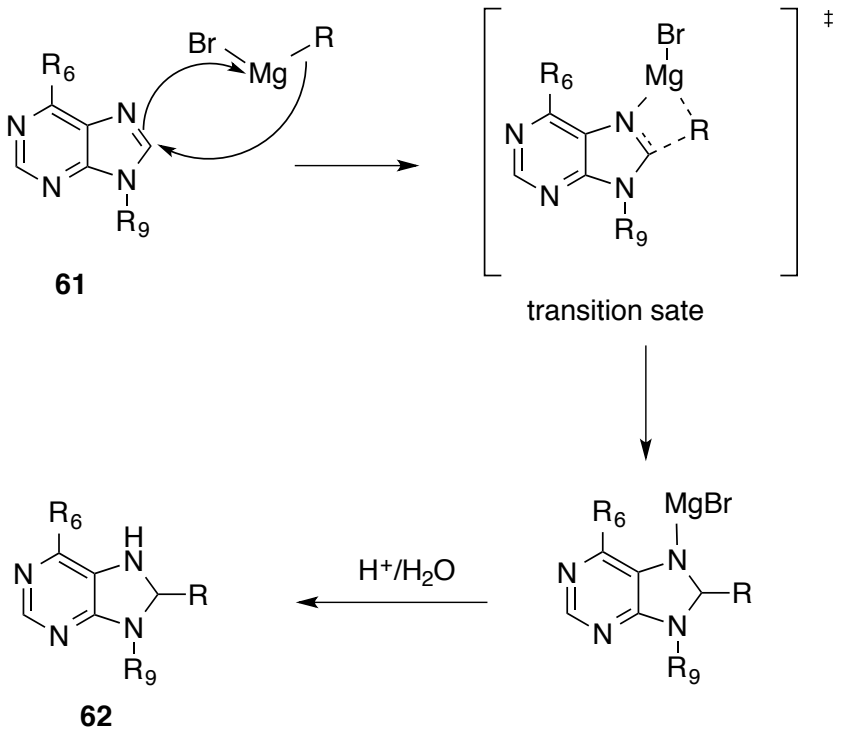
Electrophiles	R	Yield (%) **57**
		71.4
		61.5
		60.5
		38.6

Some examples of direct C-8 arylation of purines and purine nucleosides were reported.[28-29] Purines[28] **58** as well as purine nucleosides[29] were coupled to 4-iodotoluene by Pd-mediated CH activation to give 8-arylated purines **59** (**Scheme 2.16**). In both cases, some 6-arylated purines **60a** were formed when the 6-position was unsubstituted.



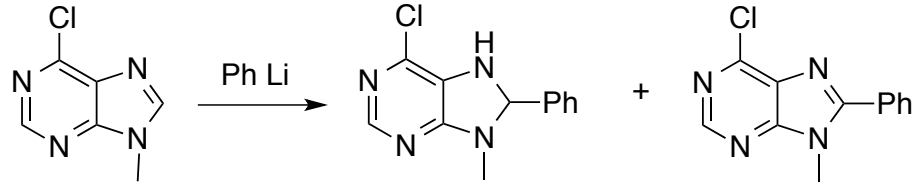
Scheme 2.16

Another approach of direct C-C bond formation at the purine 8-position is addition of an organometallic reagent followed by oxidation of the resulting adduct. The proposed mechanism of the addition of a Grignard reagent to the C-8 position of purines **61** to form the adduct **62** is shown in **Scheme 2.17**.[64]



Scheme 2.17

Phenyllithium (PhLi) added to 6-chloro-9-methylpurine **63**, giving a mixture of the adduct **64** and the target compound **65** (**Scheme 2.18** and **Table 2.7**, entry **1**).[30] Both products were enhanced by employing $Fe(BMD)_3$ as a catalyst (**Table 2.7**, entry **2**) and all the adduct was converted to rearomatized product **65** in the presence of $PhNO_2$ as an oxidizing agent (**Table 2.7**, entry **3**).



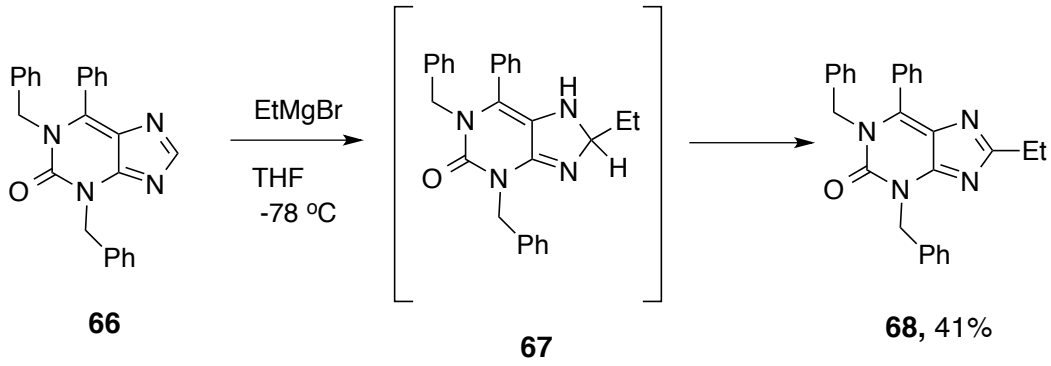
63 **64** **65**

Scheme 2.18

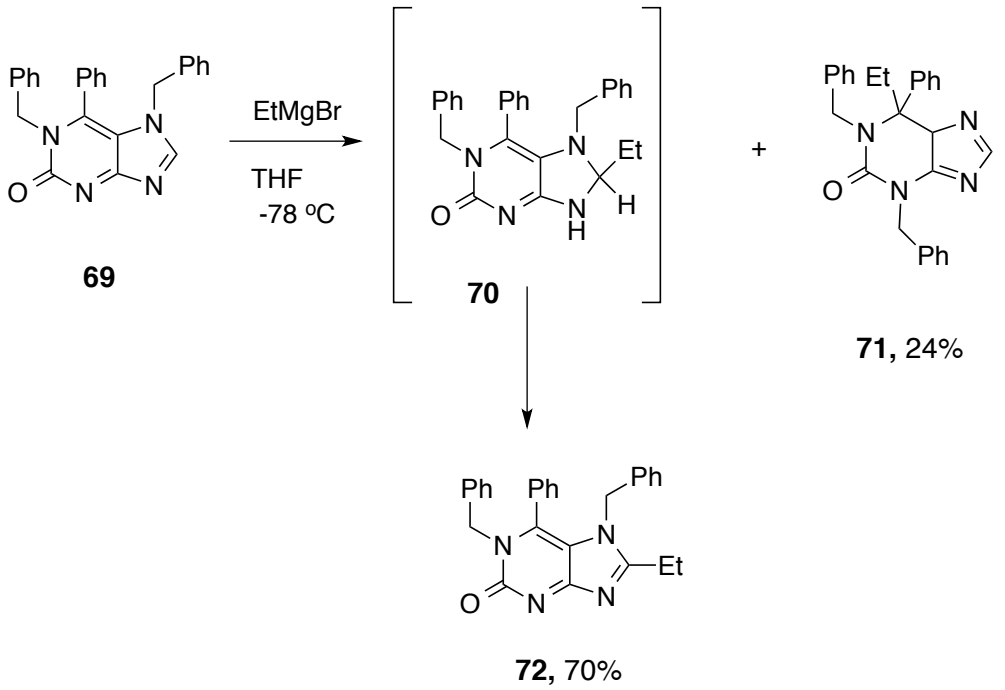
Table 2.7: Yields of the adducts and target products with various conditions of the reaction shown in **Scheme 2.18**

Entry	Additives	Yield (%) **64**	Yield (%) **65**
1	none	8	4
2	cat. $Fe(BMD)_3$	26	13
3	1. cat. $Fe(BMD)_3$, 2. $PhNO_2$	-	40

Grignard reagents can add to activated 2-oxopurines at the 8-position.[31-32] Ethylmagnesium bromide added to 6-phenyl-2-purinones **66**, forming adduct **67**, which was oxidized during the isolation process to rearomatized product **68** (**Scheme 2.19**). The C-8 addition dominantly took place in the case of 1,7-dibenzyl-2-purinone **69**, forming adduct **70**, and yielded 70% target product **72** (**Scheme 2.20**). The addition at C-6 occurred as well with 24% yield of adduct **71**.

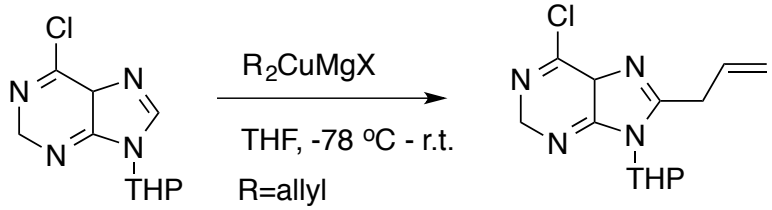


Scheme 2.19



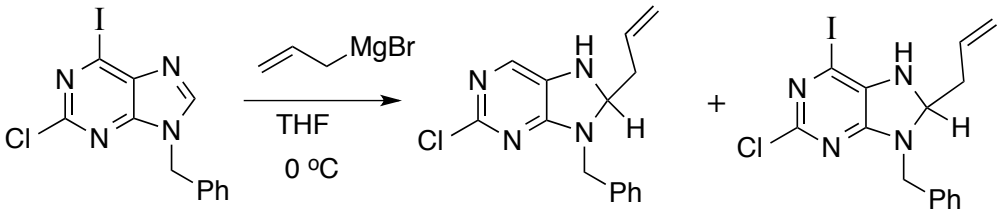
Scheme 2.20

The addition of an allylic group to the C-8 position of purines is promising in the synthesis of bioactive fused purine derivatives, *e.g.* pyrido[1,2-*e*]purines,[33] but a few reactions have been conducted. The allylic reagent, organocuprate R_2CuMgX where R is the allylic group, reacted at the 8-position of purines **73** to give compound **74**, probably *via* an addition-oxidation process (**Scheme 2.21**).[65] Likewise, allylmagnesium bromide added to compound **75**, forming two adducts **76** and **77** with similar yields (37%) (**Scheme 2.22**).[66]



73 **74**

Scheme 2.21



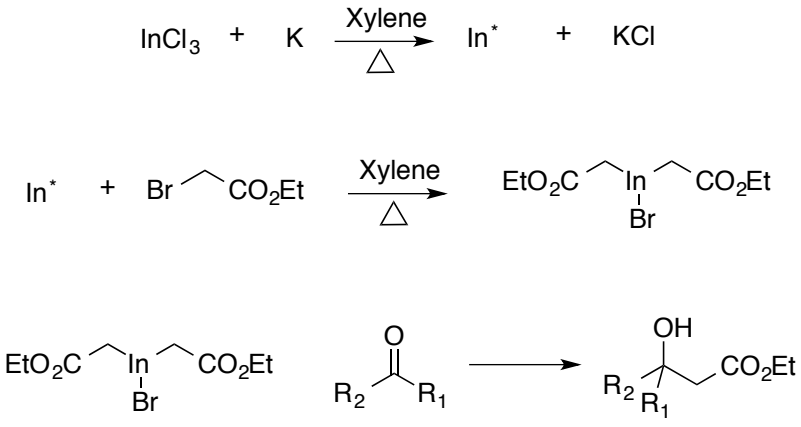
75 **76** **77**

Scheme 2.22

In the scope of this project, the C-8 addition of allylmagnesium bromide to the 8-position of a number of purines was previously conducted by Victor Marzouk and is summarized in **Table 1.1** and **Table 1.2**.[34]

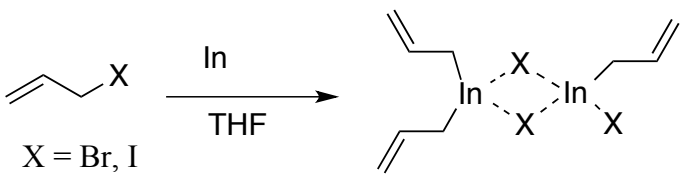
2.4 Addition of organoindium reagents

The organoindium compound was first known in 1934 when Dennis and his co-worker[31] prepared trimethylindium (Me_3In) from dimethylmercury and indium via transmetalation. The reactions of organoindium had not been as widely used as Grignard reagents until its first application in organic synthesis published by Rieke and co-workers[67-69] in 1975. This was a Reformatsky reaction of ethyl bromoacetate with carbonyl compound when ethyl bromoacetate initially reacted with indium preactivated by potassium (**Scheme 2.23**).



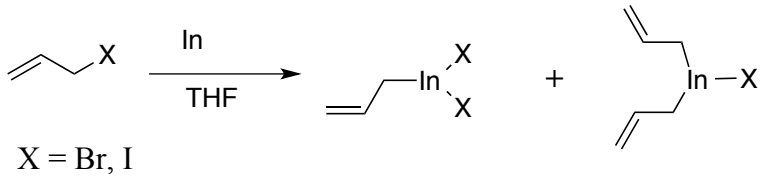
Scheme 2.23

Although being employed for long time, the structure of organoindium has been a debate. There are two suggested structures of the allylindium species that are widely used in the literature. First structure is called allylindium sesquihalide **78**,[70] which is a complex of indium metal, allylic groups, and halides (**Scheme 2.24**). Note that allyl chloride was not used in forming allylindium species because it is not reactive towards indium insertion.[71] The second structure considers allylindium halide as a mixture of allylindium dihalide **79** and diallylindium halide **80** (**Scheme 2.25**).[72] In this work, the latter structure is employed to explain our reactions. Following that allylindium halide is not much different from the allylmagnesium halide. However, the allylindium reagent is more stable than the Grignard counterparts.[71] It is highly compatible with many other functional groups and even with hydroxyl groups and water. As the result, the reactions with the allylindium reagent can be carried out in water, which is economical and environmentally friendly.[73-75] Thus, these reactions often represent the Green chemistry.[76] The stability of the allylindium species also makes it simpler to be manipulated during the reactions because moisture in the air is not an issue as it is when working with the Grignard reagents.



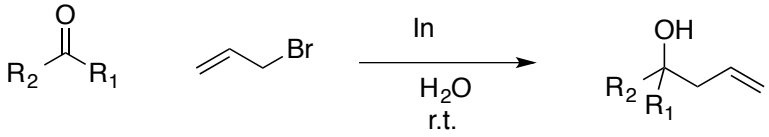
78

Scheme 2.24



Scheme 2.25

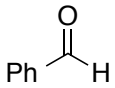
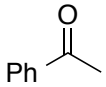
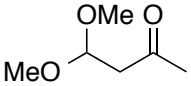
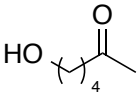
Like Grignard reagents, allylindium bromide generated *in situ* added readily to carbonyl-containing compounds and gave from satisfactory to good yields (**Scheme 2.26** and **Table 2.8**).[77-80] Furthermore, these reactions use water as reaction media at room temperature and do not need inert atmosphere (unacceptable to the Grignard reagents).



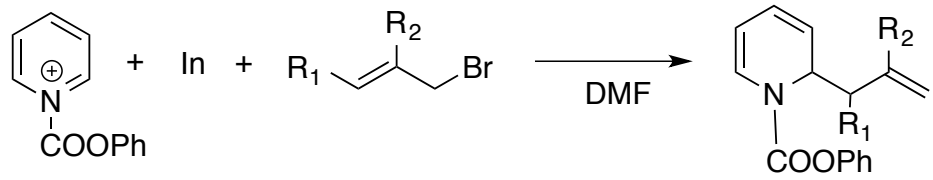
81 **82**

Scheme 2.26

Table 2.8: Carbonyl-containing substrates and the yields of reactions shown in **Scheme 2.26**

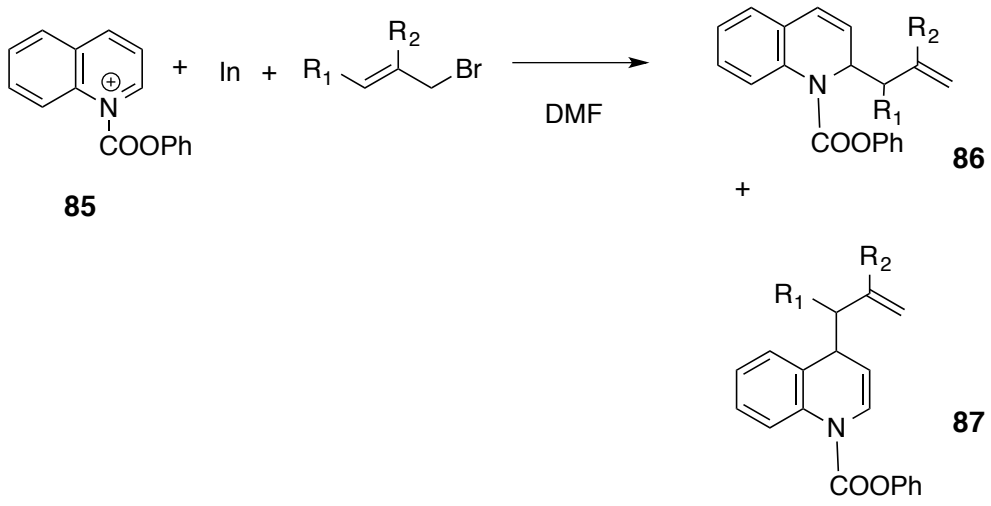
Entry	Carbonyl substrate **81**	Yield (%) **82**
1		97
2		72
3		70
4		95

Allylindium species adds to C=N bond of heterocycles in the same way as Grignard reagents, but relatively more regioselective.[81] While the addition of allylmagnesium bromide to the 1-acylpyridium salts **83** gave a mixture of 2- and 4-substitued dihydropyridines, this occurred only at C-2 position in the case of the allylindium reagent (compound **84**, **Scheme 2.27**). Similar results were observed with quinolinium **85** and isoquinolinium **88** salts. For the former, both 2- and 4-allylated dihydroquinolines (**86** and **87**, respectively, **Scheme 2.28**) were formed; highly favoring **86**, and only 1-allylated dihydroisoquioline **89** was yielded for the latter (**Scheme 2.29**).[81]



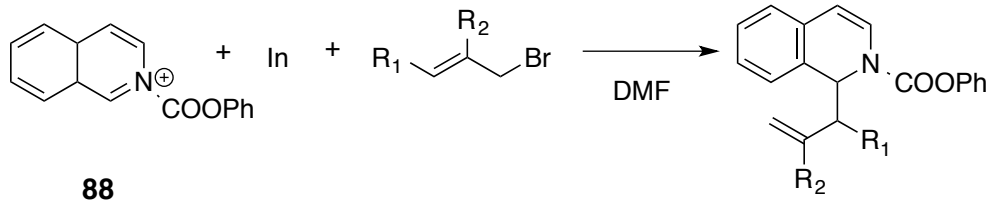
83 **84**

Scheme 2.27



85 **86** **87**

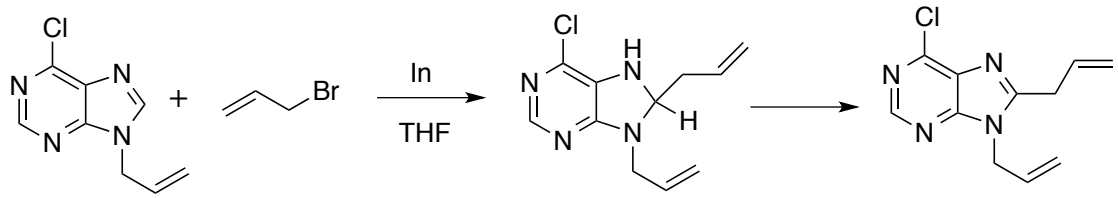
Scheme 2.28



88 **89**

Scheme 2.29

Former Master student Victor Marzouk made one attempt to add allylindium reagent to 9-allyl-6-chloropurines **90**. The addition resulted in adduct **91** which was later oxidized to rearomatized product **92** (**Scheme 2.30**).[34] More purine substrates were examined with allylindium species in this thesis.

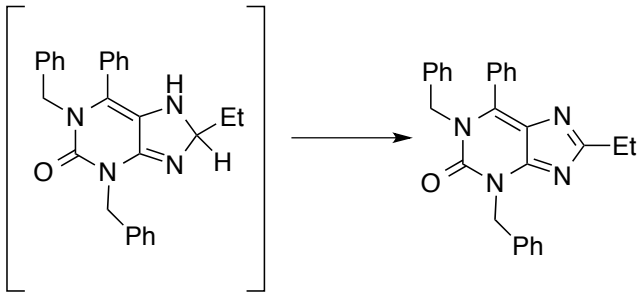


90 **91** **92**

Scheme 2.30

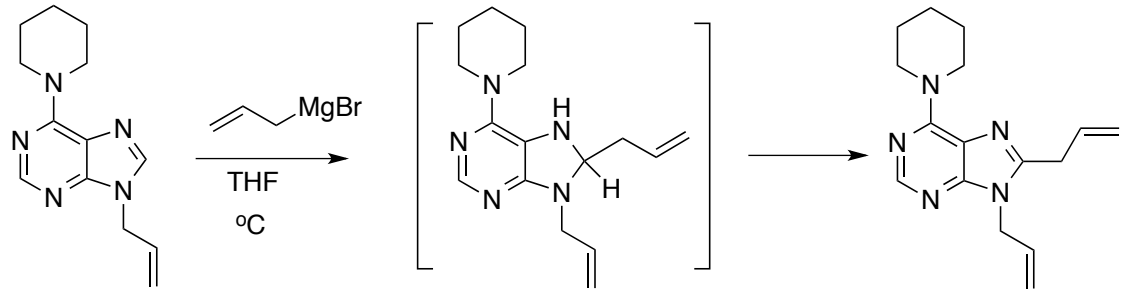
2.5 Rearomatization of adducts *via* oxidation process

It has sometimes been observed that rearomatization can take place when the adduct exposes itself to the oxygen in the air during an isolation process. The possibly formed adduct **67** of the reaction shown in **Scheme 2.31** was spontaneously rearomatized to give compound **68** without the need of any special oxidizing agents.[31] Likewise, possibly formed adduct **94**, resulted from the addition of allylmagnesium bromide to 6-piperidinylpurines **93**, was converted to rearomatized product **95** with the presence of oxygen in the air (**Scheme 2.32**).[33]



67 **68**

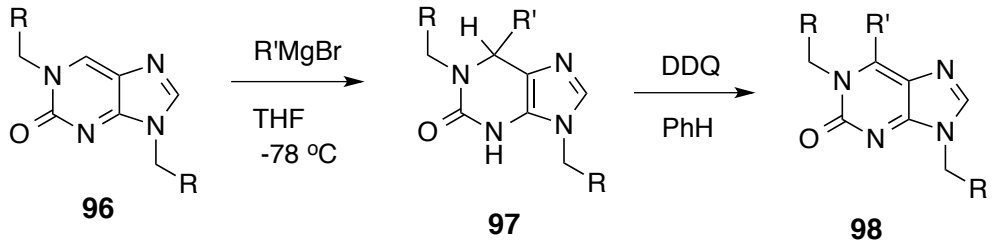
Scheme 2.31



93 **94** **95**

Scheme 2.32

In other cases, oxygen in the air may not be capable of transforming all the adduct to the oxidized product. In the reaction[30] shown in **Scheme 2.18**, the adduct **64** was partially converted to the rearomatized product **65** (**Table 2.7** , Entry **1** and **2**). When $PhNO_2$ was used as a stronger oxidizing agent, all the adduct was rearomatized to compound **65** (**Table 2.7**, Entry **3**). DDQ can be also used as an oxidizing agent towards many purine-based adducts. The addition of Grignard reagents to purines **96** at the 6-position formed adduct **97**.[31] The compound **97** then was rearomatized with DDQ to obtain compound **98**. Chloranil and MnO_2 are two other oxidizing agents that were employed to rearomatize compound **97**. All the results are shown in **Table 2.9**. MnO_2 did not work with the alkyl adducts (**Table 2.9**, Entry **c** and **d**).[31]



96 **97** **98**

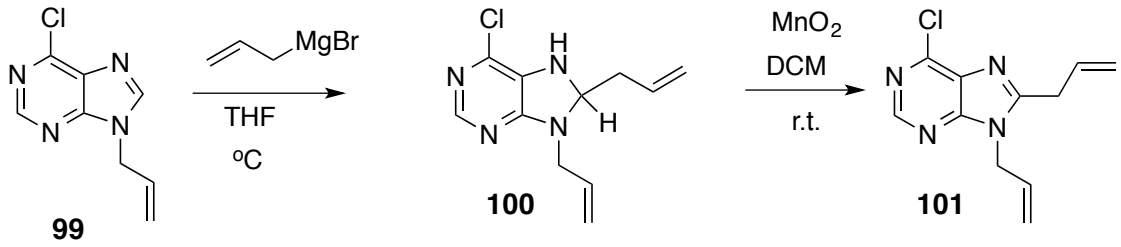
Scheme 2.34

Table 2.9: Rearomatizing the adducts **97** with various oxidizing agents

		Yield (%) **98**[31]		
Entry	R	DDQ	Chloranil	MnO_2
a	Ph-	67	50	69
b	Ph-C≡C-	60	70	50
c	CH_3-	68	81	n.r.
d	$(CH_3)_2CH$-	52	55	n.r.

MnO_2 has been widely used for rearomatize adducts due to its availability, low cost, and the satisfactory degree and selectivity of conversion even at room temperature. The reactivity of MnO_2, however, varies greatly in the reaction media, *i.e.* very high in an acidic medium, moderate in neutral one, and inactive in the alkaline.[82] Heating is often used to promote the reaction, but studies showed that the oxidation with MnO_2 lost of its selectivity when the temperature exceeded 70 °C.[83]

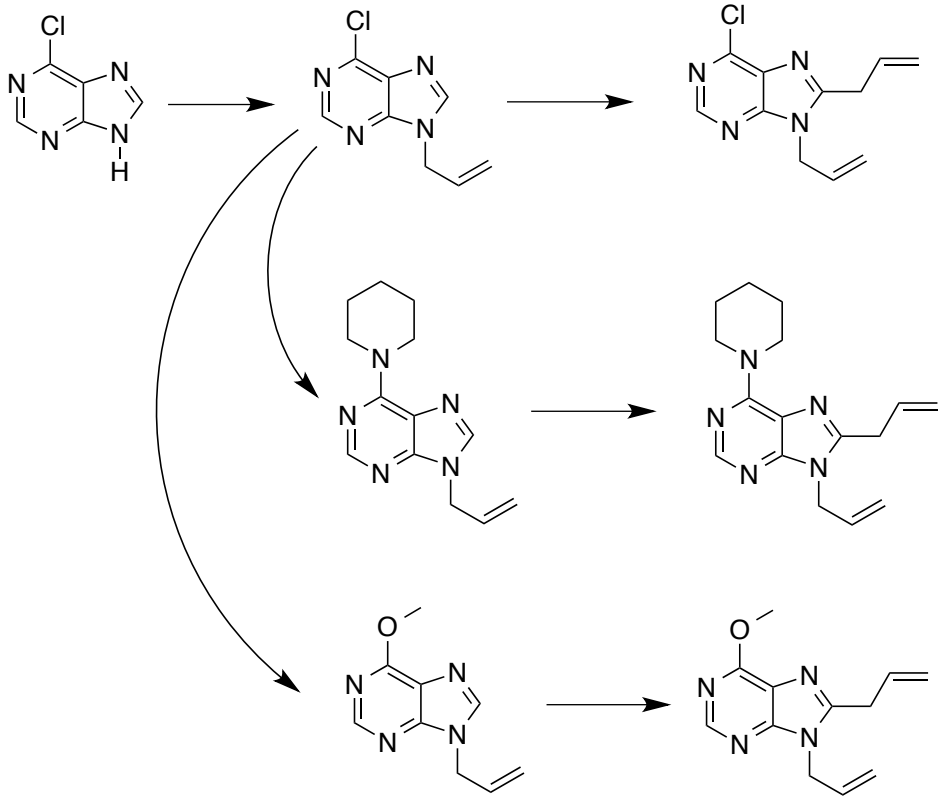
The addition of the organometals to purines produces the adducts which can conveniently be oxidized to convert back to purines. Allylmagnesium bromide added to 6-chloropurines **99**, resulting in the adduct **100**. The obtained compound **100** was oxidized with MnO_2 in DCM to give 8-allylated purines **101** with the satisfactory yield (**Scheme 2.35**).[33]



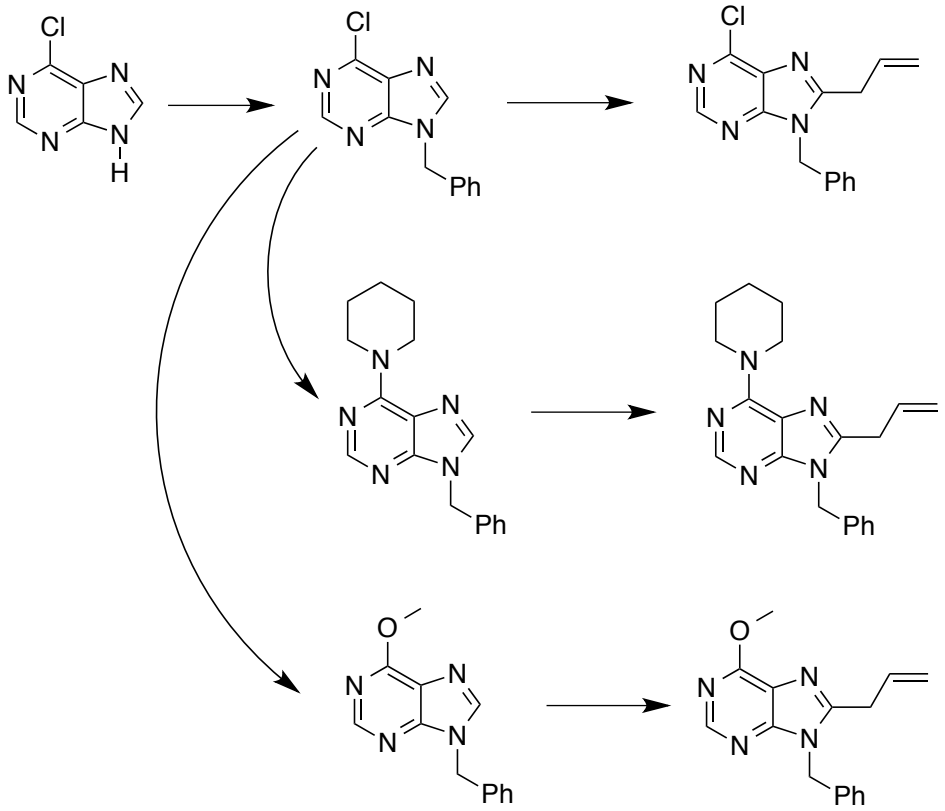
Scheme 2.35

3 Results and Discussion

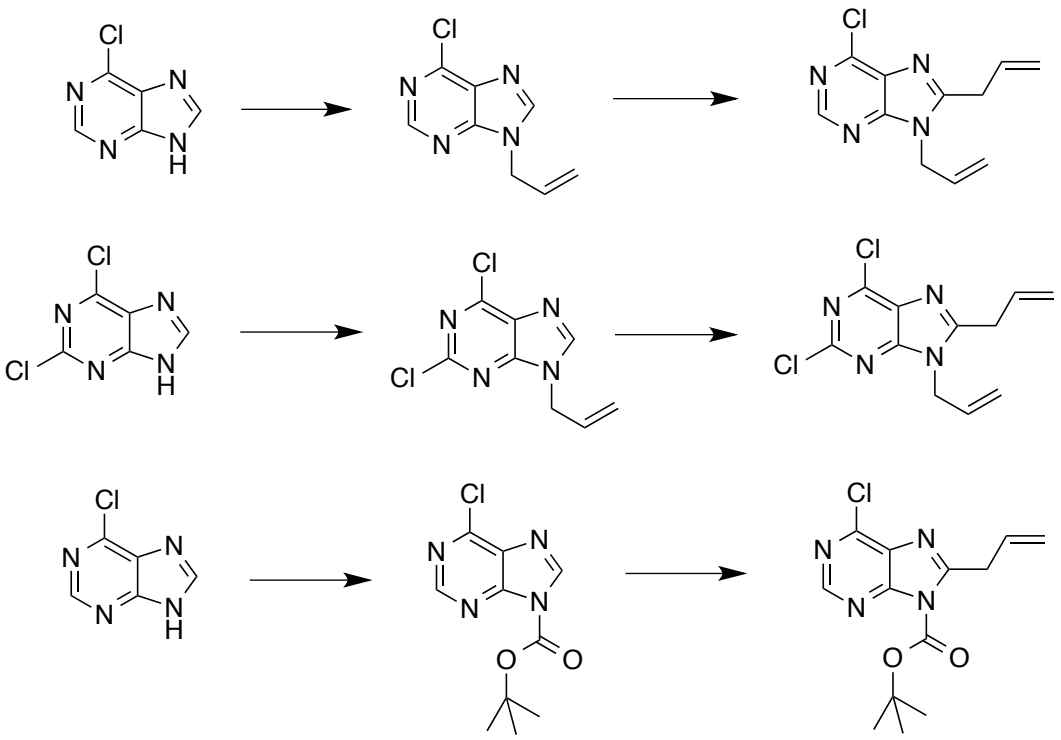
The project aims to study the addition of allylmetals to the purine 8-position. First, the addition was conducted with allylmagnesium bromide. **Scheme 3.1** and **Scheme 3.2** show the synthetic routes to obtain desired 8,9-diallylpurines and 8-allyl-9-benzylpurines from 6-cholorpurine. Second, other purines were added with the allylindium reagent. **Scheme 3.3** illustrates the synthetic routes to give desired 8-allylated purines from 6-chloropurine or 2,6-dichloropurine.



Scheme 3.1



Scheme 3.2



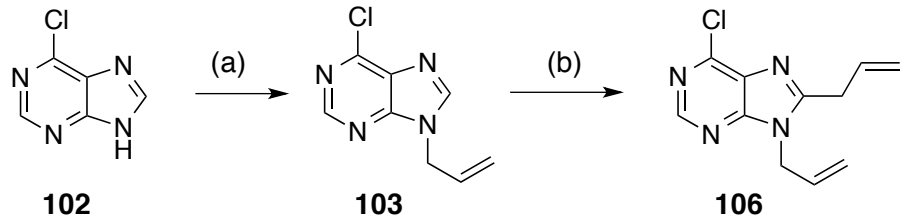
Scheme 3.3

3.1 C-8 addition *via* allylmagnesium bromide

This section focuses on the addition of allylmagnesium bromide to six purine substrates. The needed substrates first are prepared from 6-chloropurine.

3.1.1 Addition of allylmagnesium bromide to 9-allyl-6-chloro-*9H*-purine

The synthetic route from 6-chloropurine **102** to the desired 8-allylated purine **106** is shown in **Scheme 3.4**.

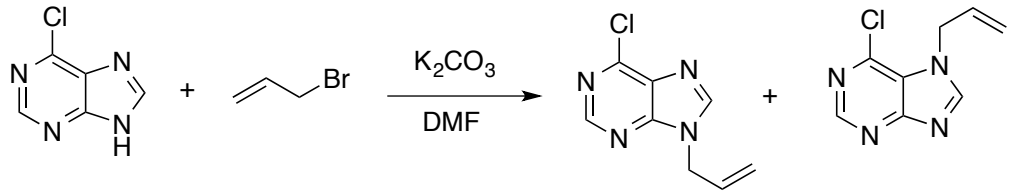


102 **103** **106**

Scheme 3.4: (a) N-alkylation, (b) C-8 allylation

Preparation of 9-allyl-6-chloro-*9H*-purine (103)

Compound **103** was prepared by the N-alkylation of 6-chloro-*9H*-purine **102** with allyl bromide in the presence of K_2CO_3 in dry DMF (**Scheme 3.5**). The reaction was conducted at room temperature under N_2-atm in 20 hours. The alkylation gave a mixture of N-9 and N-7 isomers, 9-allyl-6-chloro-*9H*-purine **103** and 7-allyl-6-chloro-*9H*-purine **104**. N-7 isomer was the minor product. According to the ^{1}H NMR spectrum of the crude product, the ratio of N-9 and N-7 isomers was 3:1 and the yields after isolation by flash chromatography were 58% and 20%, respectively. This reaction was reported with 59% for the N-9 isomer and 20% for the N-7 isomer.[34]

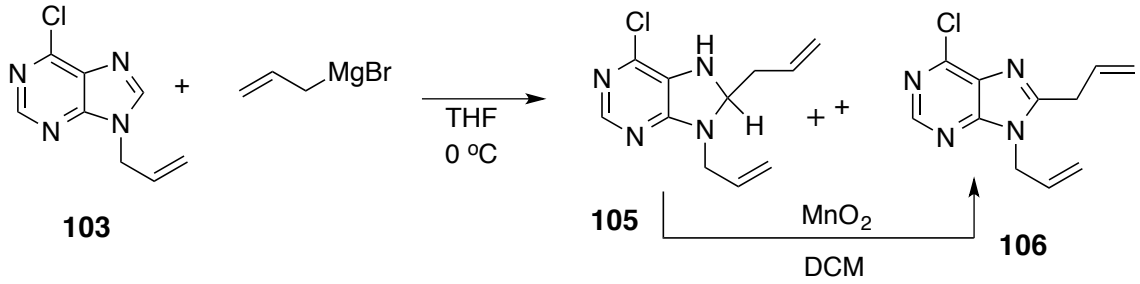


102 **103** **104**

Scheme 3.5

Synthesis of 8,9-diallyl-6-chloro-*9H*-purine (106)

Following the reported procedure,[33] 9-allyl-6-chloro-*9H*-purine **103** was allylated at the C-8 position via two steps. The addition step was carried out by adding allylmagnesium bromide to compound **103** at 0 ^{o}C in THF. The reaction produced mainly the adduct **105** containing non-aromatized imidazole ring. The second step was the oxidation of the crude product achieved from the first step with MnO_2 as an oxidizing agent. The oxidative reaction formed the rearomatized product **106** (**Scheme 3.6)**. Compound **106** was isolated with the yield of 56%. The same reaction was reported with the yield of 70% for compound **106**.[33]



103 **105** **106**

Scheme 3.6

Although employing the same procedure,[33] the yield of this reaction was lower than the one reported. It has been observed that the first step of this reaction took place as described in the report. That is full conversion after 20 minutes at 0 ^{o}C. However, the second step resulted in by-products that might contribute to the lower yield. Efforts were made to isolate the by-products, but the purification was not very successful. Based on the NMR and MS spectra of the obtained compound, the predicted structure was possibly a dimmer as shown in **Figure 3.1**. Further information on its spectra and peak assignments are listed in the **Appendix**.

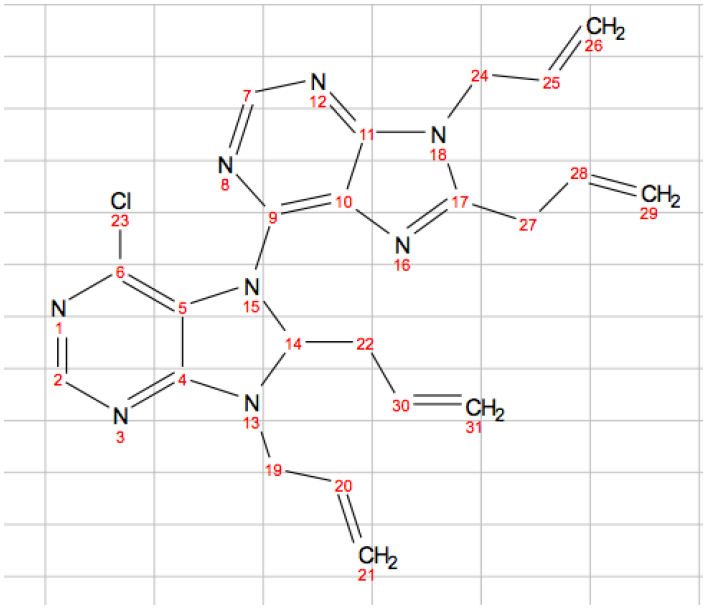
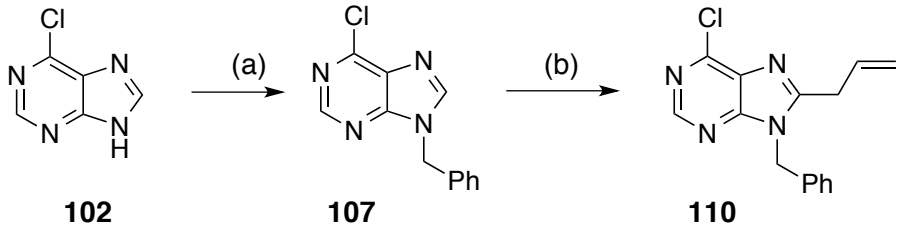


Figure 3.1: Predicted structure of the by-product

3.1.2 Addition of allylmagnesium bromide to 9-benzyl-6-chloro-*9H*-purine

The synthetic route from 6-chloropurine **102** to desired 8-allylated purine **110** is shown in **Scheme 3.7**.



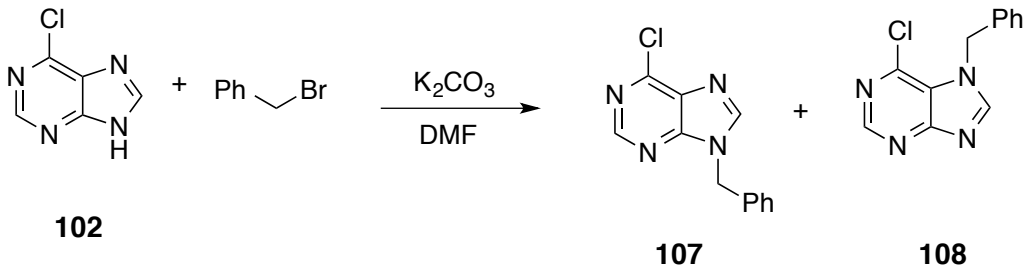
102 **107** **110**

Scheme 3.7: (a) N-alkylation, (b) C-8 allylation

Preparation of 9-benzyl-6-chloro-*9H*-purine (107)

9-Benzyl-6-chloro-9*H*-purine **107** and 7-benzyl-6-chloro-9*H*-purine **108** were obtained by treating 6-chloro-*9H*-purine **102** with benzyl bromide in K_2CO_3 and DMF for 22 hours (**Scheme 3.8**). N-9 isomer **107** was the major product. The ^{1}H NMR spectrum of the crude

product showed the ratio of the N-9 and N-7 isomers was 4:1. Yields of compounds **107** and **108** after isolation by flash chromatography were 57% and 20%, respectively. The reported yields for this reaction with a similar procedure were 66% for compound **107** and 25% for compound **108**.[41]

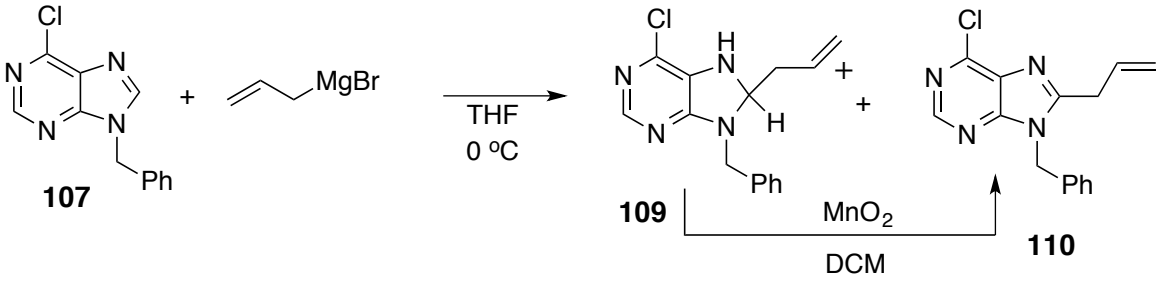


102 **107** **108**

Scheme 3.8

Synthesis of 8-allyl-9-benzyl-6-chloro-*9H*-purine (110)

C-8 Allylation of purines **107** *via* the Grignard reagent followed the previous procedure.[33] In the first step, allylmagnesium bromide was added to 9-benzyl-6-chloro-*9H*-purine **107** at 0 ^{o}C in THF. Mostly adduct **109** was formed in this step. Next, oxidation process was conducted with MnO_2 in DCM at room temperature to rearomatize the adduct, forming the desired product **110** (**Scheme 3.9**). Compound **110** was purified by flash chromatography to give 55% of the yield. Like the previous reaction between allylmagnesium bromide and 9-allyl-6-chloropurine **103**, this yield was not satisfactory due to the presence of by-products after the oxidation step. Unfortunately, the purification of these by-products was not successful.

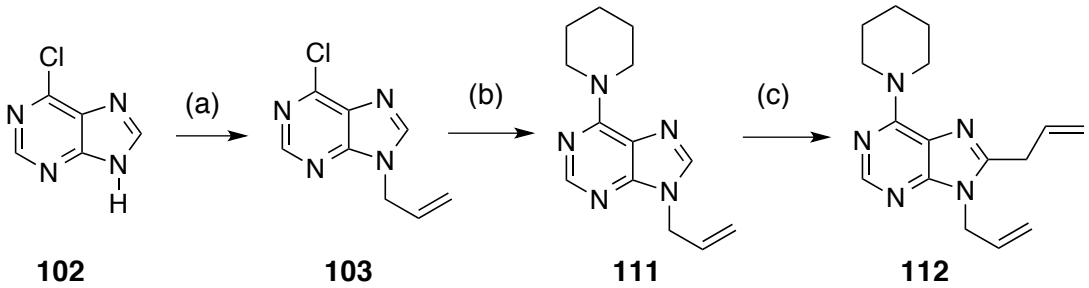


107 **109** **110**

Scheme 3.9

3.1.3 Addition of allylmagnesium bromide to 9-allyl-6-(piperidin-1-yl)-*9H*-purine

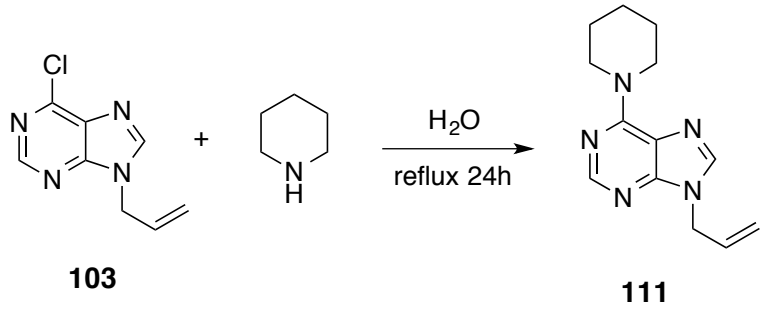
The synthetic route 8,9-diallyl-6-(piperidin-1-yl)-*9H*-purine **112** is oulined in **Scheme 3.10**.



Scheme 3.10: (a) N-alkylation, (b) C-6 piperidinylation, (c) C-8 allylation

Preparation of 9-allyl-6-(piperidin-1-yl)-*9H*-purine (111)

Compound **111** was prepared by amination of compound **103** with piperidine in H_2O, refluxing for 24 hours. The reaction gave 95% of the yield like the one reported (**Scheme 3.11**).[84] The reaction was relatively clean and did not need any further isolation method to purify the target product **111**.

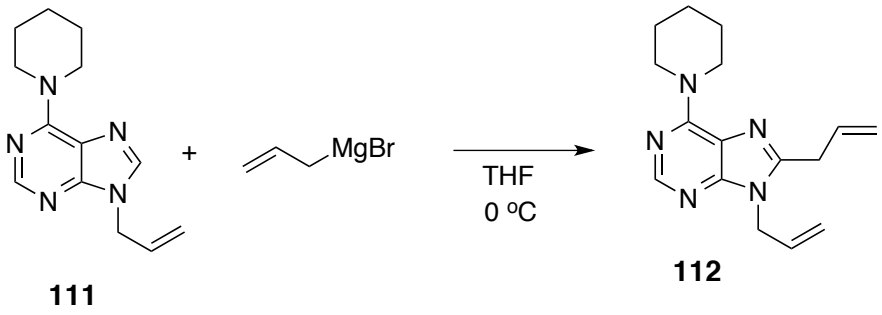


Scheme 3.11

Synthesis of 8,9-diallyl-6-(piperidin-1-yl)-*9H*-purine (112)

9-Allyl-6-(piperidin-1-yl)-*9H*-purine **111** was treated with 3.0 equivs. of allylmagnesium bromide in THF at 0 ^oC in 4 hours to obtain compound **112** (**Scheme 3.12**).[33] The conversion of this reaction was relatively low compared to the previous addition of 9-allyl-6-

chloropurine **103** with the Grignard reagent. The reason for the lower conversion may come from the electron density of the purine ring. The piperidinyl group donates electron to the purine ring by resonance, making it become richer, and consequently does not facilitate the addition of the Grignard reagent to the purine 8-position. The ^{1}H NMR spectrum of the crude product showed the ratio of the starting material **111** and the target product **112** was 3:1. The isolated yield was 24% compared to 89% in the literature.[33] The reaction time was increased up to 8 hours but the conversion remained unchanged (**Table 3.1**).



111 **112**

Scheme 3.12

Table 3.1

Allylmagnesium bromide (equivs.)	Reaction time (hours)	Ratio **111**:**112**
3.0	4	3:1
3.0	6	3:1
3.0	8	3:1

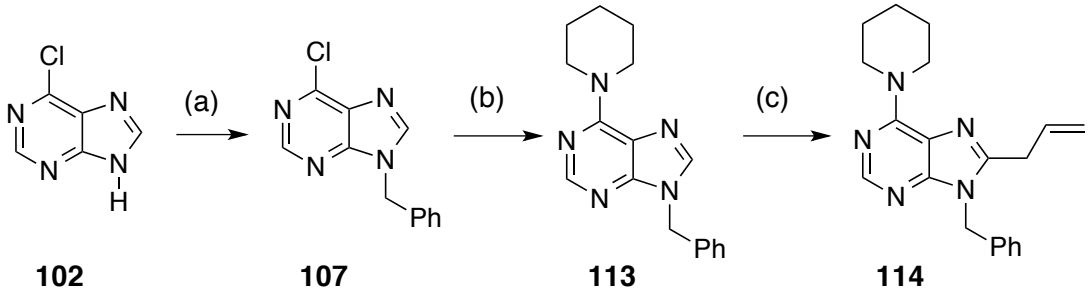
In this reaction, the formed adduct might be fully converted to the desired product **112** when exposing itself to the oxygen in the air during the work-up.

Former Master student reported 100% conversion for this reaction when 3.0 equivs. of the Grignard reagent was used while this attempt only achieved 25%. The inconsistency of the two conversions might come from the titrate techniques that led to different molar proportions of the Grignard reagent used in these reactions. However, full conversions obtained from the addition of 3.0 equivs. of allylmagnesium bromide to both 9-allyl-6-

chloropurine **103** and 9-allyl-6-(piperidin-1-yl)purine **111,** although the electron density of the purine ring in the two compounds are relatively distinctive, needs to be further inspected.

3.1.4 Addition of allylmagnesium bromide to 9-benzyl-6-(piperidin-1-yl)-*9H*-purine

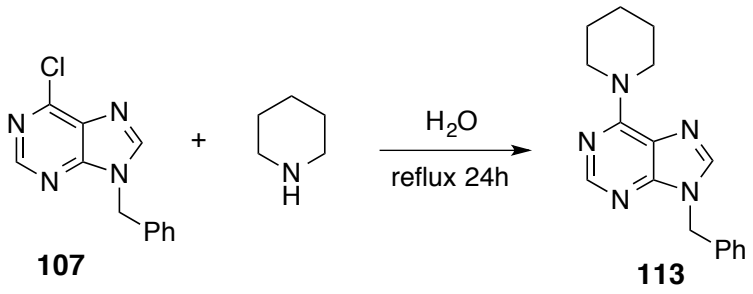
The synthetic route to obtain the desired product 8-allyl-9-benzyl-6-(piperidin-1-1yl)-*9H*-purine **114** is sketched in **Scheme 3.13**.



Scheme 3.13: (a) N-alkylation, (b) C-6 piperidinylation, (c) C-8 allylation

Preparation of 9-benzyl-6-(piperidin-1-yl)-*9H*-purine (113)

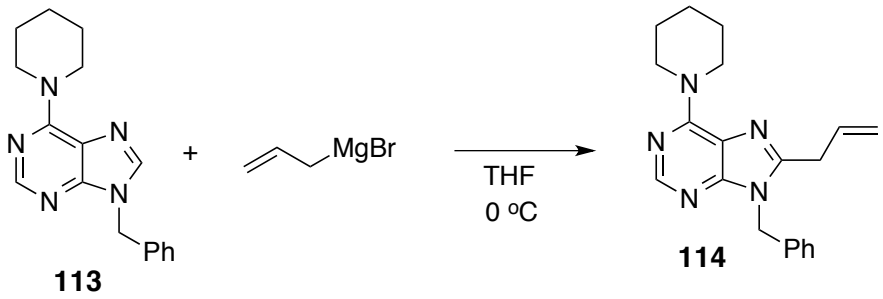
Refluxing compound **107** for 24 hours with the presence of piperidine in H_2O formed piperidine derivative **113** (**Scheme 3.14**). Like the piperidylation of 9-allylated-6-chloropurine **103**, this reaction was relatively clean and therefore the desired product **113** was obtained by extraction with DCM, without the need of further purification methods. The yield of the reaction was 95%.



Scheme 3.14

Synthesis of 8-allyl-9-benzyl-6-(piperidin-1-yl)-*9H*-purine (114)

3.0 equivs. of allylmagnesium bromide was added to the substrate **113** at 0 °C in THF. The reaction time was 4 hours, resulting in 50% of conversion (**Scheme 3.15**). The desired product **114** was purified by flash chromatography to give 42% of the yield.



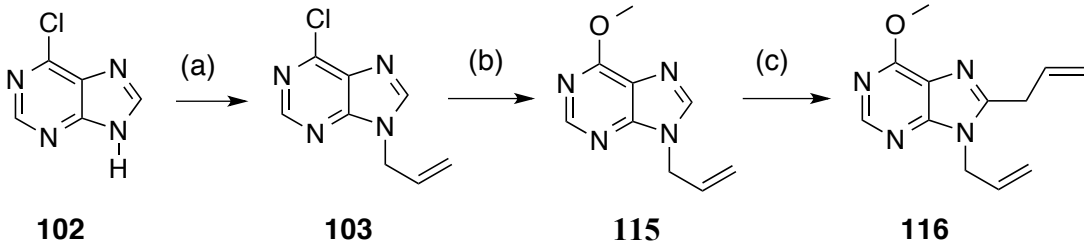
Scheme 3.15

Similar to the formation of compound **112**, the adduct resulted from the addition of the Grignard reagent might be completely converted to the rearomatized product **132** in presence of the oxygen in the air during the work-up.

The conversion of this reaction is 50% lower than that of 8-allyl-9-benzyl-6-chloropurine **110**. As previously discussed, the electron donation by resonance of the piperidinyl group to the purine ring may contribute to the decline of the conversion in the addition reaction. Furthermore, this conversion is 25% higher than that of 8,9-diallyl-6-(piperidin-1-yl)purine **112**, although the allylic and benzylic groups in the two compounds, **112** and **114**, share structural similarity. This difference need to be further inspected.

3.1.5 Addition of allylmagnesium bromide to 9-allyl-6-methoxy-*9H*-purine

The pathway to synthesize the target molecule 8,9-diallyl-6-methoxy-*9H*-purine **116** is presented in **Scheme 3.16**.

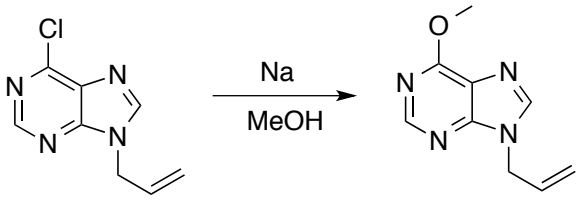


102 **103** **115** **116**

Scheme 3.16 (a) N-alkylation, (b) C-6 methoxylation, (c) C-8 allylation

Preparation of 9-allyl-6-methoxy-*9H*-purine (115)

Treating compound **103** with sodium methoxide solution, which was prepared by adding sodium metal into dry methanol, obtained compound **115** (**Scheme 3.17**). The desired product **115** was purified by flash chromatography to give 97% of the yield. The literature reported the same yield.[85]

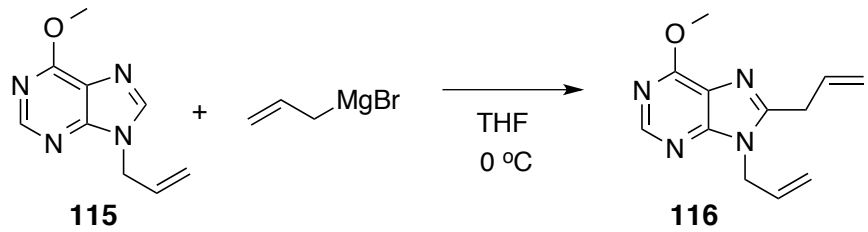


103 **115**

Scheme 3.17

Synthesis of 8,9-diallyl-6-methoxy-*9H*-purine (116)

Allylmagnesium bromide (3.0 equivs.) was added to 9-allyl-6-methoxy-*9H*-purine **115** in THF (**Scheme 3.18**). The mixture was stirred at 0 ^{o}C in 4 hours. The conversion ratio between **115** and **116** was 3:7 and the desired product was isolated with the yield of 57%. Like the piperidinyl group, the methoxide group also enriches the purine ring by resonance effect and results in lower conversion compared to the addition to 9-allyl-6-chloropurine **103**. In an effort to improve the conversion, the reaction time was increased up to 24 hours. However, there was no improvement observed with the ^{1}H NMR of the crude product.



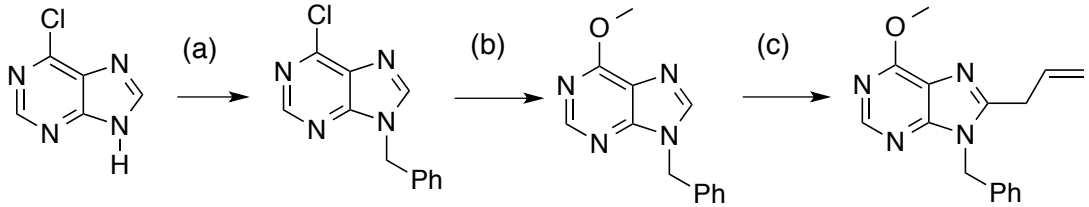
115 **116**

Scheme 3.18

Like the allylation of 6-piperidylated purines **112** and **114**, the rearomatization to form the desired product **116** occurs during the work-up due to the oxygen in the air.

3.1.6 Addition of allylmagnesium bromide to 9-benzyl-6-methoxy-*9H*-purine

The target product 8-allyl-9-benzyl-6-methoxy-*9H*-purine **118** was synthesized in the sequence sketched in **Scheme 3.19**.

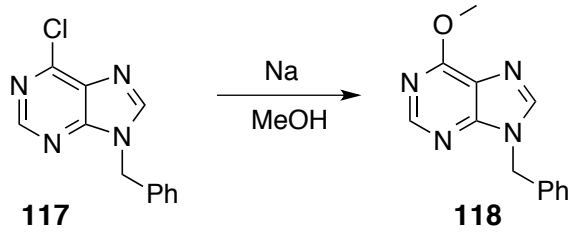


102 **107** **117** **118**

Scheme 3.19: (a) N-alkylation, (b) C-6 methoxylation, (c) C-8 allylation

Preparation of 9-benzyl-6-methoxy-*9H*-purine (117)

Methoxidation of 9-benyl-6-chloro-*9H*-purine **107** with sodium methoxide solution, which was resulted from mixing sodium metal in dry methanol, (**Scheme 3.20**), formed 9-benzyl-6-methoxy-*9H*-purine **117**. The product **117** was purified by flash chromatography to afford 96% of the yield.

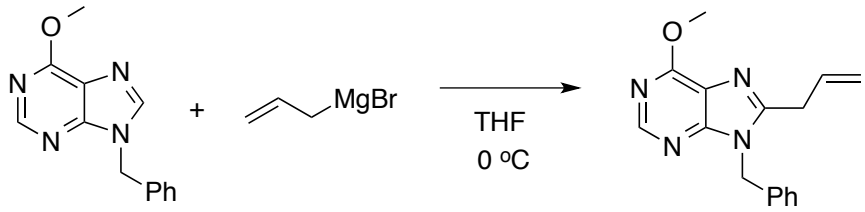


117 **118**

Scheme 3.20

Synthesis of 8-allyl-9-benzyl-6-methoxy-*9H*-purine (118)

8-Allyl-9-benzyl-6-methoxy-*9H*-purine **118** was synthesized by adding 3.0 equivs. of allylmagnesium bromide to compound **117** at 0 ^{o}C in THF (**Scheme 3.21**). The reaction was stirred in 4 hours and the conversion ratio between **117** and **118** was 3:7. This conversion was similar to that of 9-allyl-6-methoxypurine **115** because the two compounds, **115** and 9-benzyl-6-methoxypurine **117**, share structural resemblance. Compound **118** was purified by flash chromatography to give 44% of the yield. Increasing the reaction time up to 8 hours could not improve the conversion based on the ^{1}H NMR of the crude product.



117 **118**

Scheme 3.21

Like several previous reactions, the desired product **118** was achieved from the oxidation of the adduct probably by the oxygen in the air during the work-up.

3.1.7 Conclusion

Six purine substrates had been studied for addition of the Grignard reagent to the purine C-8 position. In all cases, 3.0 equivs. of allylmagnesium bromide was used but the conversion of these reactions varied with regards to the substrates. When 6-chloropurines, *i.e.* compounds

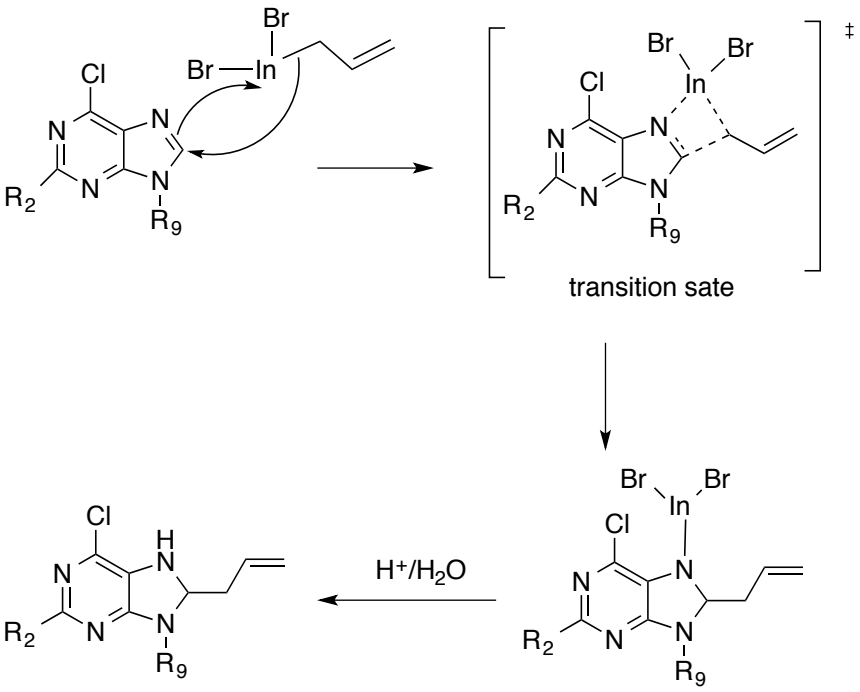
103 and **107**, were used, full conversion was observed after 20 minutes of the reaction. The conversion was moderate in the cases of 6-methoxylated purines, *i.e.* compounds **115** and **117**, and was relatively low with 6-piperidinylated purines, *i.e.* compounds **111** and **113**.

The differences in the conversion of these addition reactions lie in the electron-poverty of the purine ring. Chloride is an electron-withdrawing group and therefore reduces the electron density of the purine ring and facilitates the addition to the purine 8-position. In contrast, methoxide and piperidinyl groups donate electron to the purine ring by resonance effect and increase electron density of the purine ring. This may hamper the addition of the Grignard reagent to the purine 8-position and explains for the incomplete conversion of the above four reactions. Furthermore, the electron-withdrawing inductive effect caused by the oxygen atom in the methoxide group is stronger than that of the nitrogen atom in the piperidinyl group. As the result, the addition to 6-methoxide may be easier, giving better conversion.

The adduct, resulted from the addition step needs to be oxidized to rearomatize the purine ring. However, the adduct may or may not be observed by ^{1}H NMR spectrum of the crude product. Formed adduct, resulted from the addition to 6-methoxylated purines and 6-piperidinylated purines, may be converted to the rearomatized product probably due to the oxygen in the air. In contrast, the adduct, derived from the addition to 6-chloropurines, was achieved as the major product after the addition step and was treated with MnO_2 to retrieve the aromaticity. It suggests that the electron density of the substrate determines the need of a special oxidizing agent for the rearomatization of the adduct. If the substrate is electron rich, *i.e.* 6-methoxylated purines and 6-piperidinylated purines, then the adduct can be rearomatized quickly by oxygen in the air. If the substrate is electron poor, *i.e.* 6-chloropurines, MnO_2 is necessary to convert all the adduct to 8-alkylated purines.

3.2 C-8 addition *via* allylindium reagent

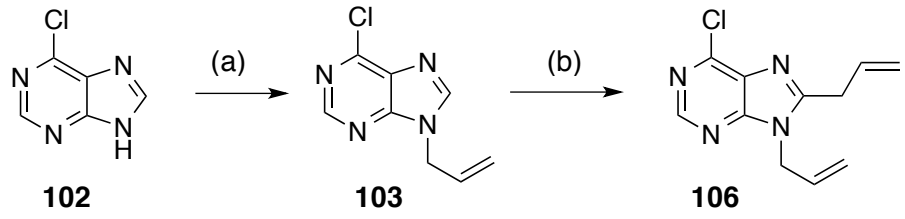
In the following reactions, allylindium reagent was employed for C-8 allylation of the substrates. Due to the structural similarity between allylmagnesium bromide and allylindium dibromide, the addition mechanism of allylindium dibromide to the purine 8-position is proposed in **Scheme 3.22**.



Scheme 3.22: Proposed mechanism of the addition of allylindium species to the C-8 position of purines to form the adduct

3.2.1 Addition of allylindium bromide to 9-allyl-6-chloro-*9H*-purine

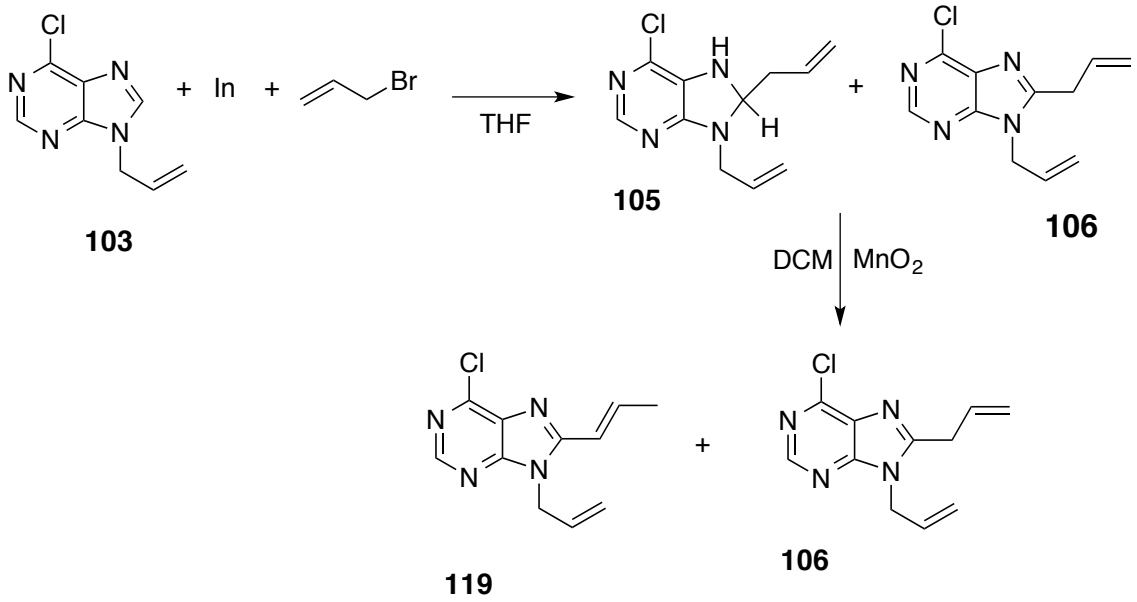
The target product 8,9-diallyl-6-chloro-*9H*-purine **106** was synthesized in the sequence sketched in **Scheme 3.23**.



Scheme 3.23: (a) N-alkylation, (b) C-8 allylation

Synthesis of 8,9-diallyl-6-chloro-*9H*-purine (106)

8,9-Dialllyl-6-chloro-*9H*-purine **106** was synthesized following the reported procedure.[34] First, allylindium dibromide generated *in situ* was added to 9-allyl-6-chloro-*9H*-purine **103** in THF. The reaction was carried out at room temperature in 24 hours, forming mainly adduct **105**. The second step involved the oxidation of the adduct with MnO_2, obtaining the aromatized product **106** (**Scheme 3.24**). It was observed that there was a migration of double bond in the allylic group attached to the purine C-8 position during the purification (based on the analysis of the NMR spectra of the purified product). Migrated allylic group had not been seen in the ^{1}H NMR spectrum of the crude product of the oxidation step.



Scheme 3.24

The ratio of reactants, starting material **103**:indium:allyl bromide, and the conditions of the reaction were varied to study the conversion of the substrate (**Table 3.2**)

The first attempt (**Table 3.2**, Entry **1**) was done by adding indium powder (8 equivs.) and allyl bromide (12 equivs.) to compound **103** in THF following the reported procedure of the former Master student Victor Marzouk.[34] The reaction was carried out for 24 hours at room temperature, achieving 90% of conversion, mainly the adduct **105** (based on ^{1}H NMR

spectrum of the crude product). The crude product then was treated with oxidizing agent, MnO_2, to rearromatize the adduct. The purification gave 63% of the mixture of two isomers **106** and **119** with the ratio of 93:7, respectively. These two isomers could not be separated by flash chromatography. According to the ^{1}H NMR spectrum of the compound **119**, the coupling constant 15.6 Hz suggested that the isomer has an *E*-alkene structure.[86] The moderate yield (63%) was obtained despite of high conversion (90%) due to difficulties during the work-up of the first step. The reaction mixture produced thick emulsion in saturated NH_4Cl solution and diethyl ether solvent that contributed to the yield loss.

In the second attempt (**Table 3.2**, Entry **2**), the reaction was repeated but the saturated NaCl solution was employed in the work-up. Unfortunately, thick emulsion was still a challenge. The conversion was achieved 90% based on the ^{1}H NMR spectrum of the crude product of the first step. The isolated yield was 63% of mixture of two isomers **106** and **119** with 56:44 distributions. These distributions are much different from the ones in the first attempt but the reason has not been understood.

In the third attempt (**Table 3.2**, Entry **3**), the proportion of reactants, compound **103**:indium: allyl bromide, was reduced to 1:4:6 in order to avoid the emulsion issue and reduce the excessive amount of the expensive indium metal. In this case, the ultrasound bath was employed to maintain the high conversion. The reaction was stirred for 27 hours at room temperature, first 11 hours in the ultrasound bath. The sonicator could not operate over night without care because the heat being produced warmed the reaction mixture. When the ultrasound bath was employed, the adduct **105** was formed sooner than the previous attempts. The conversion in the addition step was 67% and the emulsion was reduced but still a problem during the work-up. The crude product subsequently was oxidized to obtain two isomers **106** and **119** with the ratio of 79:21, respectively.

The ratio of reactants was reduced to 1:2:3 (**Table 3.2**, Entry **4**) to suppress the emulsion during work-up. The conversion in the first step was 50%, the emulsion was no longer a problem for the work-up. The isolated yield by flash chromatography was 47% of the mixture **106** and **119** with the distribution of 96:4, respectively.

Table 3.2 summarizes the discussed attempts of the addition of various proportions of allylindium species to 9-allyl-6-chloropurine **103**. The achieved distributions of the two

isomers **106** and **119** were significantly different but the reason for such achievements are not understood.

Table 3.2

Entry	**103**:In: Allyl Br	Conditions (First step)	Sonicator	Conversion [a] (First step)	Yield[b] (**106**+**119**)	**106:119**
1	1:8:12	24 h, work-up with NH_4Cl	-	90%	63%	93:7
2	1:8:12	24 h, work-up with NaCl	-	90%	63%	56:44
3	1:4:6	27 h, work-up with NaCl	Bath (11 h)	67%	-[c]	79:21
4	1:2:3	28 h, work-up with NaCl	Bath (11.5 h)	50%	47%	96:4

a: According to the ^{1}H NMR spectrum of the crude product in the first step.

b: The oxidation steps took place in the same conditions

c: The yield was not accurate due to grease in ^{1}H NMR spectrum.

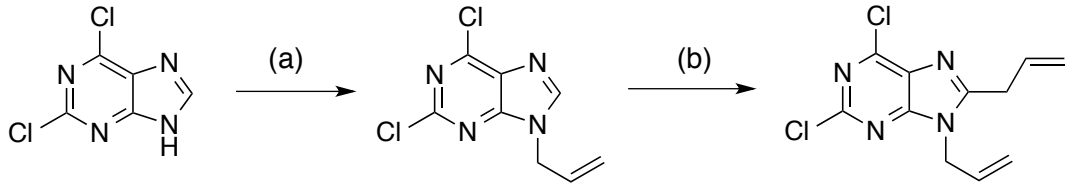
Another ultrasonic source was employed in hope of improving the conversion. It was an ultrasonic probe, which was placed submerged in the reaction mixture. Unfortunately, the employment of probe was not successful after several attempts. However, unsuccessful results might not come from the probe, but the new indium source. The quality of the indium was poor and that was confirmed when the reaction did not work in the same condition of the previous successful attempts. Because the new batch of indium was not in good quality, a treating procedure was applied to probably remove its oxidized surface that prevented the reaction.[87] The treated indium worked as one in the first batch, which was in good quality. These attempts are summarized in **Table 3.3**.

Table 3.3: Reactions when indium metal with poor quality with and without being treated

Entry	**103**:In: Allyl Br	Treated indium	Conditions (First step)	Sonicator	Conversion [a]
1	1:2:3	No	24 h	Probe (8 h)	-
2	1:2:3	No	24 h	Bath (11 h)	-
3	1:2:3	Yes	28 h, work-up with NaCl	Bath (11 h)	50%

3.2.2 Addition of allylindium bromide to 9-allyl-2,6-dichloro-*9H*-purine

It is assumed that electron deficient purines could give better addition at the C-8 position. 9-Allyl-2,6-dichloro-*9H*-purine **120** was chosen as the substrate to inspect the assumption. The pathway for allylation at the C-8 position is shown in **Scheme 3.25.**



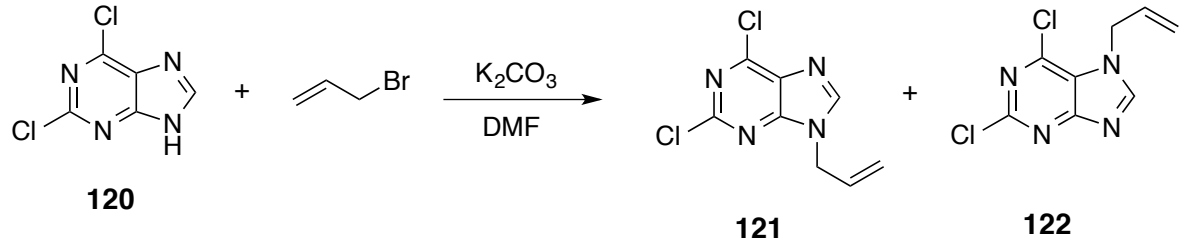
120 **121** **124**

Scheme 3.25: (a) N-alkylation, (b) C-8 allylation

Preparation of 9-allyl-2,6-dichloro-*9H*-purine (121)

Allylation of compound 2,6-dichloro-9*H*-purine **120** in the presence of K_2CO_3 in DMF gave mixtures of two isomers 9-allyl-2,6-dichloro-9*H*-purine **121** and 7-allyl-2,6-dichloro-9*H*-purine **122**, highly favoring compound **121** (**Scheme 3.26**). The ^{1}H NMR spectrum of the crude product showed the ratio of N-9 and N-7 isomers was 7:3 and the yields after isolation

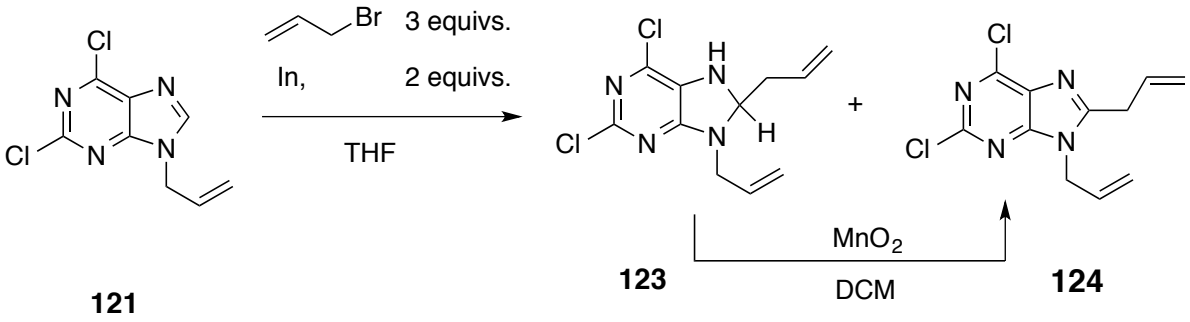
were 65% and 26%, respectively. In the literature, compounds **121** and **122** were formed with 73% and 18.5%, respectively *via* the Mitsunobu reaction but the drawback of this reaction was the hardship of removing hydrazine and phosphine oxide from the target products.[88]



120 **121** **122**

Scheme 3.26

Synthesis of 8,9-diallyl-2,6-dichloro-*9H*-purine (124)



121 **123** **124**

Scheme 3.27

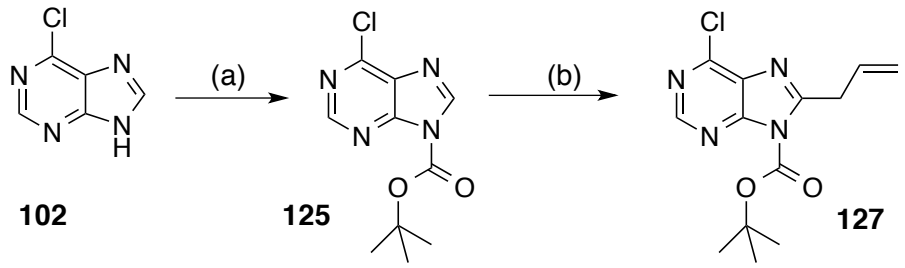
Allyl bromide (3 equivs.) was added to the mixture of indium powder (2 equivs.) in THF. The reaction mixture was sonicated in 30 minutes before being added with compound **121**. Note that after the failed attempts with the ultrasound probe, the later reactions with indium were carried out in the ultrasound bath, and indium powder was processed before each reaction. The mixture was stirred for 28 hours, first 10 hours in the ultrasound bath, forming mainly the adduct **123**. The crude product in step one was treated with MnO_2 to achieve the desired product **124** (**Scheme 3.27**).

In this reaction, the conversion was ca. 79% in first step, and the adduct was completely converted after the oxidation step. However, the isolated yield was 44%. Some amount of the

desired product might be lost during the separation process. Fortunately, the double migration was not observed in the target product.

3.2.3 Addition of allylindium bromide to *tert*-butyl-6-chloro-*9H*-purine-9-carboxylate

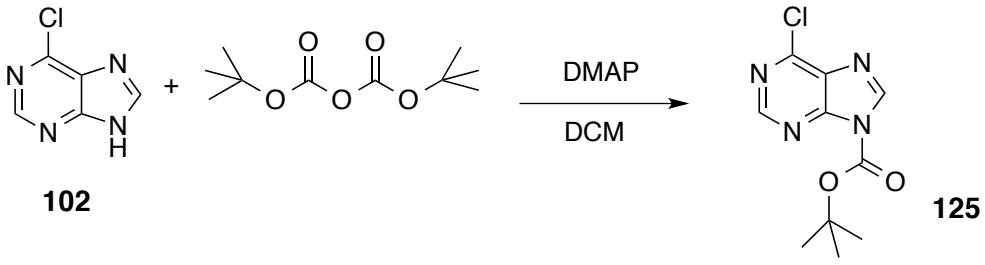
Another electron deficient purine derivative, *tert*-butyl-6-chloro-*9H*-purine-9-carboxylate **125**, was selected for the allylation. The desired synthetic route is shown in **Scheme 3.28**



Scheme 3.28: (a) N-Acylation, (b) C-8 allylation

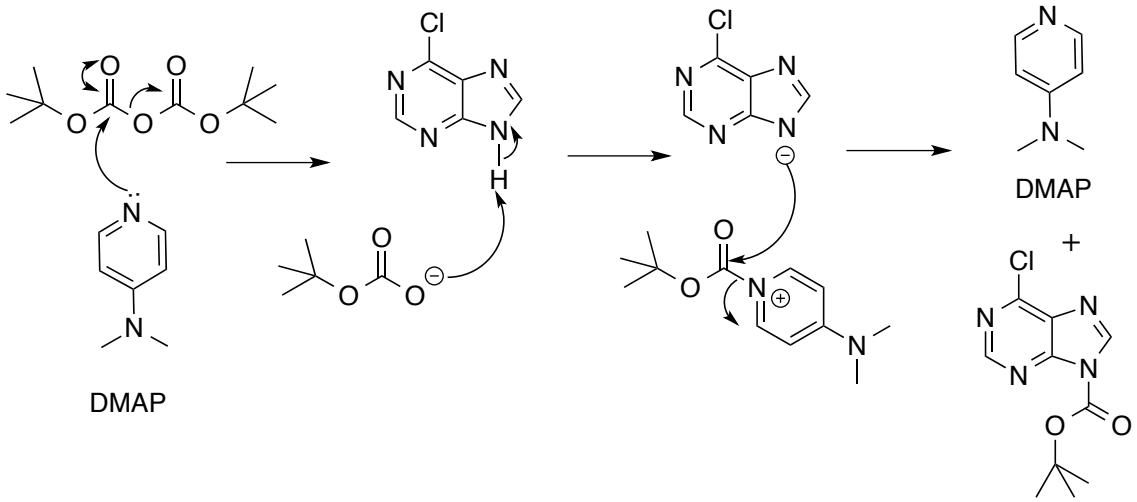
Preparation of *tert*-butyl-6-chloro-*9H*-purine-9-carboxylate (125)

Following the procedure reported in the literature,[89] *tert*-butyl-6-chloro-*9H*-purine-9-carboxylate **125** was prepared by adding di-*tert*-butyl-dicarbonate (Boc_2O) and DMAP (4-dimethylaminopyridine) to 6-chloropurine **102** in DCM (**Scheme 3.29**). The target product **125** was formed and purified by flash chromatography in silica gel, achieving 94% of isolated yield. In the report[89] that produced the procedure, 89% of the yield was obtained by the crystallization.



Scheme 3.29

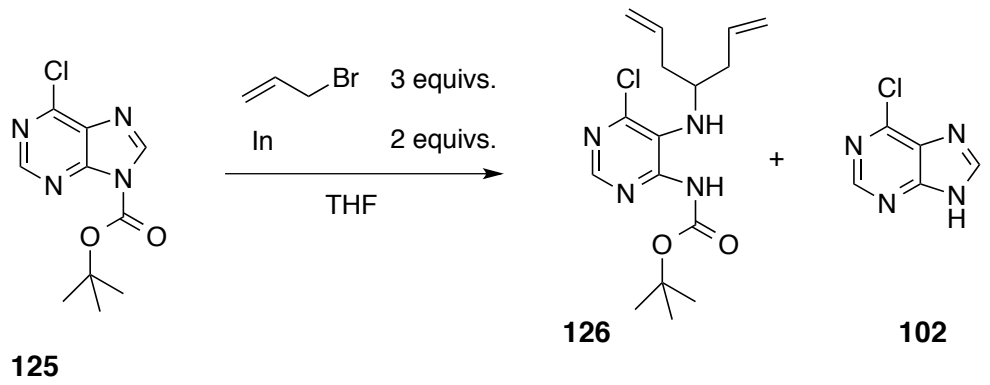
The mechanism of the reaction shown in **Scheme 3.29** is sketched in **Scheme 3.30**. DMAP works as a nucleophilic catalyst and attacks the carbonyl side of Boc_2O, forming 1-acyl pyridinium salt and releasing *tert*-butyl-carbonate anion. This anion works as a base which deprotonates the 6-chloropurine. The protonated purine attacks the Boc pyridinium salt, returning DMAP. The role of DMAP in this reaction is to form the Boc pyridinium salt, which is more reactive than parent anhydride, promoting the acylation.



Scheme 3.30

Addition of allylindium bromide to *tert*-butyl-6-chloro-*9H*-purine-9-carboxylate causes ring opening

Allyl bromide (3 equivs.) was added to the mixture of indium powder (2 equivs.) in THF. The reaction mixture was sonicated in 30 minutes before being added with compound **125**. After being sonicated in 3 hours, the starting material **125** was gone. The isolation process gave two products but none of them was the desired product. The first product was compound **126** and the second product was 6-chloropurine **102** (**Scheme 3.31**). The yields of the two compounds were 33% and 32%, respectively.

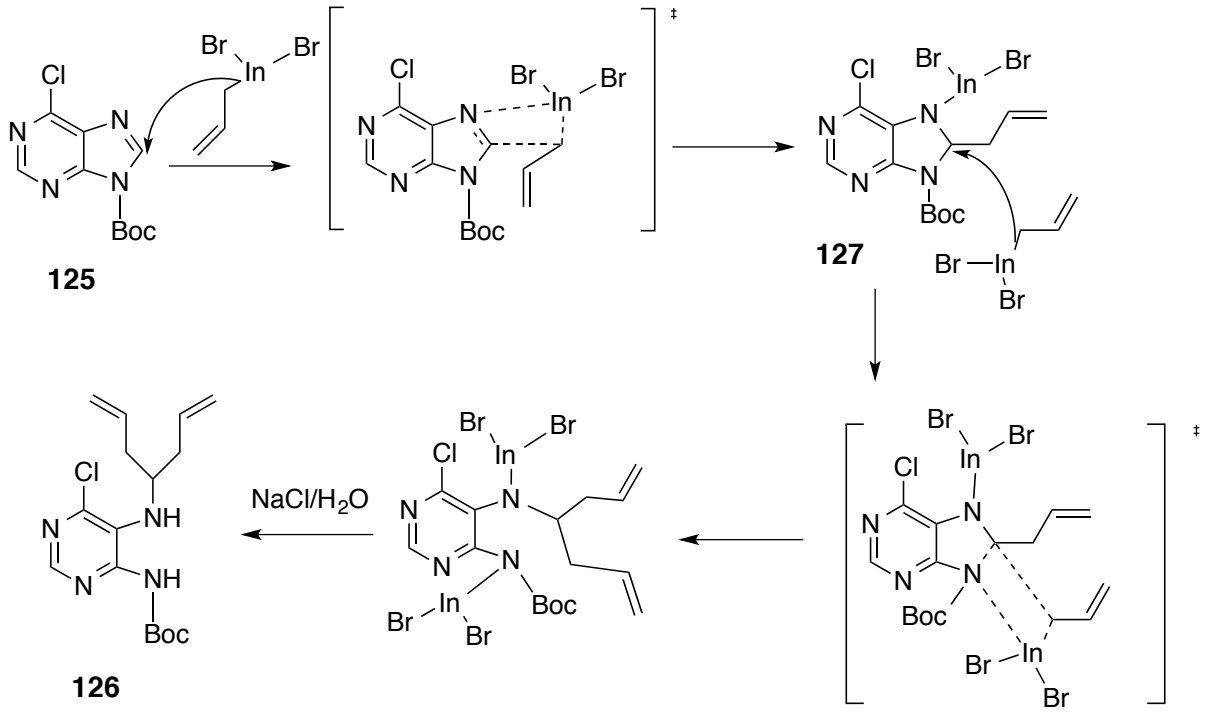


125 **126** **102**

Scheme 3.31

The formation of 6-chloropurine is easily recognized. The generated allylindium dibromide attacks the carbonyl group in the *tert*-butyl-carbonate (Boc), releasing 6-chloropurine because it is a better leaving group than *tert*-butoxide group.

The mechanism forming the compound **126** is suggested in **Scheme 3.32.** First, the allylic group in the allylindium dibromide adds to the purine 8-position of the compound **125**, forming the adduct **127**. Since Boc is a relatively strong electron-withdrawing group, the sigma bond between the C-8 and N-9 positions is highly polarized towards the N-9. The polarization of the bond attracts the attack of another allylic groupfrom the allylindium species. The attack takes place at the C-8 position, breaking the sigma bond, opening the five-membered heterocycle and forming the compound **126** that contains two allylic groups.



Scheme 3.32

3.2.4 Conclusion

The allylindium reagent can add to the 8-position purines as the Grignard reagent. However, with the same substrate, *i.e.*9-allyl-6-chloropurine, the Gignard reagent is more reactive than the allylindium reagent. Specially, the addition to 9-allyl-6-chloropurine gave full conversion with 3.0 equivs. of allylmagnesium bromide after 20 minutes while 4 equivs. of allylindium bromide (indium:allyl bromide = 8:12) resulted in 90% of conversion after 24 hours of reaction. Furthermore, the employment of high molar proportion of allylindium bromide caused thick emulsion during the work-up and contributed to the yield loss. Unfortunately, the decreasing of the indium proportion led to the lowering of the conversion. It was found that an ultrasonic source could significantly improve the conversion of the reaction.

Like Grignard reagent, the allylindium reagent adds to purine 8-position more readily if the purines are more electron-deficient. As the result, the conversion of the addition was 50% with 9-allyl-6-chloropurine, 79% with 9-allyl-2,6-dichloropurine, and 100% with *tert*-butyl-6-chloropurine-9-carboxylate. However, the addition to highly electron poor purines can lead to ring opening, forming undesired products (not 8-allylated purines).

4 Conclusion and further work

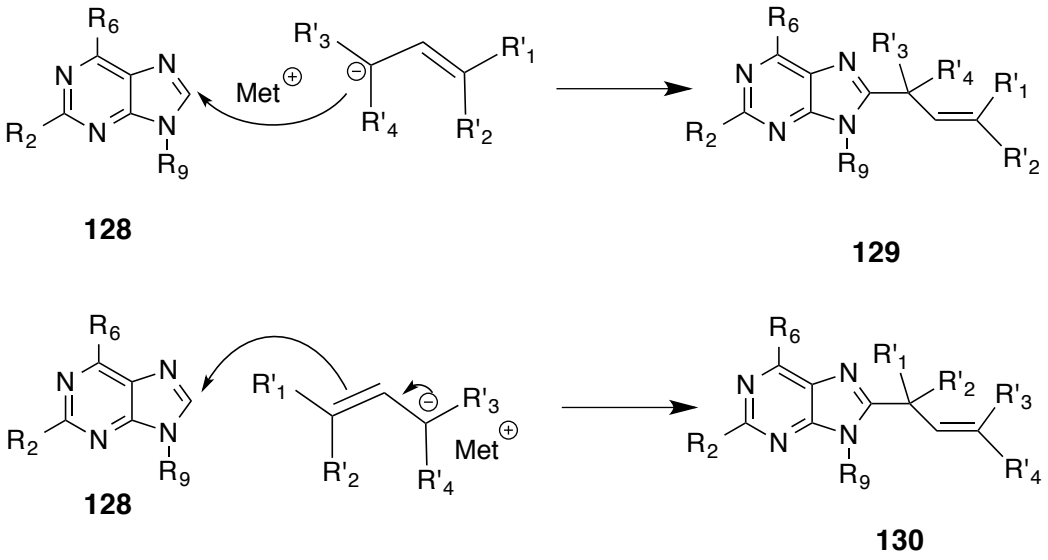
The Grignard reagent, *i.e.* allylmagnesium bromide, and the allylindium reagent can add their allylic groups to the 8-unsubstituted purines at the C-8 position. The addition forms purine-based adducts which is subsequently oxidized to give corresponding 8-allylated purines.

It can be concluded that the electron density of the purine ring in the purine substrates influences the addition of the allylmetals to the purine 8-position. If the substituents on the purine ring are electron-withdrawing groups, they may impoverish the electron density of the ring and consequently facilitate the addition, resulting in good conversion to the adducts. In contrast, the electron-donating substituents may enrich the purine ring and hamper the addition. However, the high electron poverty of the imidazole moiety, despite facilitating the addition of the allylmetals to the C-8 position, may cause ring opening after the addition, forming undesired products (not 8-allylated purines).

The rearomatization of the adducts is conducted though an oxidation process with the presence of an oxidizing agent. It can also be concluded that if the substrates are electron rich, the corresponding adducts can be fully converted to the 8-allylated purines by the oxygen in the air during the work-up. In contrast, the adducts derived from electron-deficient purines can only fully oxidized to the rearomatized products with the aid of a stronger oxidizing agent such as manganese dioxide.

This work can be expanded with the addition of substituted allylmetals to the purine 8-position. The substituted allylmetals may add to the purines **128** in two different ways giving rise to two regioisomers **129** and **130** as shown in **Scheme 4.1**. The formation of the two regioisomers with respect to the specific substituted allylmetals needs to be further inspected.

Double bond migration occurred during the separation process to isolate the 8-allylated purines but the mechanism for such transformation are not understood and may be subject to further investigation.



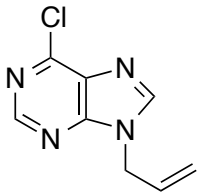
Scheme 4.1

5 Experimental

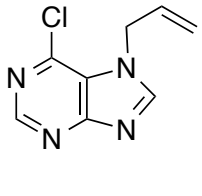
The ^{1}H NMR spectra were acquired on a 400 MHz on a Bruker AVII 400 instrument or at 300 MHz on a Bruker Avance DPX 300 instrument and the 1H decoupled. 13C NMR spectra were recorded at 100 MHz using the Bruker AVII 400 spectrometer. Assignments of 1H and 13C resonances were based on HMBC and HSQC NMR. Mass spectra under electron impact conditions were recorded with a VG Prospec instrument at 70 eV ionizing voltage, and are presented as *m/z* (% rel. int.). Electrospray MS spectra were recorded with a Bruker Apex 47e FT-ICR mass spectrometer. Dry THF, DCM, DMF were obtained from a solvent purification system, MB SPS-800 from MBraun, Garching, Germany. Melting points were determined on a Büchi Melting Point B-545 apparatus.

Allyl magnesium bromide in the presence of 1,10-phenanthroline as a color-indicator, was titrated with the solution of 1M sec-butyl alcohol in xylene.[90]

Synthesis of 9-allyl-6-chloro-9*H*-purine (103) and 7-allyl-6-chloro-7*H*-purine (104)



103



104

Potassium carbonate (4.15 g, 30.0 mmol) was added to a stirred solution of 6-chloropurine **102** (1.58 g, 10.2 mmol) in dry DMF (40 mL) at ambient temperature under N_2-atm. After 20 min., allyl bromide (1.70 mL, 19.7 mmol) was added and the resulting mixture was stirred for 20 hours, filtered and evaporated *in vacuo*. The crude product was purified by flash chromatography on silica gel eluting first with 0.5 % MeOH in DCM followed by 1 % MeOH in DCM. This gave 1.14 g (58%) of 9-allyl-6-chloro-9*H*-purine **103** as a colorless solid and 395 mg (20%) of 7- allyl-6-chloro-9*H*-purine **104** as a yellow solid.

***9-Allyl-6-chloro-9H-purine* (103)**

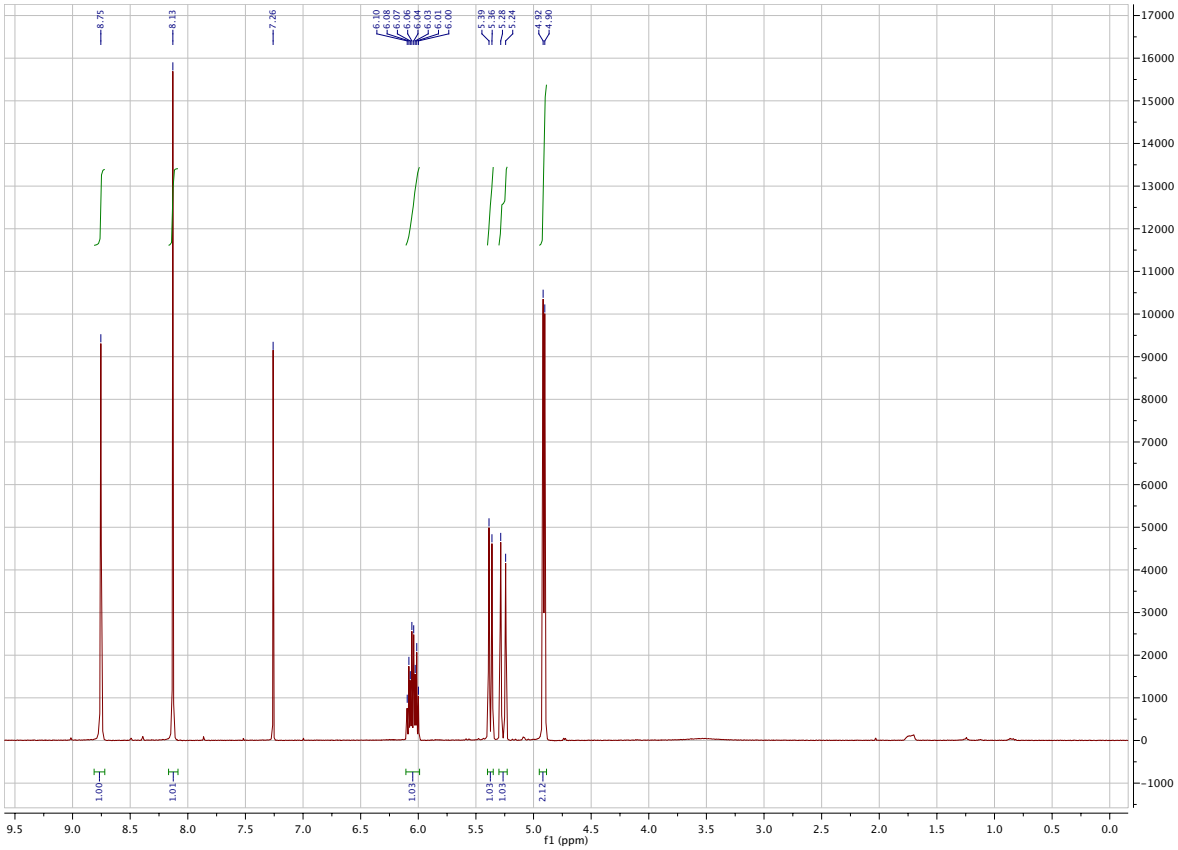
^{1}H NMR ($CDCl_3$, 400 MHz) δ 4.91 (d, *J*= 6.0 Hz, 2H, CH_2), 5.27 (d, *J*= 17.2 Hz, 1H, $=CH_{2a}$), 5.38 (d, *J*= 10.0 Hz, 1H, $=CH_{2b}$), 6.00-6.10 (m, 1H, =CH), 8.13 (s, 1H, H- 8), 8.76 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 46.46 (CH_2), 120.17 ($=CH_2$), 131.07 (=CH), 131.69 (C-5), 145.05 (C-8), 151.27 (C-4), 151.82 (C-6), 152.22 (C-2).

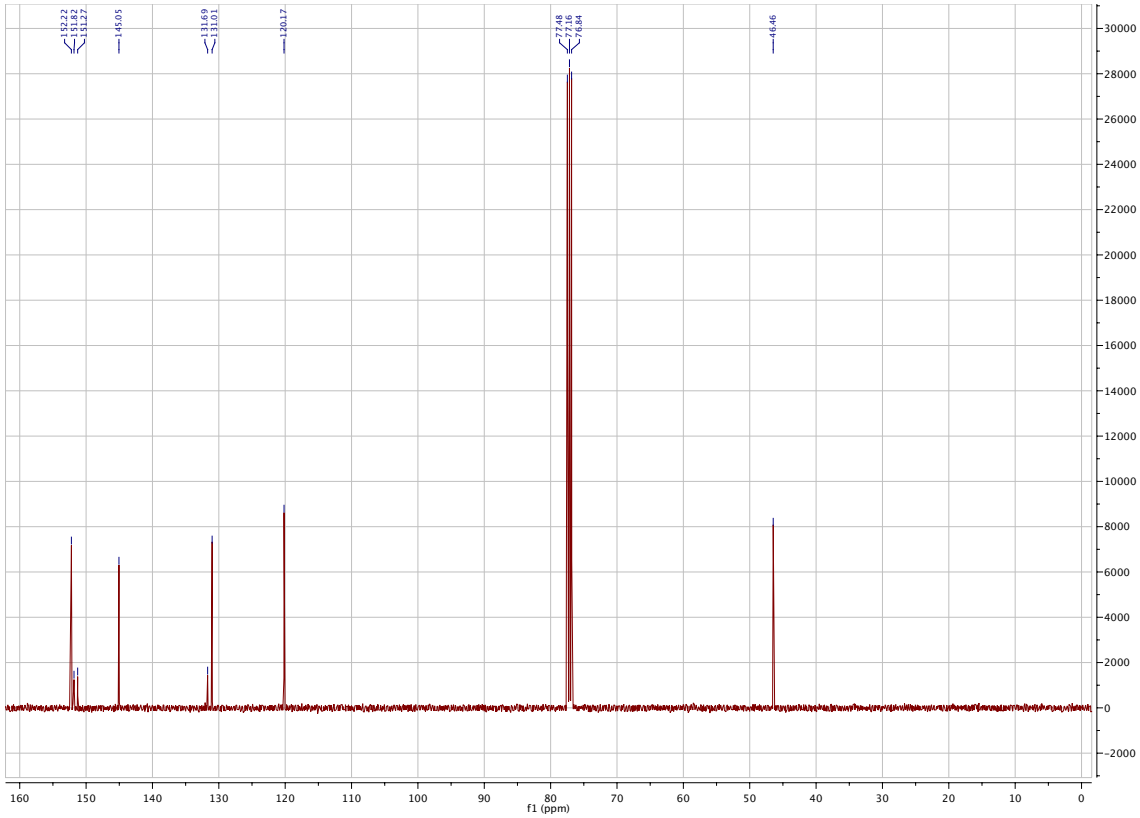
MS (EI). *m/z* (rel. %): 195/193 (M^+, 41/100), 193 (100), 169 (8), 167 (25), 154 (12), 132 (10), 119 (6), 77 (6).

HRMS Found 194.0350 calculated for $C_8H_7N_4Cl$ 194.0359.

M.p. 76-78 °C (Lit.[40] 79.6-80.1 °C).



Spectrum 1. 400 MHz, $CDCl_3$, ^{1}H NMR of 9-allyl-6-chloro-9H-purine (**103**)



Spectrum 2. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-allyl-6-chloro-9H-purine (**103**)

7-Allyl-6-chloro-*9H*-purine (104)

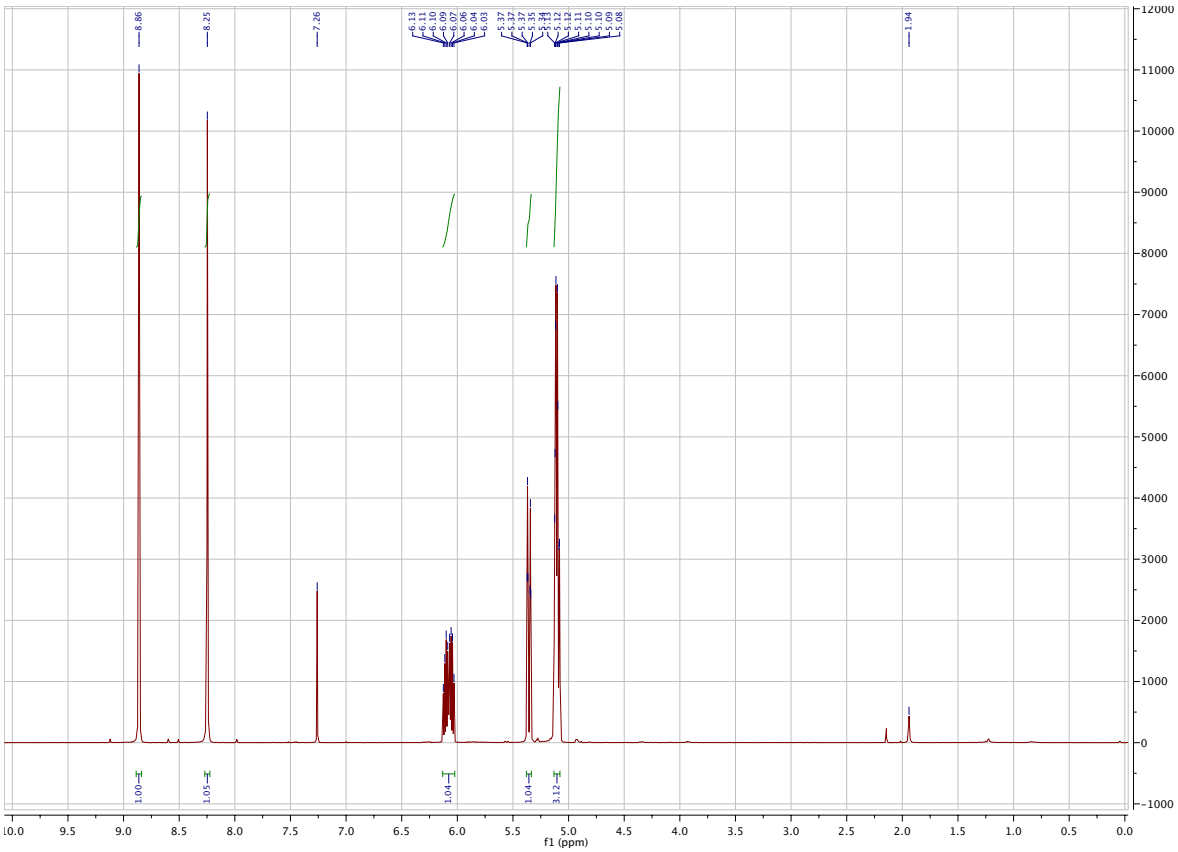
^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.08-5.12 (m, 3H, CH_2 and $=CH_{2a}$), 5.35 (dt, J = 10.4, 1.2 Hz, 1H, $=CH_{2b}$), 6.03-6.11 (m, 1H, =CH), 8.25 (s, 1H, H-8), 8.86 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 49.38 (CH_2), 119.66 ($=CH_2$), 122.50 (C-5), 131.87 (=CH), 143.22 (C-6), 148.99 (C-8), 152.63 (C-2), 162.03 (C-4).

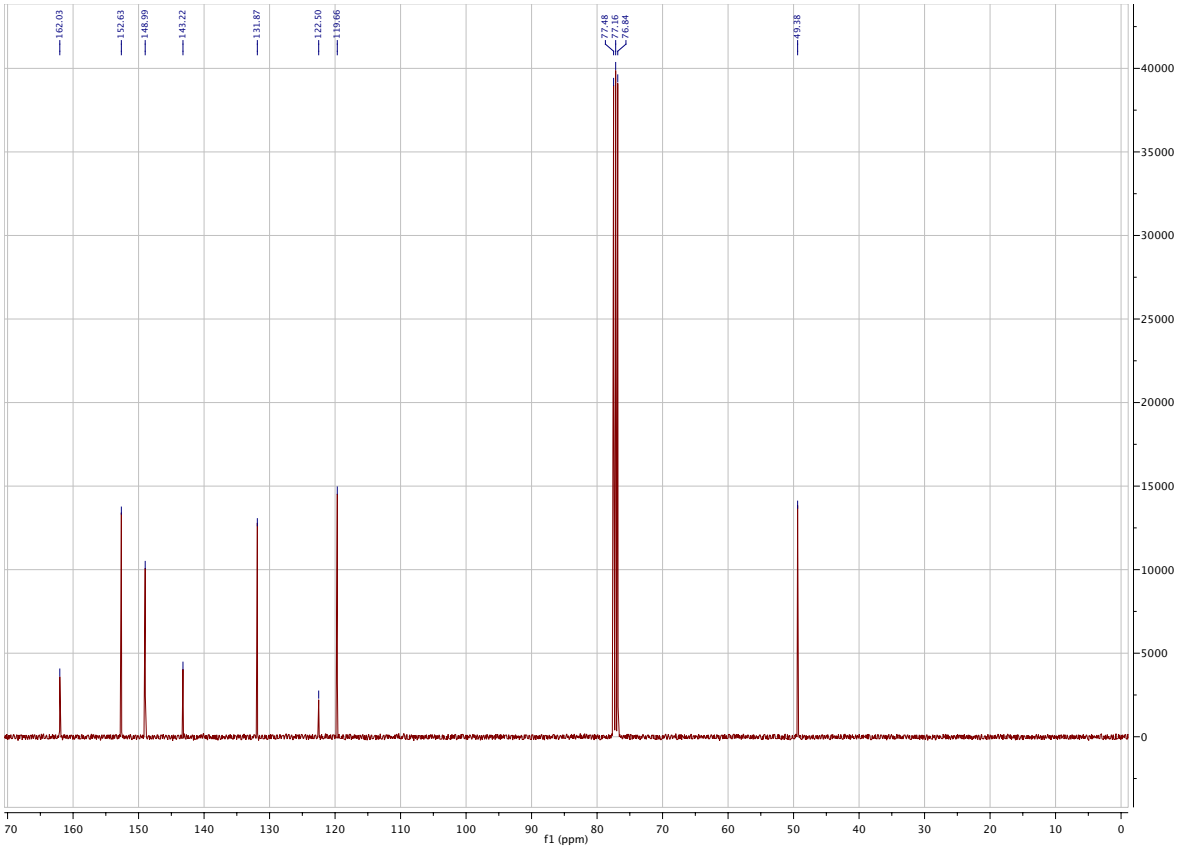
MS (EI). m/z (rel. %): 196/194 (35/100, M^+), 167 (10), 159 (8), 132 (19), 105 (6), 77 (5).

HRMS Found 194.0352 calculated for $C_8H_7N_4Cl$ 194.0359.

M.p. 89-91 °C (Lit.[40] 92.8-93 °C).

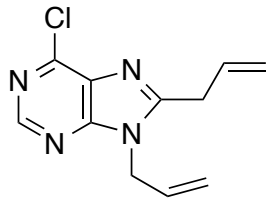


Spectrum 3. 400 MHz, $CDCl_3$, ^{1}H NMR of 7-allyl-6-chloro-*7H*-purine (**104**)



Spectrum 4. 100 MHz, $CDCl_3$, ^{13}C NMR of 7-allyl-6-chloro-*7H*-purine (**104**)

Synthesis of 8,9-diallyl-6-chloro-9*H*-purine (106)



106

Allyl magnesium bromide (1.19 mL, 0.95 mmol of 0.80 M solution in diethyl ether) was added to a solution of compound 9-allyl-6-chloro-9*H*-purine **103** (88 mg, 0.45 mmol) in THF (5 mL) at 0 ºC under N_2-atm, and the resulting mixture was stirred at 0 ºC for 20 min. Sat. aq. NH_4Cl (10 mL) was added, the phases were separated and the water layer was extracted with EtOAc (2 x10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The crude product was dissolved in dry DCM (3 mL), MnO_2 (196 mg, 2.25 mmol) was added and the mixture was stirred at r.t. for 2 hours and evaporated *in vacuo*. The product was purified by flash chromatography on silica gel eluting with acetone-EtOAc-hexane (1:1:8) to give 59 mg (56%) of 8,9-diallyl-6-chloro-9*H*-purine **106** as a yellow oil.

***8,9-Diallyl-6-chloro-9H-purine* (106)**

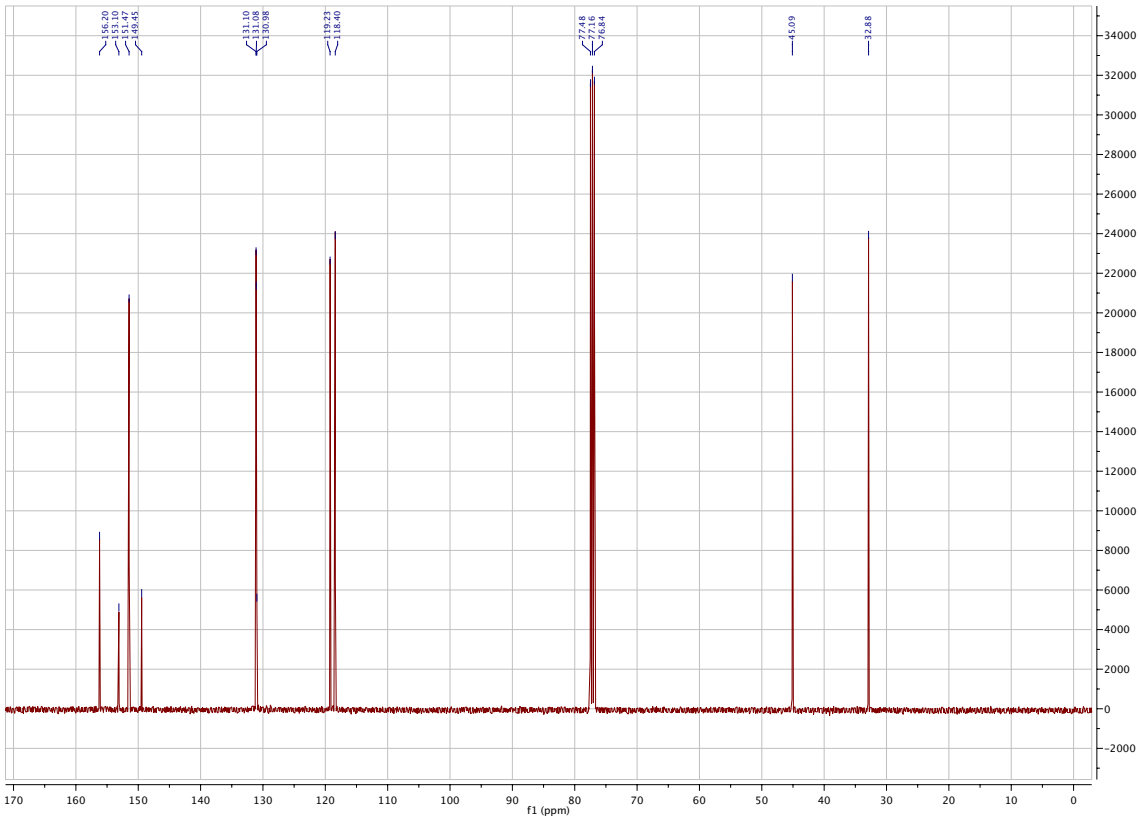
^{1}H NMR ($CDCl_3$, 400 MHz) 3.72 (d, J = 6.4 Hz, 2H, C(8)CH_2), 4.86 (d, J = 4.8 Hz, 2H, N(9)CH_2), 4.99 (d, J = 17.2 Hz, 1H, =CH_{2a} in C(8) allyl), 5.19 (d, J = 17.2 Hz, 1H, =CH_{2a} in N(9) allyl), 5.25 (d, J = 10.4 Hz, 2H, =CH_{2b} in N(9) allyl and =CH_{2b} in C(8) allyl), 5.88-6.07 (m, 2H, 2 x CH=), 8.64 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 32.88 (C(8)$\underline{C}H_2$), 45.09 (N(9)CH_2), 118.40 (=CH_2 in C(8) allyl), 119.23 (=CH_2 in N(9) allyl), 130.98 (C-5), 131.08 (CH= in N(9) allyl), 131.10 (CH= in C(8) allyl), 149.45 (C-4), 151.47 (C-2), 153.10 (C-6), 156.20 (C-8).

MS (EI) m/z (rel. %): 236/234 (26/76, M^+), 233 (100), 219 (8), 207 (20), 193 (41), 168 (6), 157 (11).

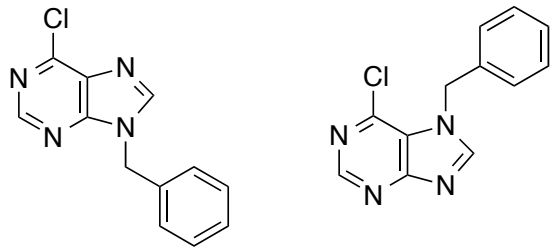
HRMS Found 234.0672 calculated for $C_{11}H_{11}N_4Cl$ 234.0672.

Spectrum 5. 400 MHz, $CDCl_3$, ^{1}H NMR of 8,9-diallyl-6-chloro-*9H*-purine (**106**)



Spectrum 6. 100 MHz, $CDCl_3$, ^{13}C NMR of 8,9-diallyl-6-chloro-*9H*-purine (**106**)

Synthesis of 9-benzyl-6-chloro-9*H*-purine (107) and 7-benzyl-6-chloro-7*H*-purine (108)



107 **108**

Potassium carbonate (4.145 g, 30 mmol) was added to a stirring solution of 6-chloropurine **102** (1.58 g, 10.2 mmol) in dry DMF (40 ml) at ambient temperature under N_2. After 20 min. benzyl chloride (2.34 ml, 19.7 mmol) was added, the resulting mixture was stirred for 22 hours, filtered and evaporated. The isomers were separated by flash chromatography on silica gel using EtOAc-hexane (2:1) followed by (3:1) for elution. This gave 1.388 g (57%) of 9-benzyl-6-chloro-9*H*-purine **107** and 304mg (12%) of 7- allyl-6-chloro-9*H*-purine **108** as a yellow solid.

9-Benzyl-6-chloro-9H-purine **(107)**

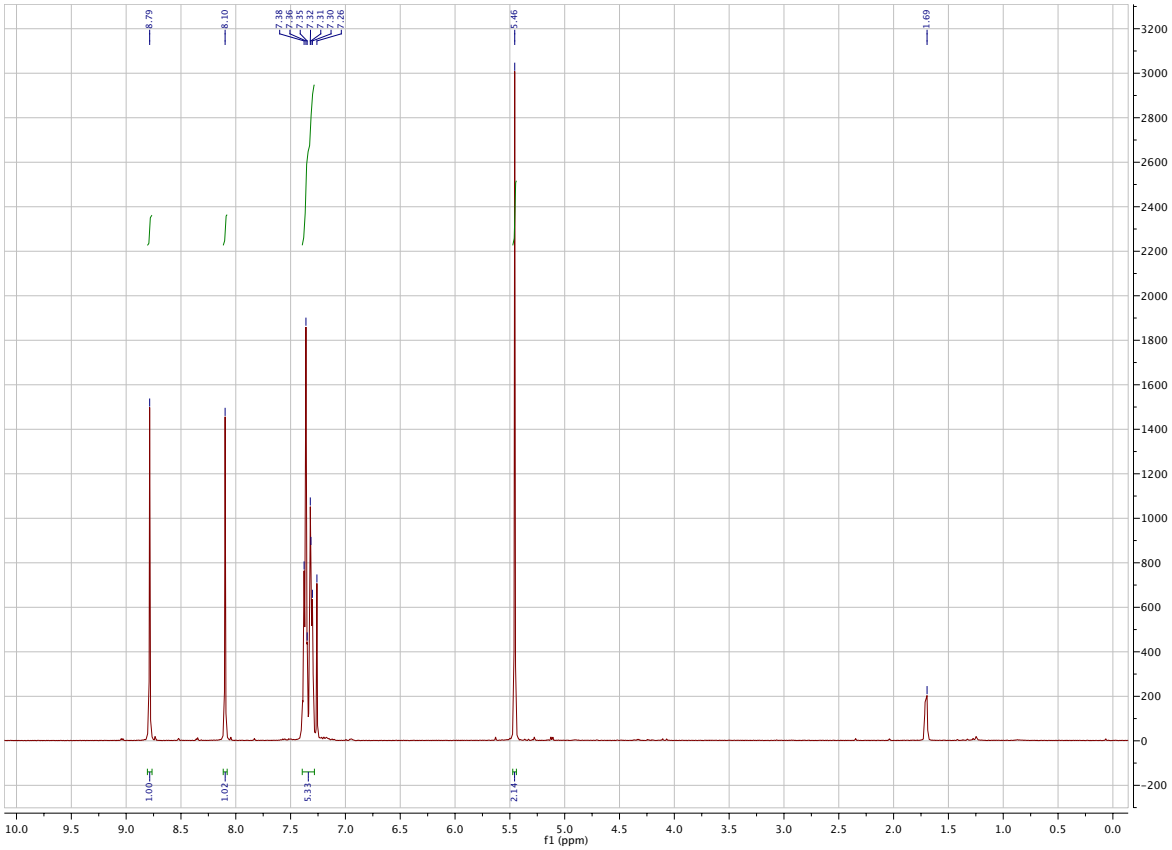
^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.46 (s, 2H, N(9)CH_2), 7.30-7.37 (m, 5H, H in Ph), 8.10 (s, 1H, H-8), 8.79 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 48.03 (CH_2), 128.07 (CH in Ph), 129.02 (CH in Ph), 129.41 (CH in Ph), 131.66 (C-5), 134.64 (C in Ph), 145.08 (C-8), 151.29 (C-4), 152.00 (C-6), 152.32 (C-2).

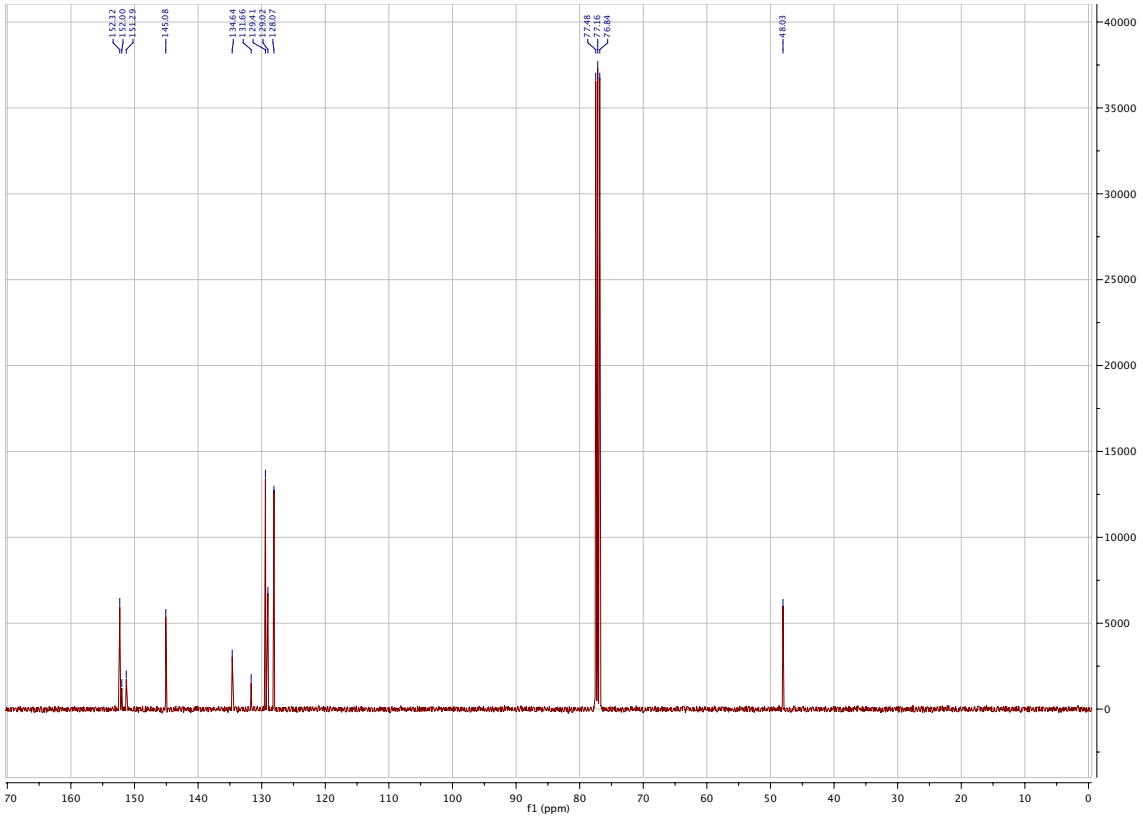
MS (EI) 246/244 (20/62, M^+), 209 (6), 182 (12), 167 (6), 91 (100), 65 (21).

M.p. 84-85 ^{o}C (Lit.[91] 86-87 ^{o}C).

HRMS Found 244.0511 calculated for $C_{12}H_9N_4Cl$ 244.0516.



Spectrum 7. 400 MHz, $CDCl_3$, ^{1}H NMR of 9-benzlyl-6-chloro-*9H*-purine (**107)**



Spectrum 8. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-benzyl-6-chloro-*7H*-purine (**107**)

7-Benzyl-6-chloro-7H-purine **(108)**

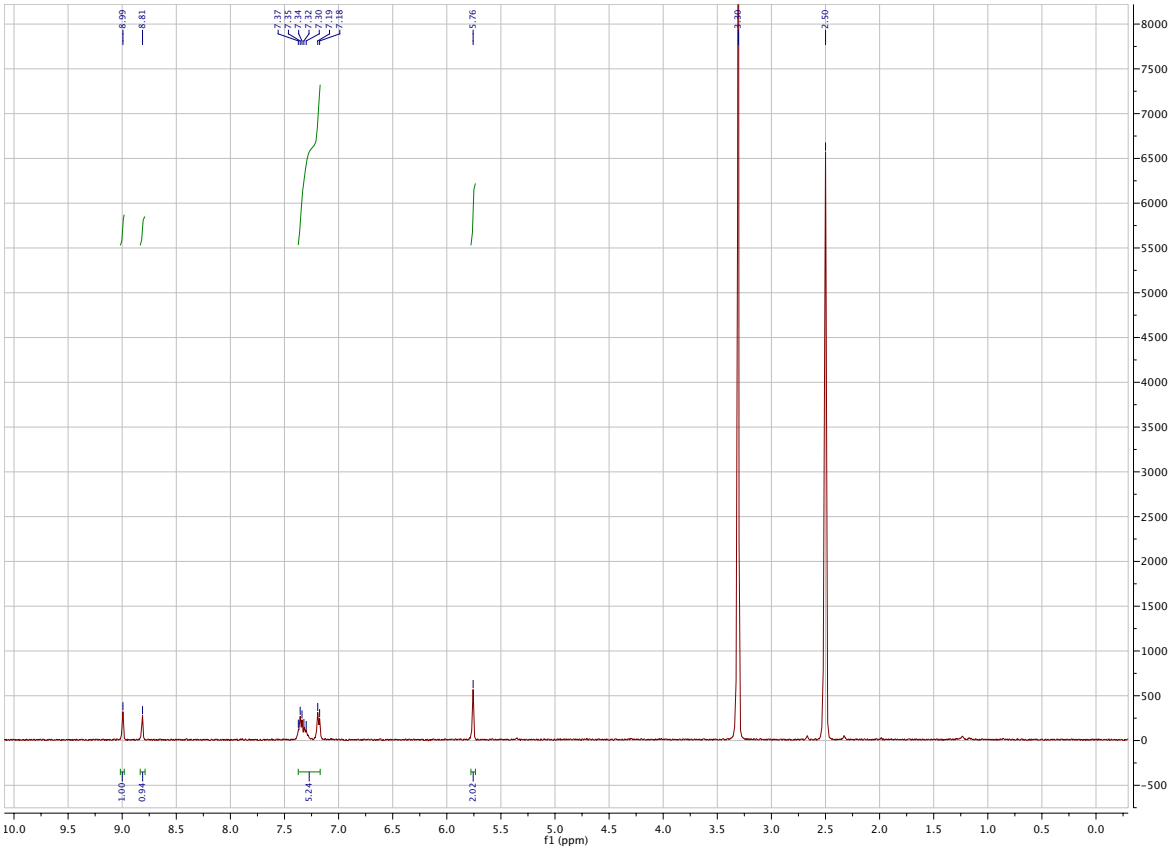
^{1}H NMR (DMSO-d_6, 400 MHz) δ 5.76 (s, 2H, N(9)CH_2), 7.18-7.37 (m, 5H, H in Ph), 8.81 (s, 1H, H-8), 8.99 (s, 1H, H-2).

^{13}C NMR (DMSO-d_6, 100 MHz) δ 49.44 (CH_2), 122.03 (C-5), 126.48 (CH in Ph), 127.87 (CH in Ph), 128.82 (CH in Ph), 136.71 (C in Ph), 142.24 (C-6), 151.36 (C-8), 151.81 (C-2), 161.71 (C-4).

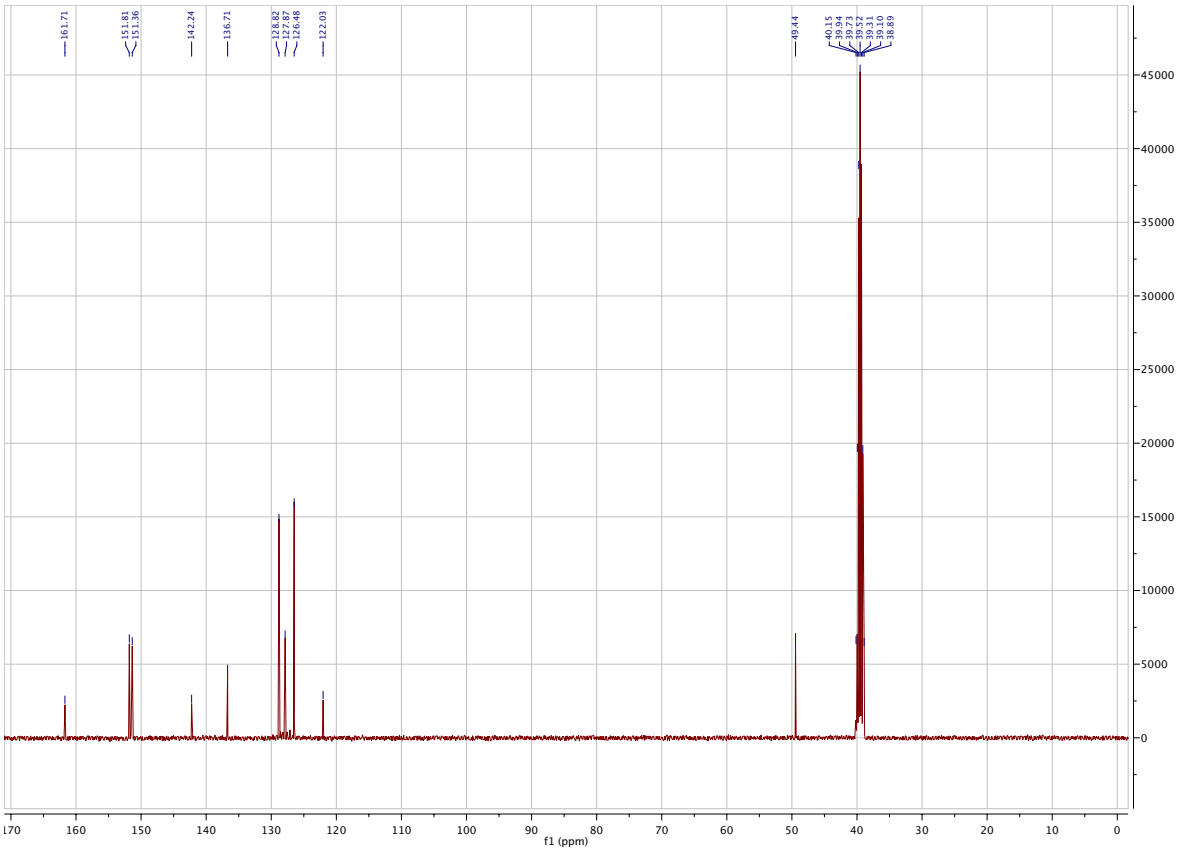
MS (EI) 246/244 (13/41, M^+), 91 (100).

HRMS Found 244.0513 calculated for $C_{12}H_9N_4Cl$ 244.0516.

M.p. 151-152 ^{o}C (Lit.[91] 153-154 ^{o}C).

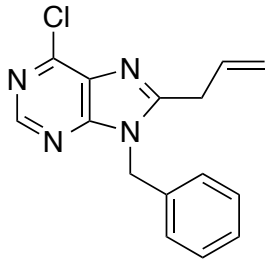


Spectrum 9. 400 MHz, DMSO-d_6, ^{1}H NMR of 7-benzlyl-6-chloro-*9H*-purine (**108**)



Spectrum 10. 100 MHz, DMSO-d_6, ^{13}C NMR of 7-benzyl-6-chloro-*7H*-purine (**108**)

Synthesis of 8-allyl-9-benzyl-6-chloro-9*H*-purine (110)



110

Allylmagnesium bromide (1.19 mL, 0.95 mmol of 0.80 M solution in diethyl ether) was added to a solution of compound 9-benzyl-6-chloropurine **107** (110 mg, 0.45 mmol) in THF (5 mL) at 0 ºC under N_2-atm, and the resulting mixture was stirred at 0 ºC for 20 min. Sat. aq. NH_4Cl (10 mL) was added, the phases were separated and the water layer was extracted with EtOAc (2 x10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The crude product was dissolved in dry DCM (3 mL), MnO_2 (196 mg, 2.25 mmol) was added and the mixture was stirred at r.t. for 2 hours and evaporated *in vacuo*. The product was purified by flash chromatography on silica gel eluting with acetone-EtOAc-hexane (1:1:8) to give 70 mg (55%) of 8-allyl-9-benzyl-6-chloro-9*H*-purine **110** as a yellow oil.

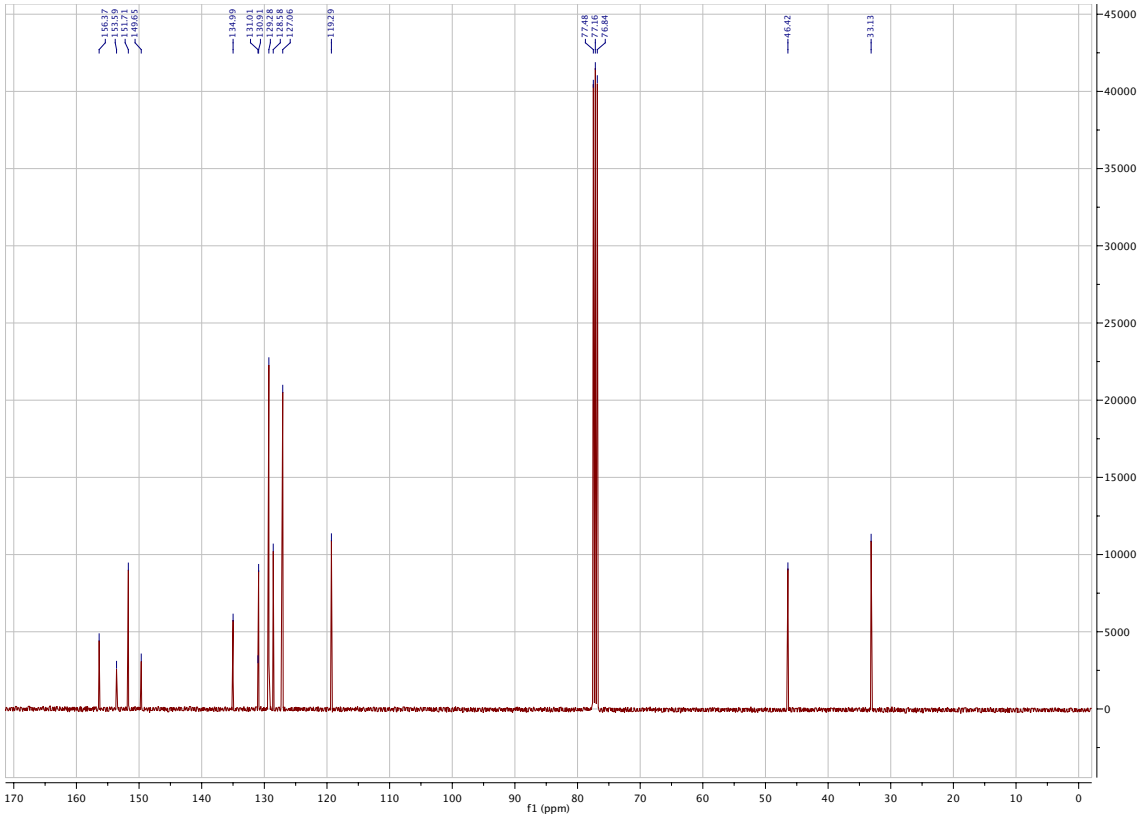
1H NMR ($CDCl_3$, 400 MHz) δ 3.64 (dt, J = 6.0, 1.6 Hz, 2H, C(8)CH_2), 5.15 (dd, J = 17.2, 1.6 Hz, 1H, =CH_{2a} in C(8) allyl), 5.23 (dd, J = 10.4, 1.6 Hz, 1H, =CH_{2b} in C(8) allyl), 5.47 (s, 1H, N(9)CH_2), 6.03-5.94 (m, 1H, =CH), 7.12-7.14 (m, 2H, H in Ph), 7.30-7.35 (m, 3H, H in Ph), 8.72 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 33.13 (C(8)CH_2), 46.42 (N(9)CH_2), 119.29 (=CH_2 in C(8) allyl), 127.06 (CH in Ph), 128.58 (CH in Ph), 129.28 (CH in Ph) 130.91 (C-5), 131.01 (CH= in C(8) allyl), 134.99 (C in Ph), 149.65 (C-4), 151.72 (C-2), 153.59 (C-6), 156.37 (C-8).

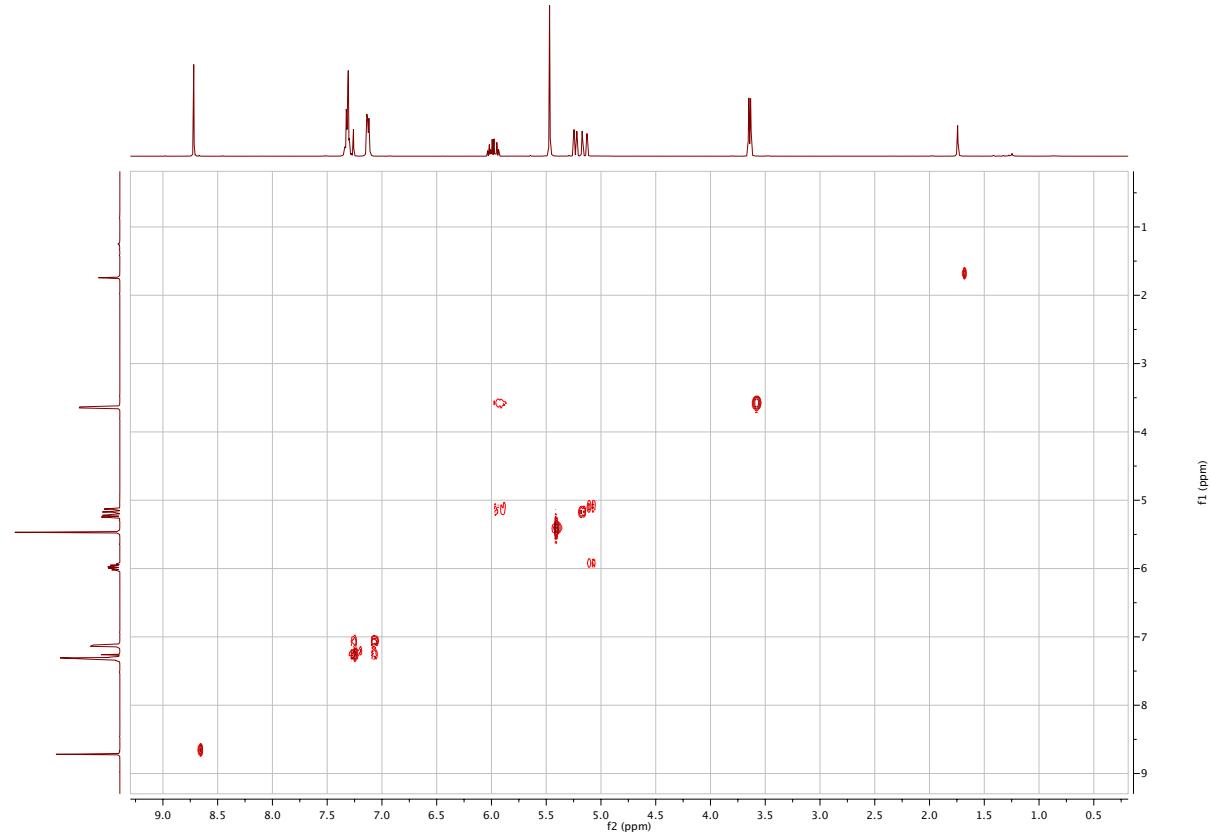
MS (EI) *m/z* (rel. %): 286/284 (24/69, M^+), 193 (14), 91 (100), 65 (11).

HRMS Found 284.0824 calculated for $C_{15}H_{13}ClN_4$ 284.0829.

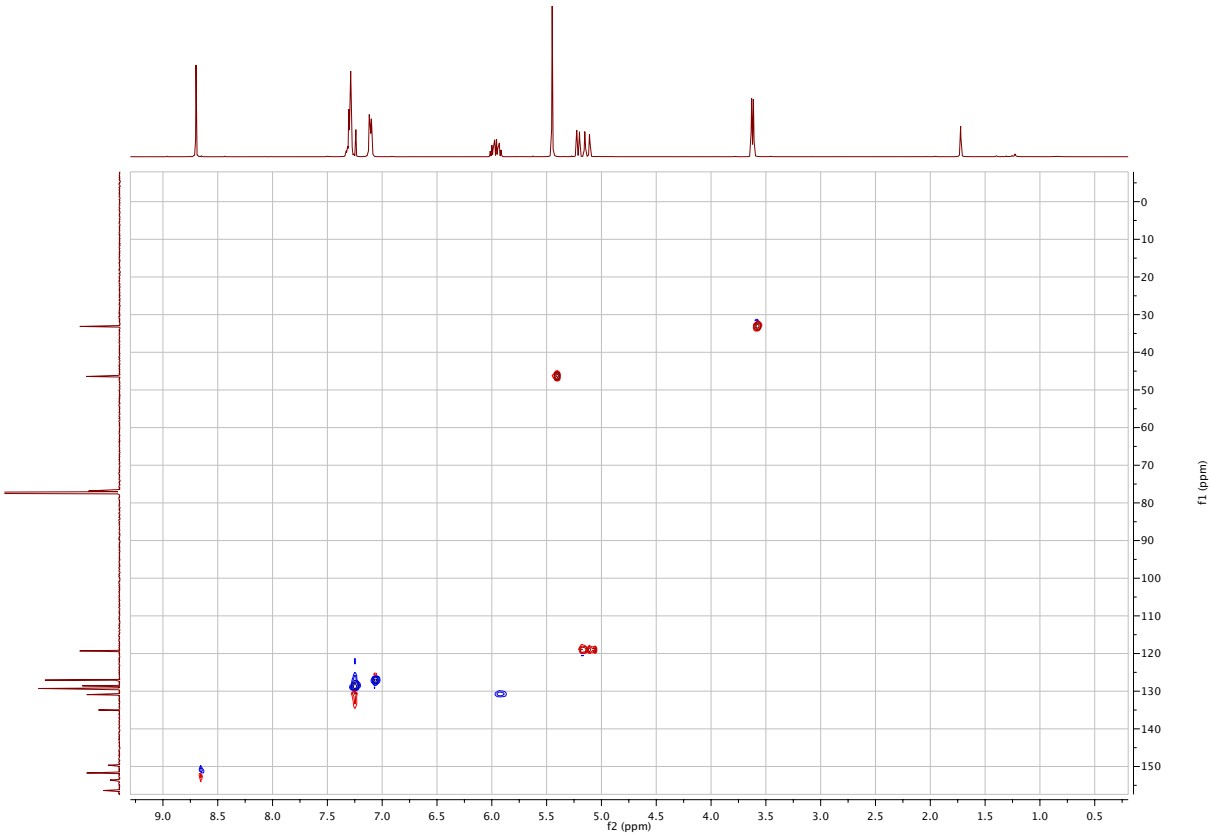
Spectrum 11. 400 MHz, $CDCl_3$, ^{1}H NMR of 8-allyl-9benzyl-6-chloro-*9H*-purine (**110**)



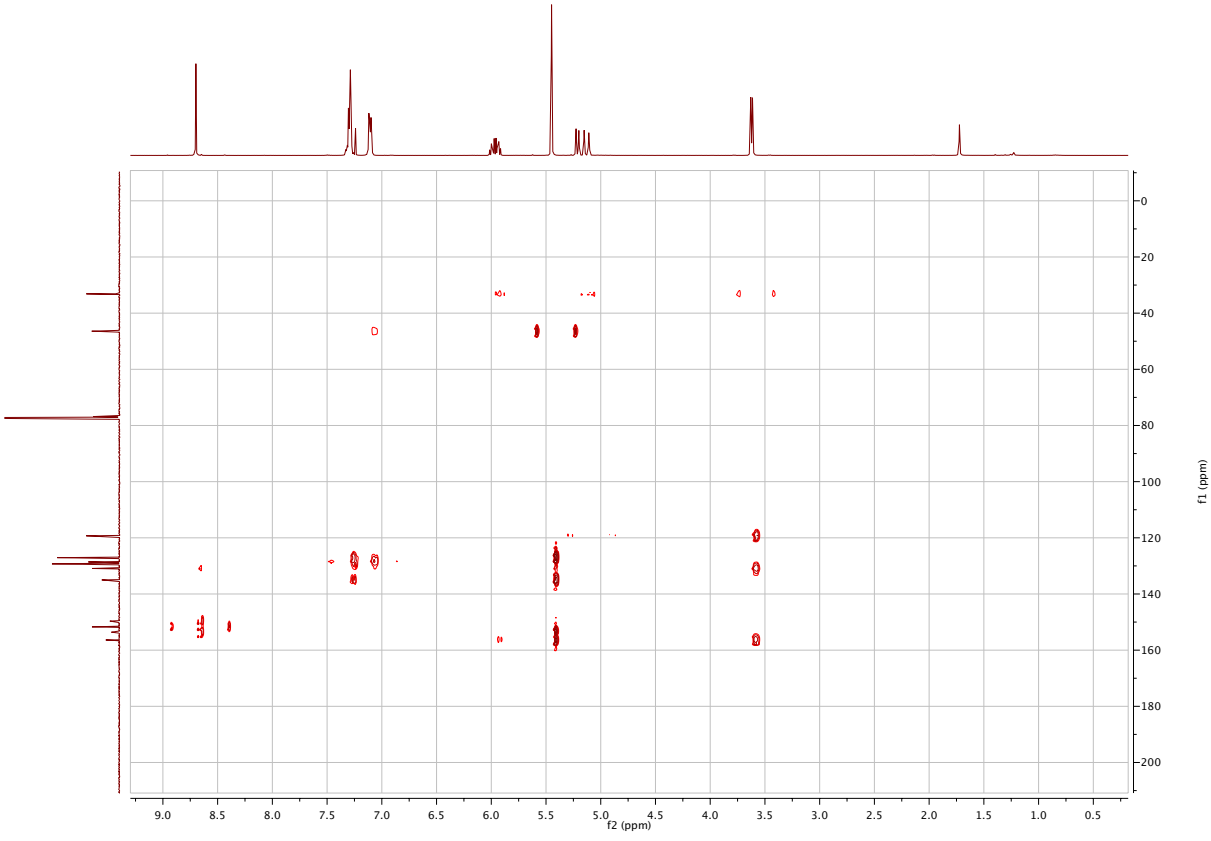
Spectrum 12. 100 MHz, $CDCl_3$, ^{13}C NMR of 8-allyl-9benzyl-6-chloro-*9H*-purine (**110**)



Spectrum 13. 400 MHz, $CDCl_3$, COSY of 8-allyl-9-benzyl-6-chloro-*9H*-purine (**110**)

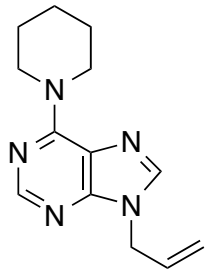


Spectrum 14. 400 MHz, $CDCl_3$, HSQC of 8-allyl-9-benzyl-6-chloro-*9H*-purine (**110**)



Spectrum 15. 400 MHz, $CDCl_3$, HMBC of 8-allyl-9-benzyl-6-chloro-*9H*-purine (**110**)

Synthesis of 9-allyl-6-(piperidin-1-yl)-9*H*-purine (111)



111

A mixture of 9-allyl-6-chloro-*9H*-purine **103** (864 mg, 4.44 mmol) and piperidine (0.88 mL, 8.91 mmol) in H_2O (8 mL) was refluxed for 24 hours. After cooling, the mixture was extracted with DCM (2 x 20 mL) and the organic layer was washed with H_2O (2 x 20 mL), dried with $MgSO_4$ and evaporated *in vacuo.* to give 1.026 g (95%) 9-allyl-6-(piperidin-1-yl)-9*H*-purine **111** as a yellow solid.

9-Allyl-6-(piperidin-1-yl)-*9H*-purine (111)

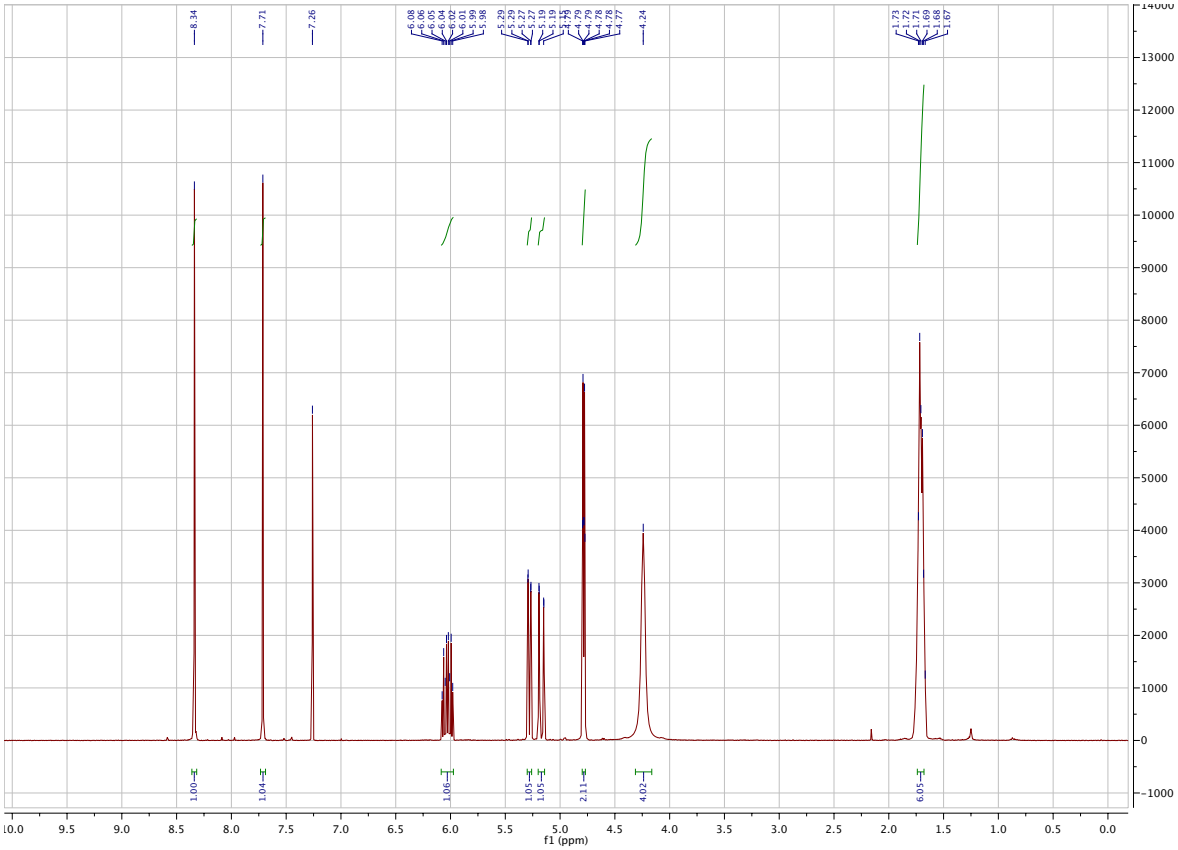
^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.67-1.72 (m, 6H, 3 x CH_2 in piperidinyl), 4.24 (br.s, 4H, 2 x CH_2 in piperidinyl), 4.78 (dt, *J* = 1.6, 5.6 Hz, 2H, CH_2 in allyl), 5.17 (dd, *J* = 17.2 Hz, 1H, $=CH_{2a}$), 5.28 (dd, *J* = 10.4 Hz, 1H, $=CH_{2b}$), 5.98-6.08 (m, 1H, =CH), 7.71 (s, 1H, H-8), 8.34 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 24.98 (CH_2 in piperidinyl), 26.28 (2 x CH_2 in piperidinyl), 45.69 (CH_2 in allyl), 46.50 (2 x CH_2 in piperidinyl), 118.70 ($=CH_2$), 119.88 (=CH), 132.25 (C-8), 137.87 (C-4), 150.85 (C-2), 152.75 (C-6), 154.09 (C-5).

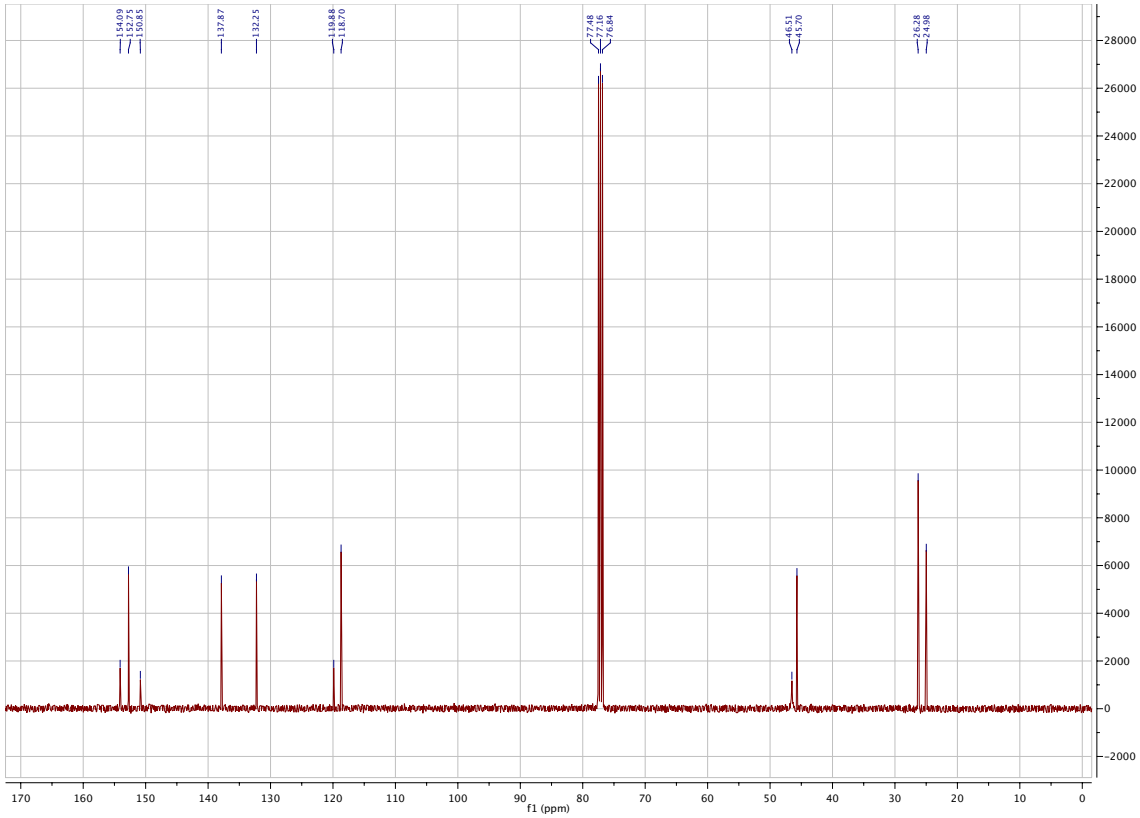
MS (EI) m/z (rel. %): 244/243 (18/100, M^+), 228 (11), 214 (51), 202 (27), 187 (24), 174 (22), 160 (19), 147 (9), 132 (7), 119 (11), 84 (14).

HRMS Found 243.1479 calculated for $C_{13}H_{17}N_5$ 243.1484.

M.p. 79-81 ^{o}C (Lit.[92] 54-56 ^{o}C).

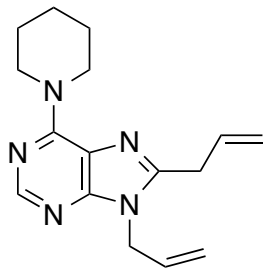


Spectrum 16. 400 MHz, $CDCl_3$, ^1H NMR of 9-allyl-6-(piperidin-1-yl)-9*H*-purine (**111**)



Spectrum 17. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-allyl-6-(piperidin-1-yl)-9*H*-purine (**111**)

Synthesis of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine (112)



112

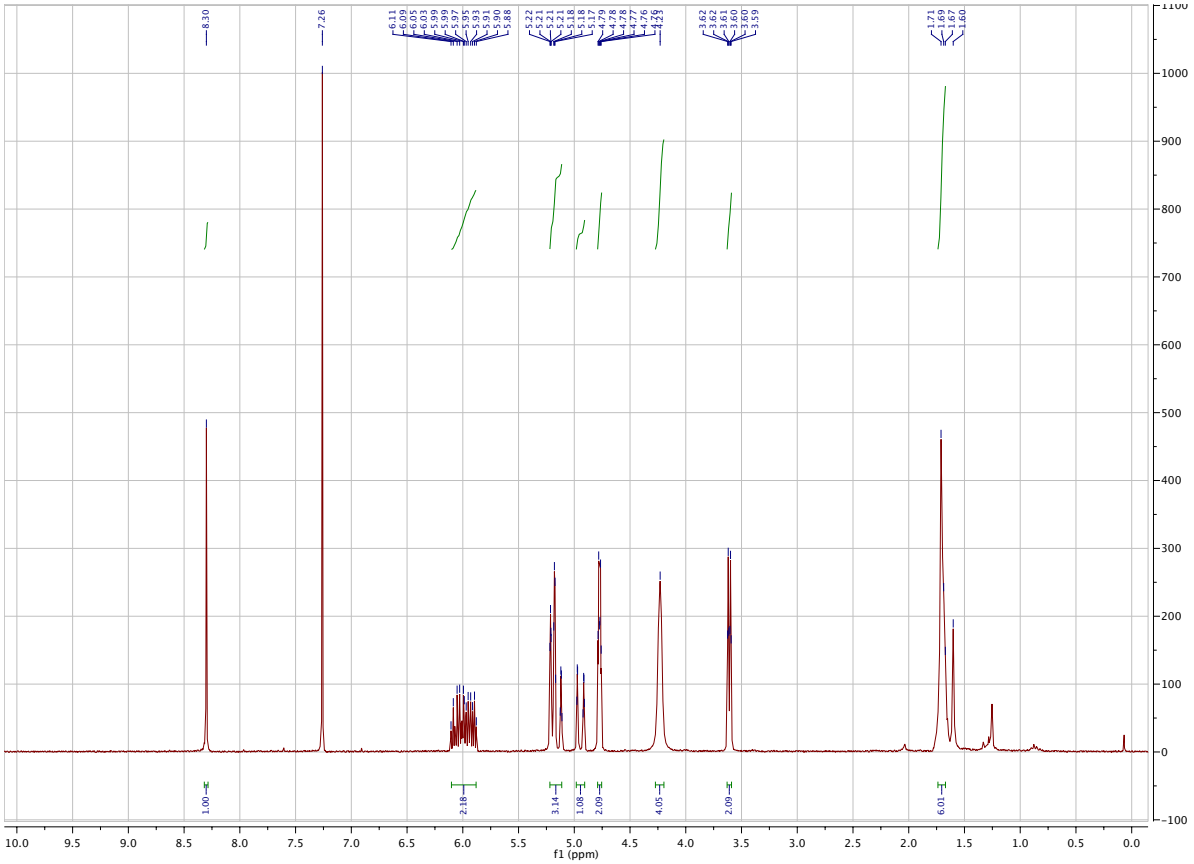
Allylmagnesium bromide (2.08 mL, 1.35 mmol of 0.65 M solution in diethyl ether) was added to a solution of compound **111** (109 mg, 0.448 mmol) in THF (5 mL) at 0 ºC under N_2-atm and the resulting mixture was stirred at 0 ºC for 4 hours. Sat. aq. NH_4Cl (10 mL) was added, the phases were separated and the water layer was extracted with EtOAc (2 x10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The product was purified by flash chromatography eluting with acetone-EtOAc-hexane (2:3:15) to give 52 mg (24%) of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine **112** as a yellow oil.

^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.65-1.71 (m, 6H, 3xCH_2 in piperidinyl), 3.61 (dt, J = 6.0, 1.8 Hz, 2H, C(8)CH_2), 4.23 (brs, 4H, 2 x NCH_2 in piperidinyl), 4.76-4.79 (m, 2H, N(9)CH_2), 4.95 (dt, J = 17.1, 1.8 Hz, 1H, =CH_{2a} in C(8) allyl), 5.11-5.22 (m, 3H, =CH_{2b} in C(8) allyl and =CH_2 in N(9) allyl), 5.88-6.16 (m, 2H, 2 x CH=), 8.30 (s, 1H, H-2).

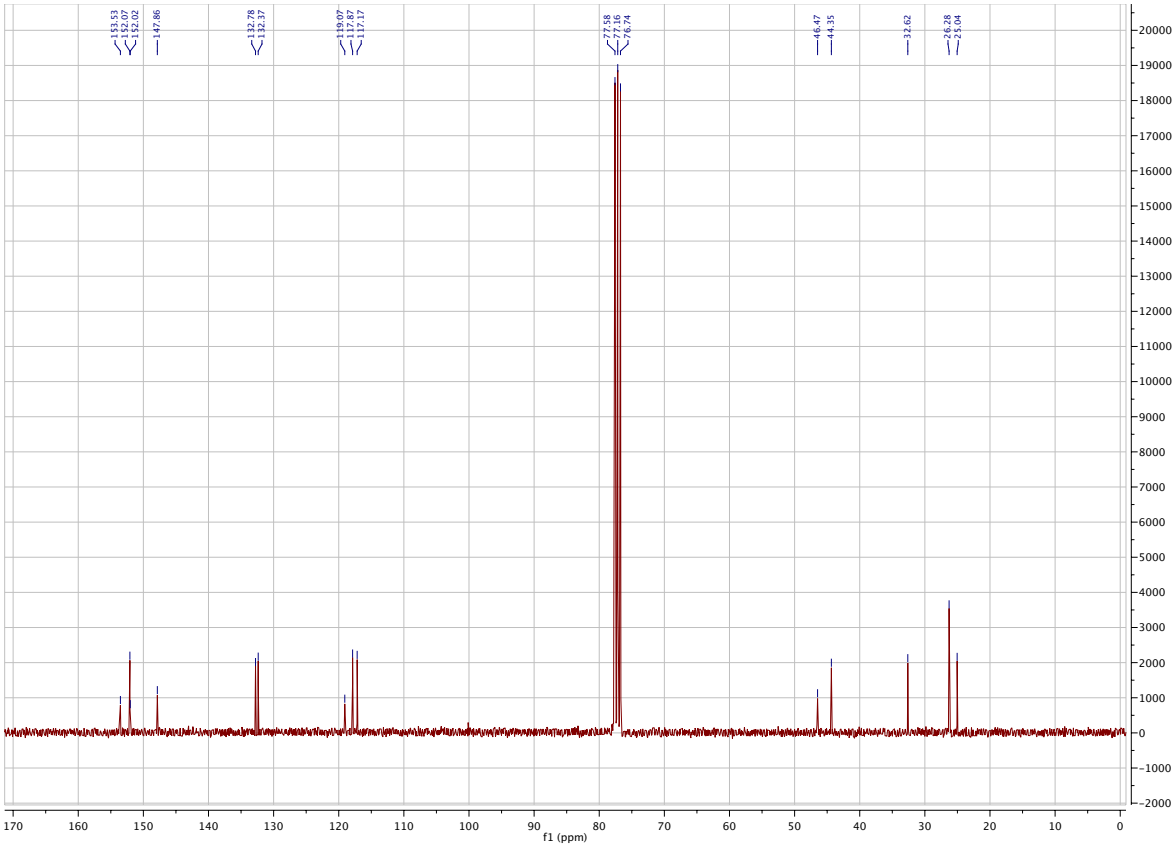
^{13}C NMR ($CDCl_3$, 75 MHz) δ 25.04 (CH_2 in piperidinyl), 26.28 (2 x CH_2 in piperidinyl), 32.62 (C(8)$\underline{C}H_2$), 44.36 (N(9)$\underline{C}H_2$), 46.47 (2 x NCH_2 in piperidinyl), 117.17 (=CH_2 in C(8) allyl), 117.87 (=CH_2 in N(9) allyl), 119.08 (C-5), 132.37 (CH= in N(9) allyl), 132.38 (CH= in C(8) allyl), 147.86 (C-8), 152.02 (C-4), 152.07 (C-2), 153.53 (C-6).

MS (EI) *m/z* (rel. %): 284/283 (20/100, M^+), 254 (38), 242 (30), 227 (37), 214 (20), 200 (16), 187 (8), 159 (7).

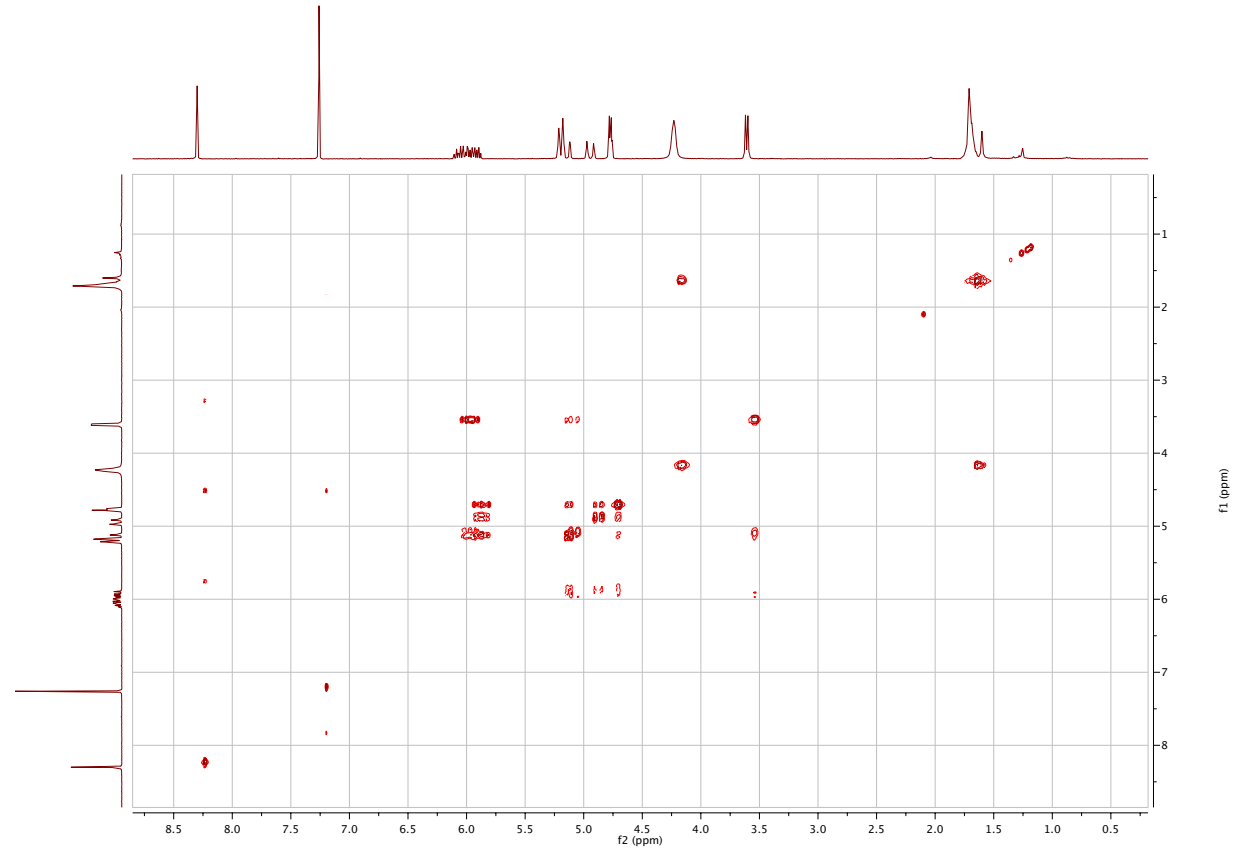
HRMS Found 283.1795 calculated for $C_{16}H_{21}N_5$ 283.1796.



Spectrum 18. 300 MHz, $CDCl_3$, ^{1}H NMR of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine (**112**)



Spectrum 19. 75 MHz, $CDCl_3$, ^{13}C NMR of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine (**112**)

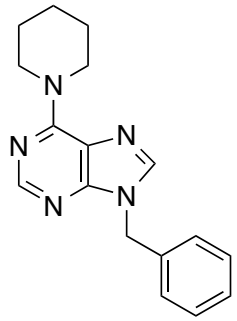


Spectrum 20. 300 MHz, $CDCl_3$, COSY of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine (**112**)

Spectrum 21. 300 MHz, $CDCl_3$, HSQC of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine (**112**)

Spectrum 22. 300 MHz, $CDCl_3$, HMBC of 8,9-diallyl-6-(piperidin-1-yl)-9*H*-purine (**112**)

Synthesis of 9-benzyl-6-(piperidin-1-yl)-9*H*-purine (113)



113

A mixture of compound **107** (1.09 g, 4.44 mmol) and piperidine (0.88 mL, 8.91 mmol) in H_2O (8 mL) was refluxed for 24 hours. After cooling, the mixture was extracted with DCM (2 x 20 mL) and the organic layer was washed with H_2O (2 x 20 mL), dried with $MgSO_4$ and evaporated *in vacuo.* to give 1.236 g (95%) 9-benzyl-6-(piperidin-1-yl)-9*H*-purine **113** as a yellow solid.

9-Benzyl-6-(piperidin-1-yl)-9H-purine (**113**)

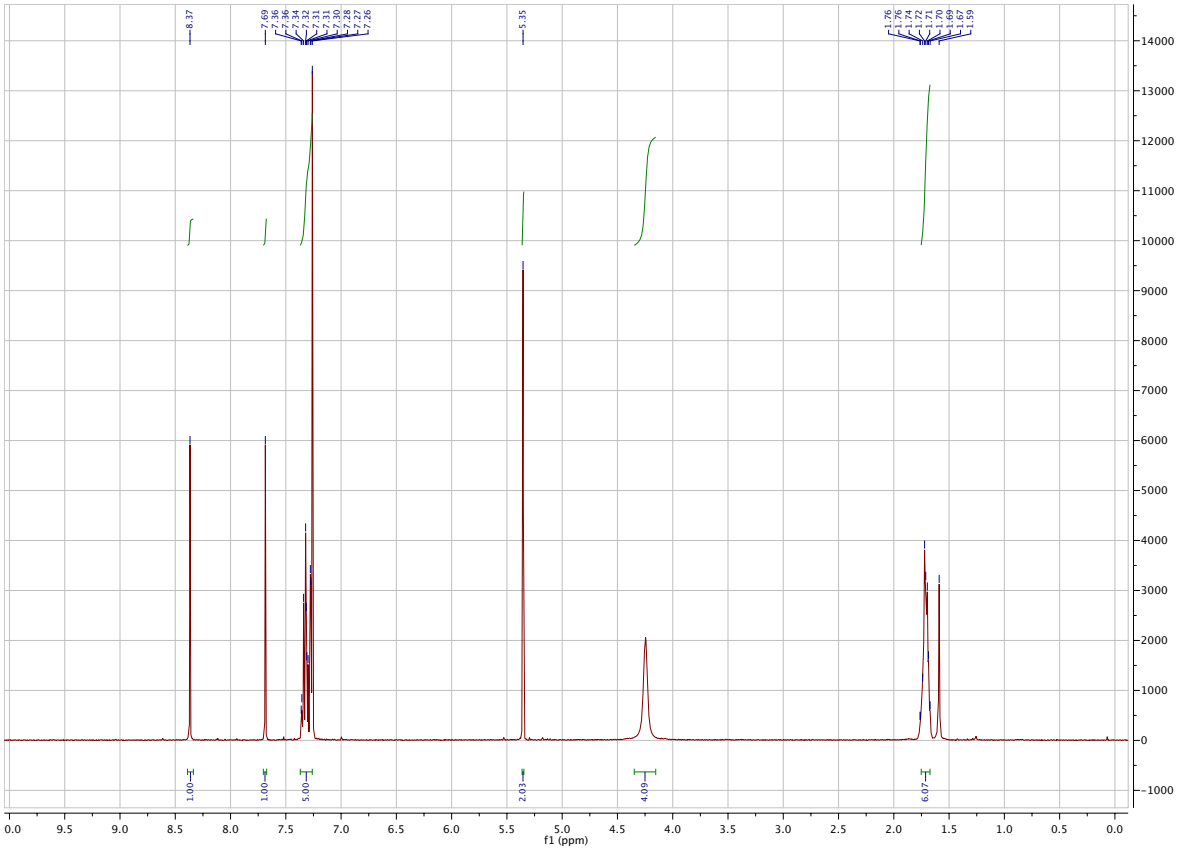
^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.63-1.67 (m, 6H, 3 x CH_2 in piperidinyl), 4.26 (br.s, 4H, 2 x CH_2 in piperidinyl), 5.35 (s, 2H, N9(CH_2)), 7.28-7.36 (m, 5H, CH in Ph), 7.69 (s, 1H, H-8), 8.34 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 24.99 (CH_2 in piperidinyl), 26.30 (2 x CH_2 in piperidinyl), 46.53 (2 x CH_2 in piperidinyl), 47.13 (N(9)CH_2), 119.85 (CH in Ph), 127.82 (CH in Ph), 128.37 (CH in Ph), 129.12 (C in Ph), 136.06 (C-5), 137.95 (C-8), 151.12 (C-4), 152.88 (C-2), 154.12 (C-6).

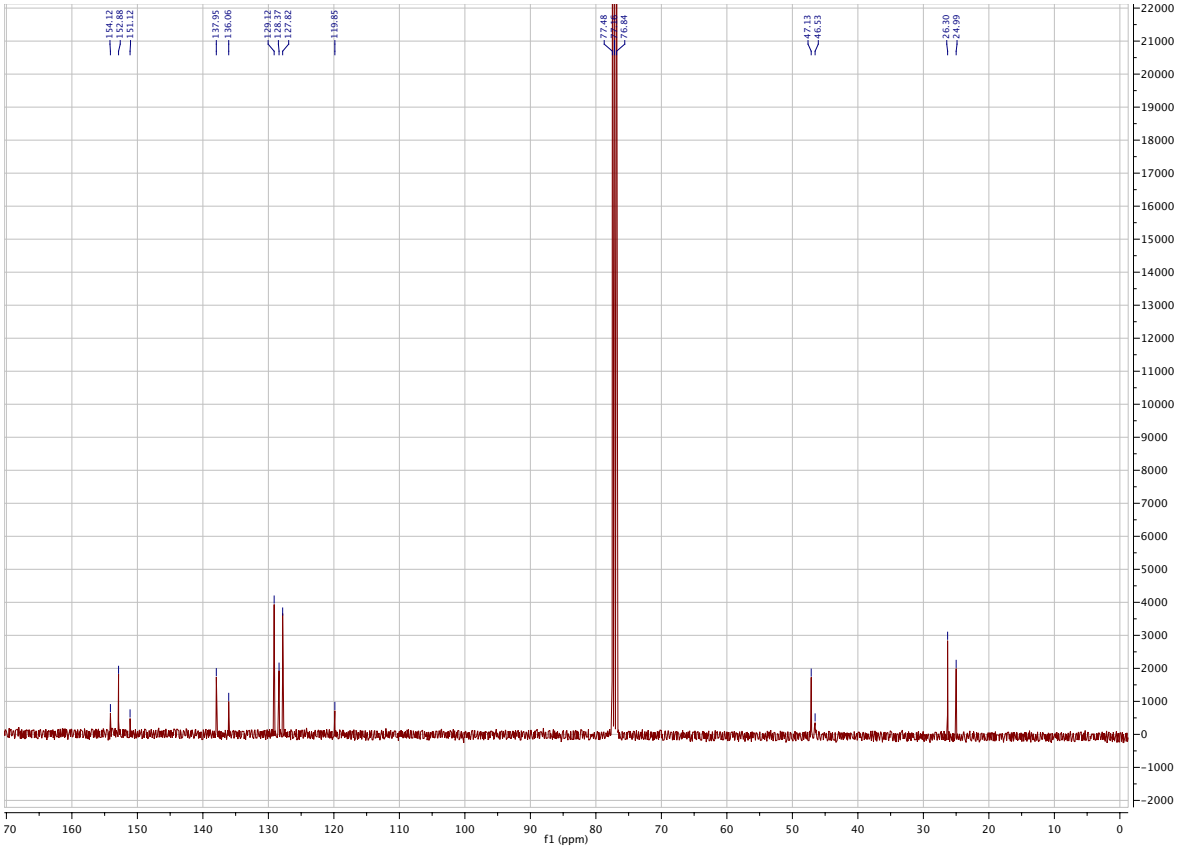
MS (EI) *m/z* (rel. %): 294/293 (22/100, M^+), 264 (26), 202 (33), 174 (11), 91 (69).

HRMS Found 293.1667 calculated for $C_{17}H_{19}N_5$ 293.1640.

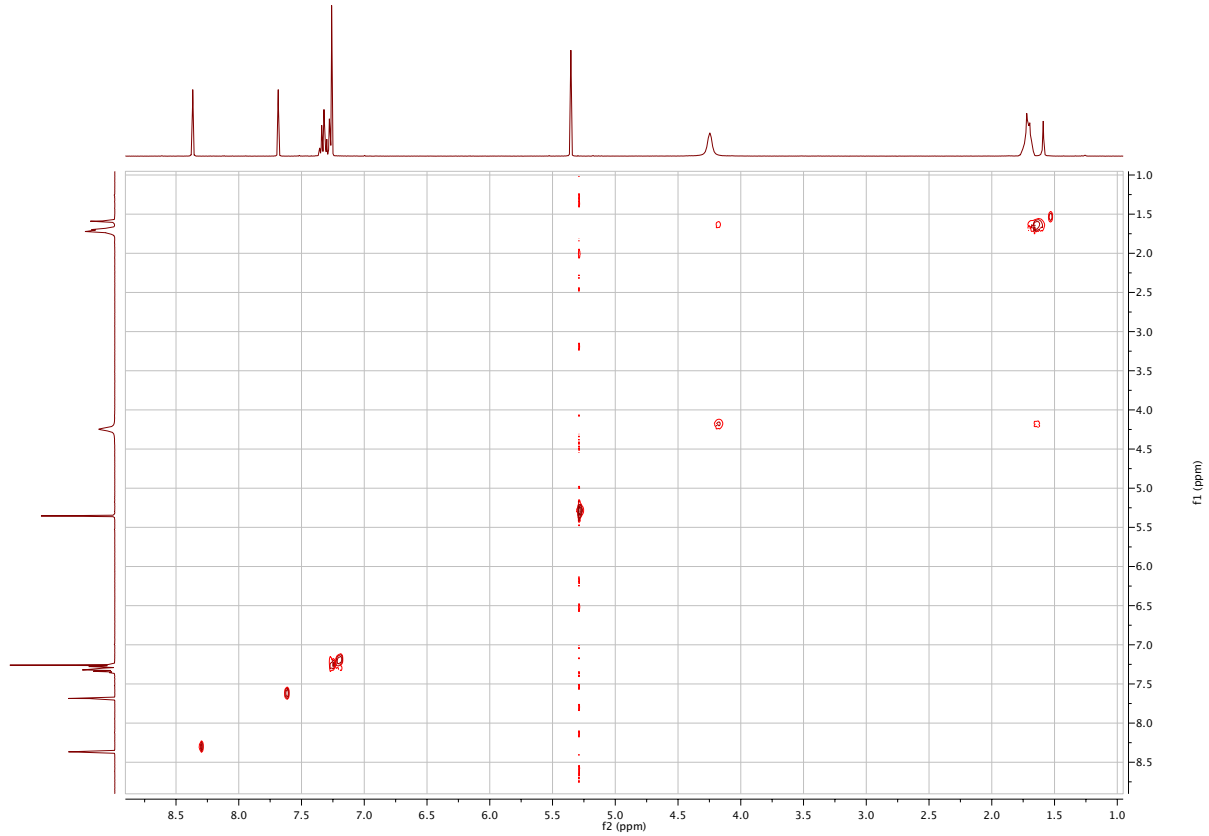
M.p. 91-93 ^{o}C.



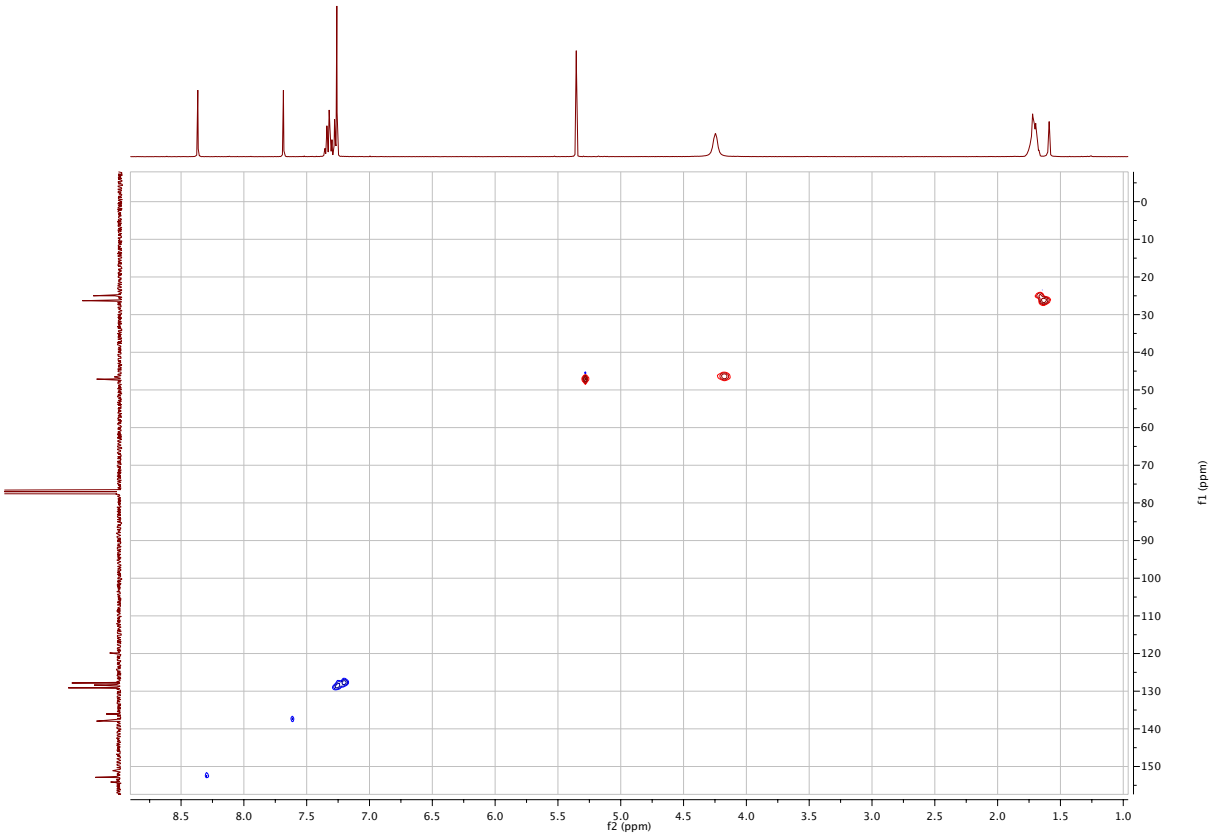
Spectrum 23. 400 MHz, $CDCl_3$, ^{1}H NMR of 9-benzyl-6-(piperidin-1-yl)-*9H*-purine (**113**)



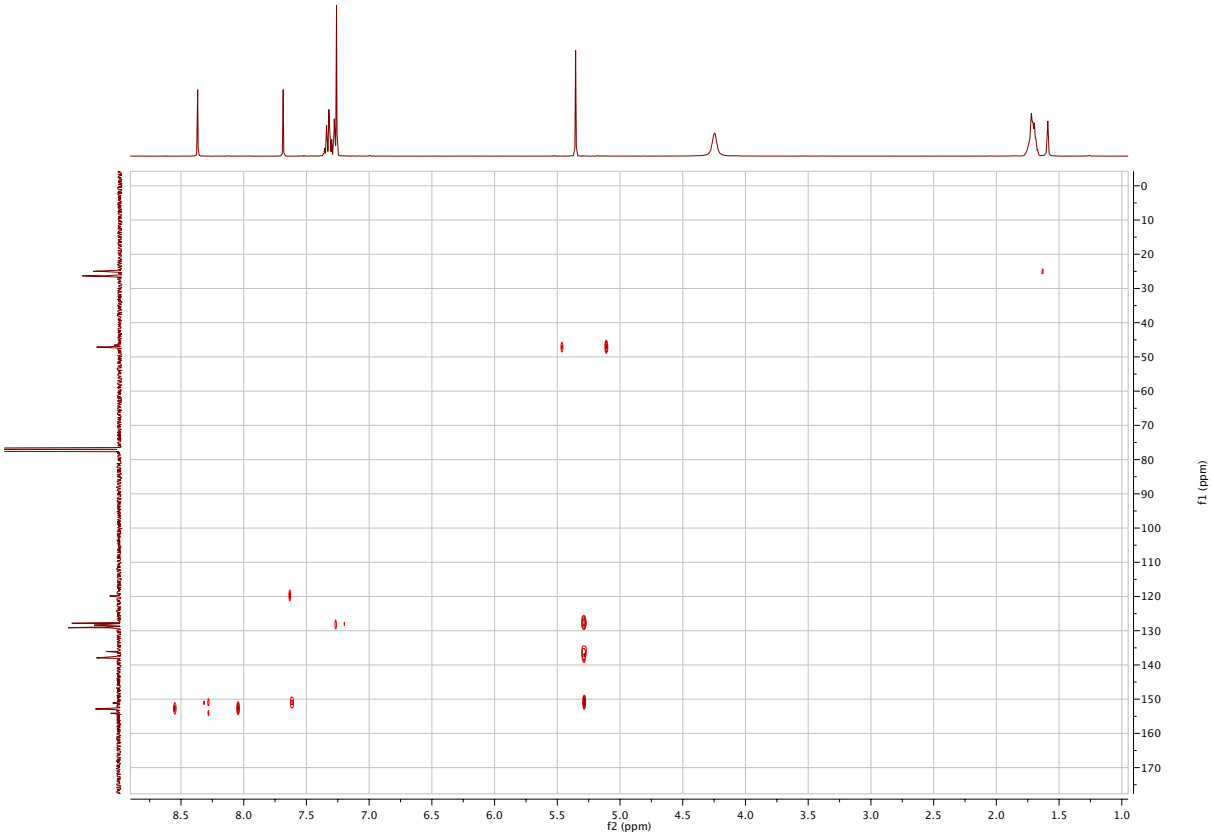
Spectrum 24. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-benzyl-6-(piperidin-1-yl)-*9H*-purine (**113**)



Spectrum 25. 400 MHz, $CDCl_3$, COSY of 9-benzyl-6-(piperidin-1-yl)-*9H*-purine (**113**)

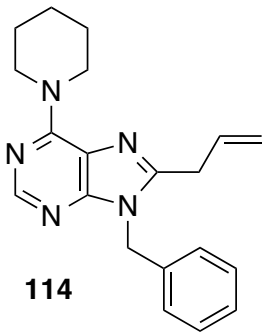


Spectrum 26. 400 MHz, $CDCl_3$, HSQC of 9-benzyl-6-(piperidin-1-yl)-*9H*-purine (**113**)



Spectrum 27. 400 MHz, $CDCl_3$, HMBC of 9-benzyl-6-(piperidin-1-yl)-*9H*-purine (**113**)

Synthesis of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (114)



114

Allyl magnesium bromide (2.08 mL, 1.35 mmol of 0.65 M solution in diethyl ether) was added to a solution of compound **113** (131 mg, 0.448 mmol) in THF (5 mL) at 0 ºC under N_2-atm and the resulting mixture was stirred at 0 ºC for 4 hours. Sat. aq. NH_4Cl (10 mL) was added, the phases were separated and the water layer was extracted with EtOAc (2 x10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The product was purified by flash chromatography eluting with acetone-EtOAc-hexane (1:1:8) to give 63 mg (42%) of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine **114** as a yellow oil.

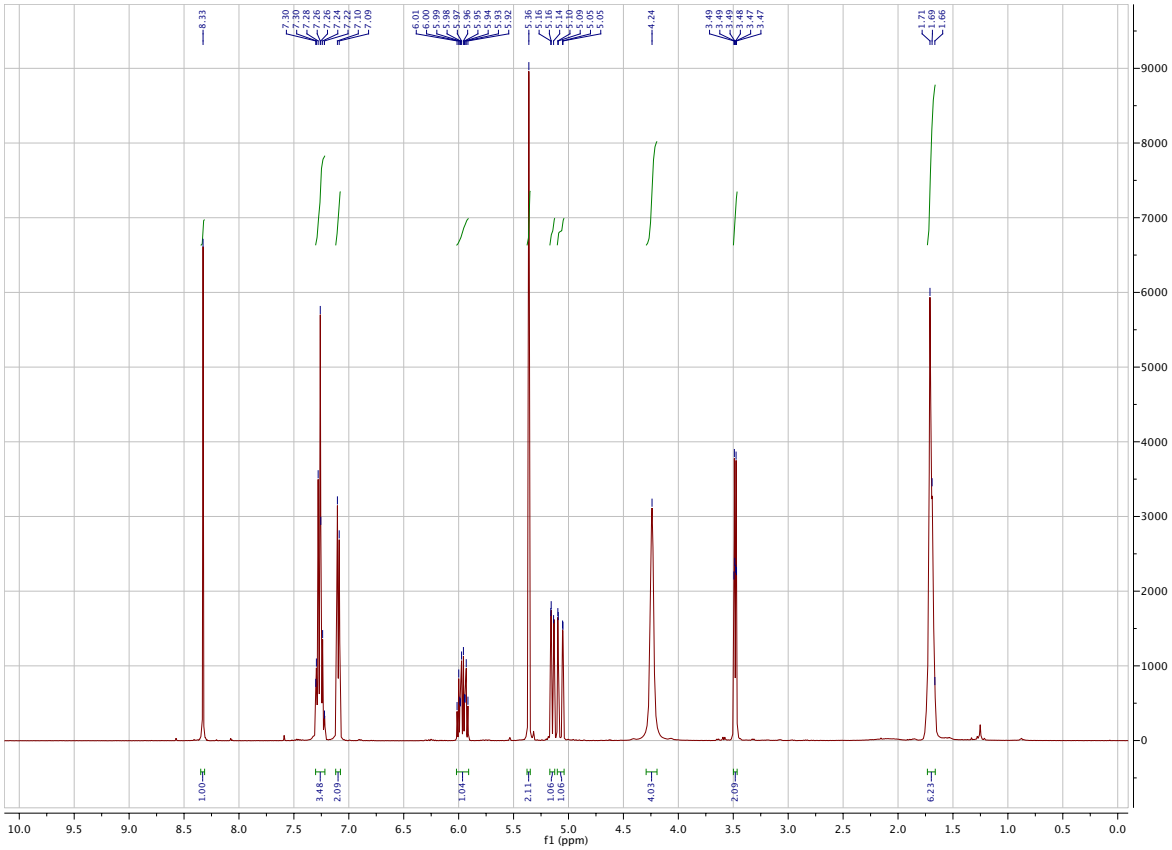
8-Allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (114)

^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.66-1.71 (m, 6H, 3xCH_2 in piperidinyl), 3.48 (dt, J = 6.4, 1.6 Hz, 2H, C(8)CH_2), 4.24 (brs, 4H, 2 x NCH_2 in piperidinyl), 5.07 (dd, J = 17.2, 1.6 Hz, 1H, =CH_{2a} in C(8) allyl), 5.15 (dd, J = 10.0, 1.6 Hz, 1H, =CH_{2b} in C(8) allyl), 5.36 (s, 2H, N(9)CH_2), 5.91-6.01 (m, 1H, CH= in C(8)), 7.08-7.10 (m, 2H, H in Ph), 7.22-7.30 (m, 3H, H in Ph), 8.33 (s, 1H, H-2).

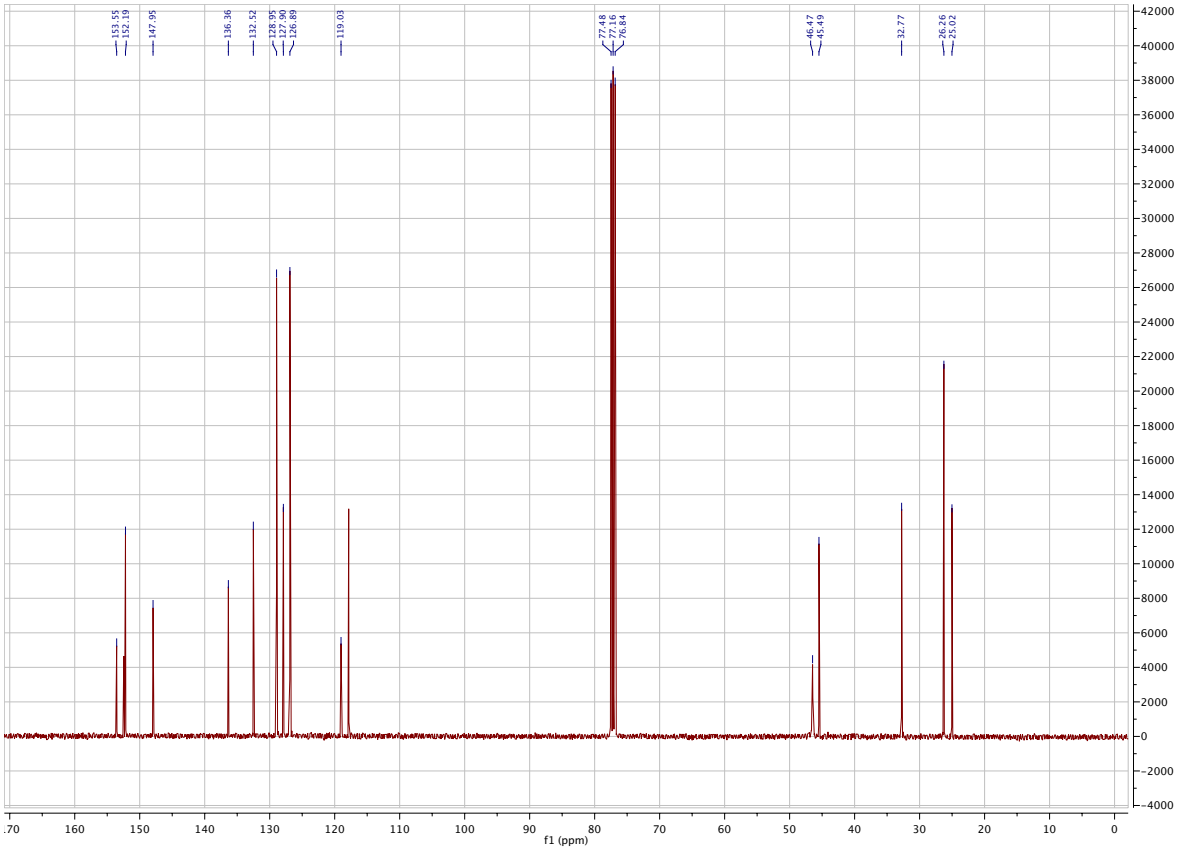
^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.02 (CH_2 in piperidinyl), 26.26 (2 x CH_2 in piperidinyl), 32.77 (C(8)$\underline{C}H_2$), 45.49 (N(9)CH_2), 46.47 (2 x NCH_2 in piperidinyl), 117.84 (=CH_2 in C(8) allyl), 119.03 (C-5), 126.89 (CH in Ph), 127.90 (CH in Ph), 128.95 (CH in Ph), 132.52 (CH= in C(8) allyl), 136.36 (C in Ph), 147.95 (C-8), 152.19 (C-4), 152.46 (C-2), 153.55 (C-6).

MS (EI) *m/z* (rel. %): 334/333 (22/100, M^+), 304 (18), 290 (14), 277 (28), 264 (6), 250 (8), 242 (36), 214 (8), 91 (44).

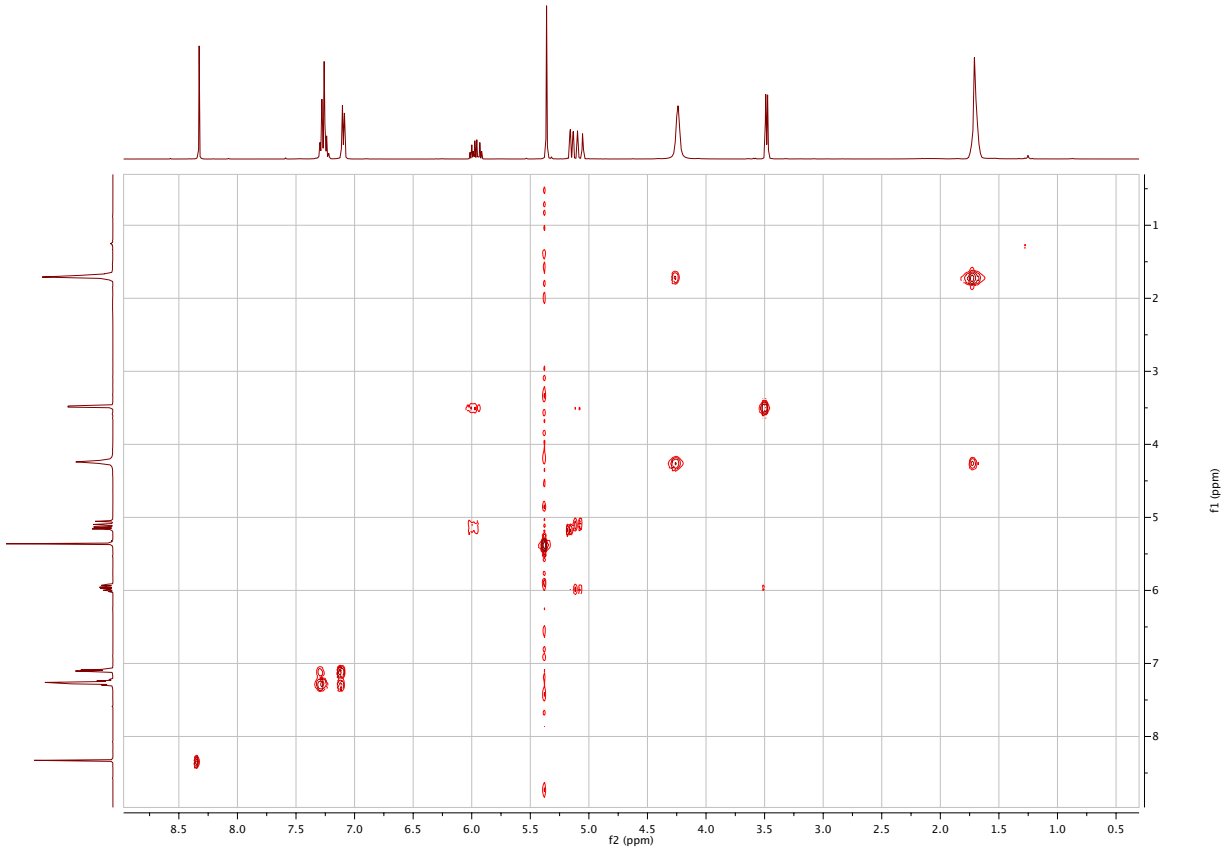
HRMS Found 333.1949 calculated for $C_{20}H_{23}N_5$ 333.1953.



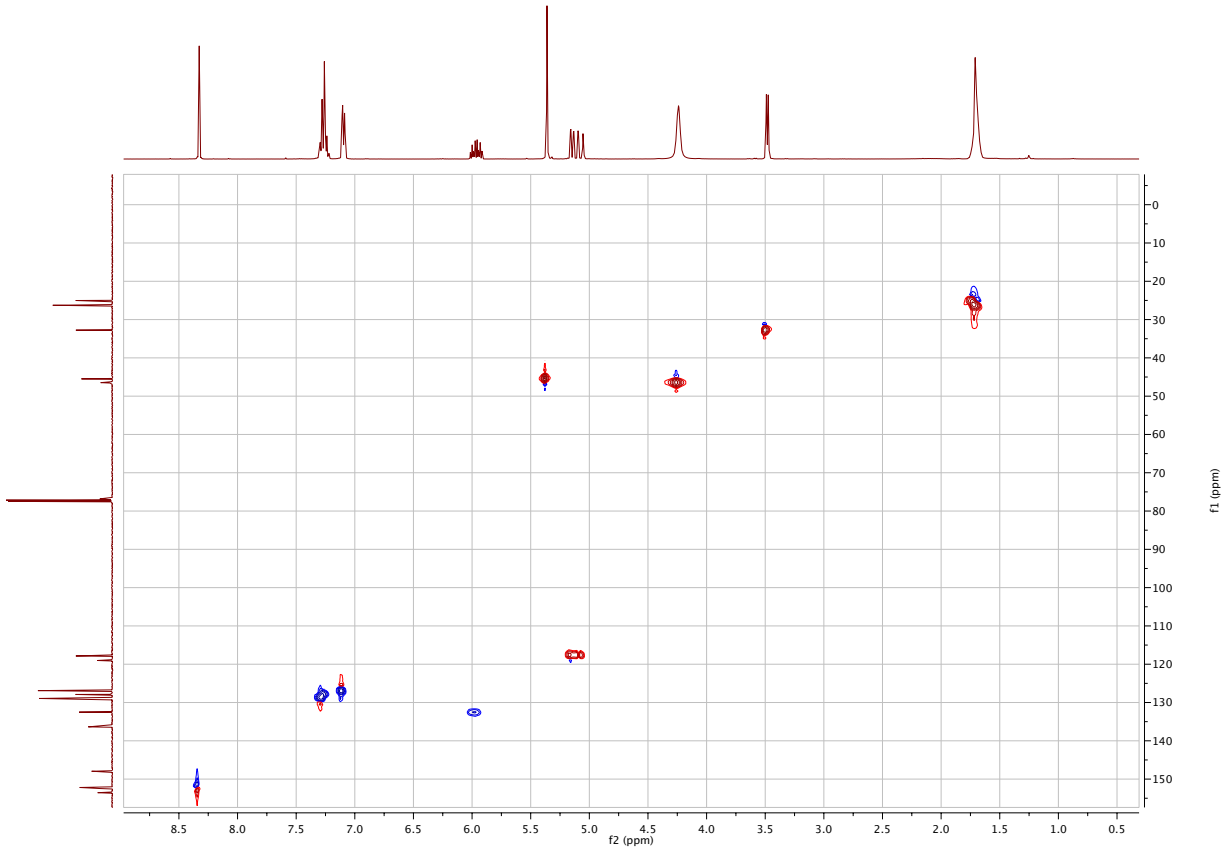
Spectrum 28. 400 MHz, $CDCl_3$, ^1H NMR of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (**114**)



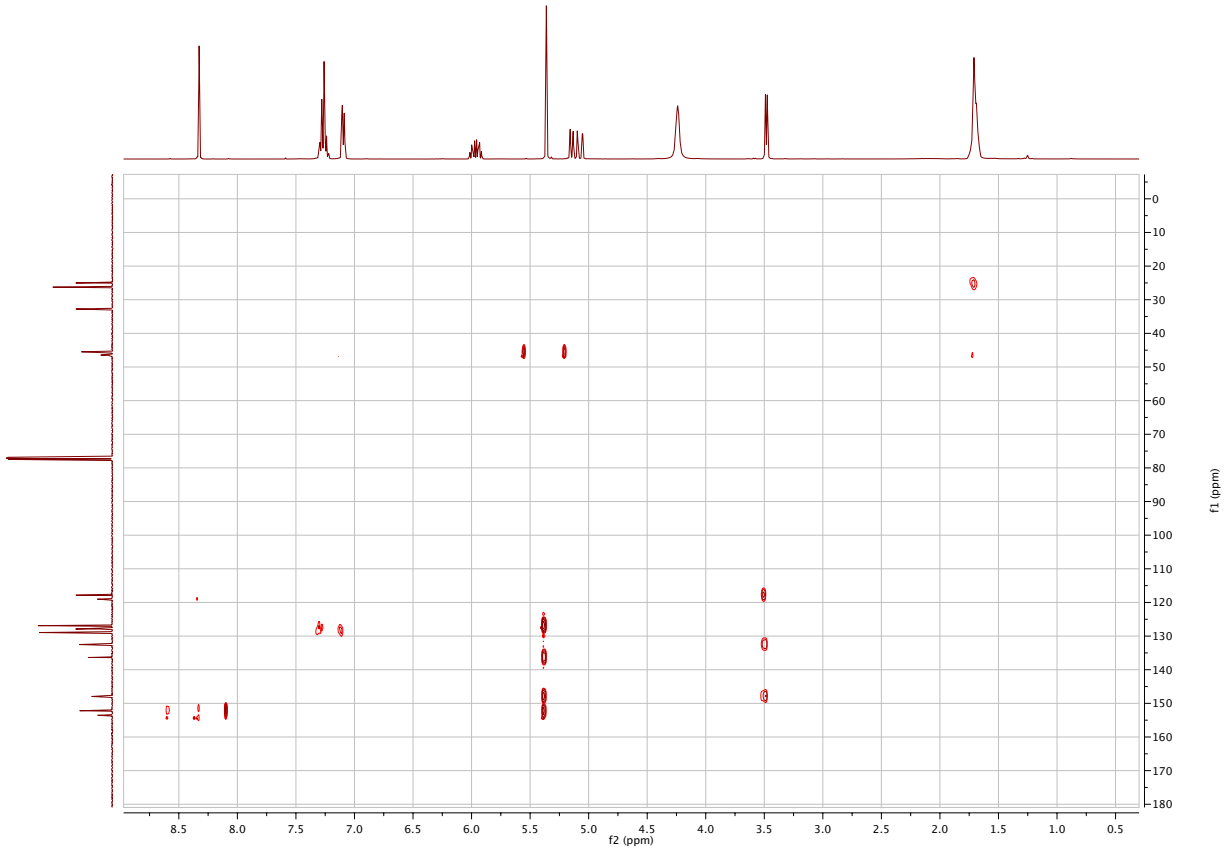
Spectrum 29. 100 MHz, $CDCl_3$, ^{13}C NMR of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (**114**)



Spectrum 30. 400 MHz, $CDCl_3$, COSY of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (**114**)

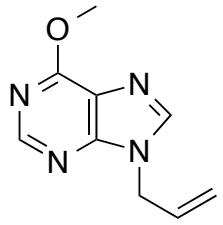


Spectrum 31. 400 MHz, $CDCl_3$, HSQC of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (**114**)



Spectrum 32. 400 MHz, $CDCl_3$, HMBC of 8-allyl-9-benzyl-6-(piperidin-1-yl)-9*H*-purine (**114**)

Synthesis of 9-allyl-6-methoxy-9*H*-purine (115)



115

9-Allyl-6-chloro-9*H*-purine **103** (200 mg, 1.02 mmol) was added to a stirred solution of sodium (90mg, 3.9mmol) in dry MeOH (10mL). The reaction was stirred for 28 hours at ambient temperature under Ar-atm. Water (20 mL) was added and the pH was adjusted to neutral by the addition of 1M HCl. The mixture was extracted with EtOAc (100 mL, followed by 5 × 20 mL). The combined organic extracts were washed with brine (20 mL), dried ($MgSO_4$) and evaporated *in vacuo*. The product **115** was purified by flash chromatography on silica gel eluting with MeOH-DCM (1:49); yield 189 mg (97%) as a pale yellow solid.

***9-Allyl-6-methoxy-9H-purine* (115)**

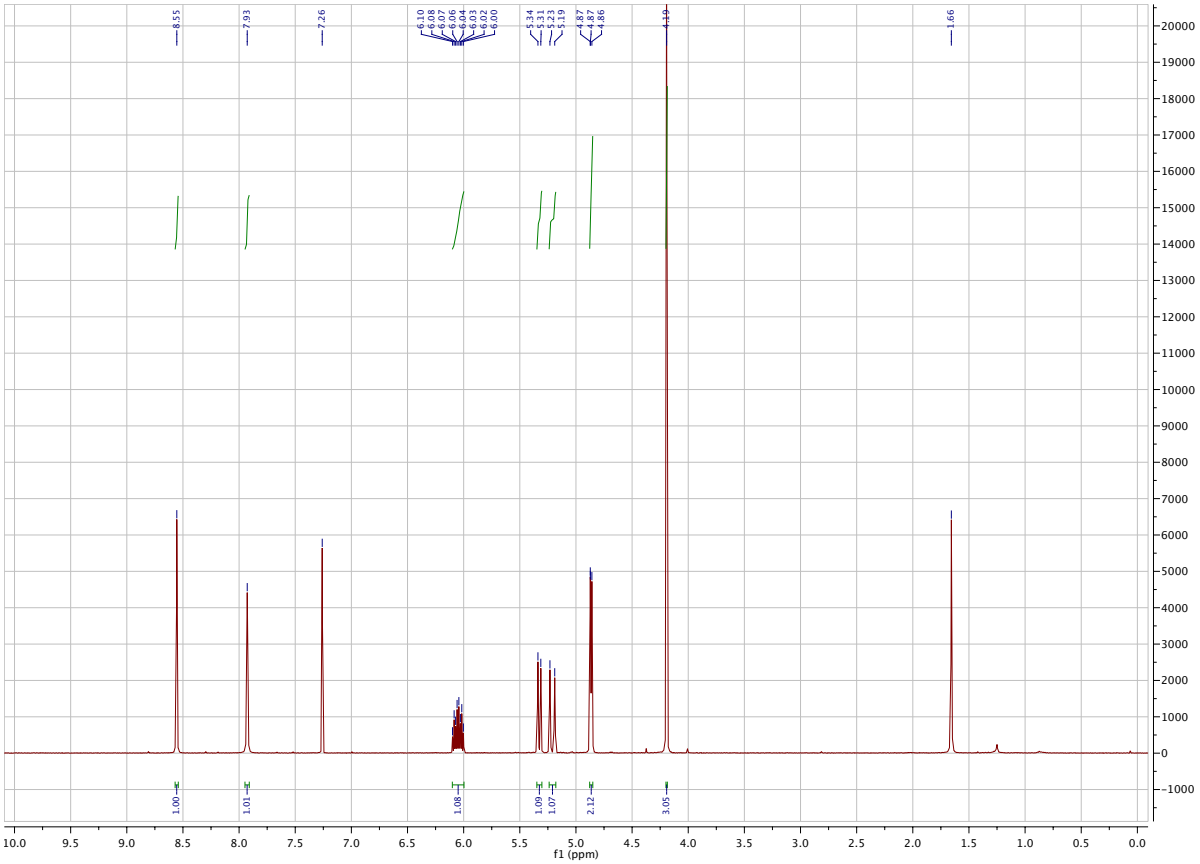
^{1}H NMR (400 MHz, $CDCl_3$): δ 4.19 (s, 3H, CH_3O), 4.86 (d, J = 5.6 Hz, 2H, N(9)CH_2), 5.21 (d, J = 17.2 Hz, 1H, H_a in =CH_2), 5.32 (d, J = 10.0 Hz, 1H, H_b in =CH_2), 6.00-6.10 (m, 1H, CH=), 7.93 (s, 1H, H-8), 8.55 (s, 1H, H-2).

^{13}C NMR (100 MHz, $CDCl_3$): δ 46.1 (NCH_2), 54.4 (OCH_3), 119.3 (=CH_2), 121.6 (C-5), 131.7 (CH=), 142.1 (C-8), 150.9 (C-4), 152.4 (C-2), 161.3 (C-6).

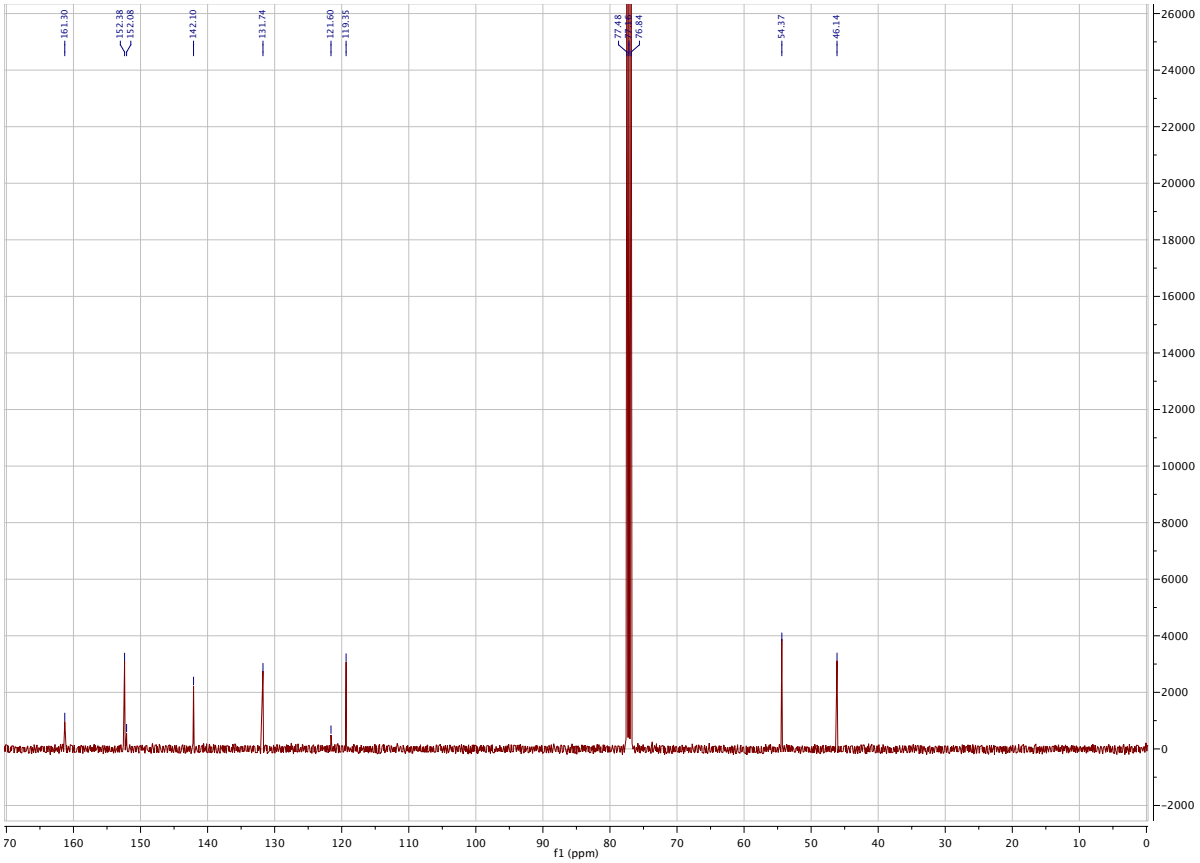
MS (EI) *m/z* (rel. int.): 190 (100, M^+), 160 (7), 148 (20), 132 (9), 120 (9).

HRMS Found 190.0861 calculated for $C_9H_{10}N_4O$ 190.0855.

Mp: 64-66 °C (Lit.[93] 77-79 °C).

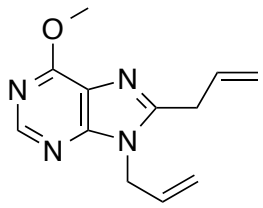


Spectrum 33. 400 MHz, $CDCl_3$, ^1H NMR of 9-allyl-6-methoxy-*9H*-purine (**115**)



Spectrum 34. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-allyl-6-methoxy-*9H*-purine (**115**)

Synthesis of 8,9-diallyl-6-methoxy-9*H*-purine (116)



116

Allyl magnesium bromide (3.90 mL, 2.70 mmol of 0.69 M solution in diethyl ether) was added to a solution of compound **115** (170 mg, 0.896 mmol) in THF (10 mL) at 0 ºC under N_2-atm and the resulting mixture was stirred at 0 ºC for 4 hours. Sat. aq. NH_4Cl (20 mL) was added, the phases were separated and the water layer was extracted with EtOAc (2 x 20 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The product was purified by flash chromatography eluting with acetone-EtOAc-hexane (1:1:8) to give 118 mg (57%) of 8,9-diallyl-6-methoxy-9*H*-purine **116** as a yellow oil.

8,9-Diallyl-6-methoxy-9*H*-purine (116)

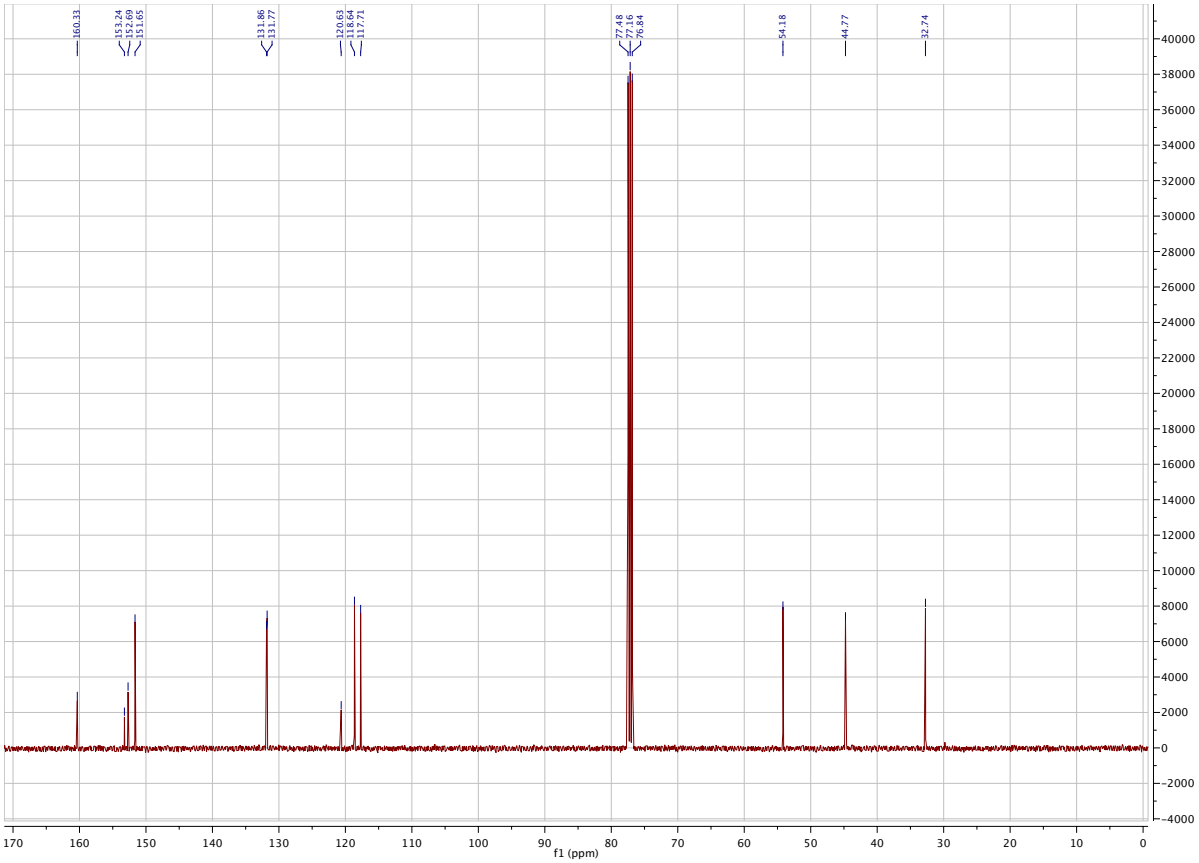
^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.66 (dt, *J* = 6.4, 1.2 Hz, 2H, C(8)CH_2), 4.16 (s, 3H, OCH_3), 4.84 (dt, *J* = 5.2, 1.6 Hz, 2H, N(9)CH_2), 4.95 (d, *J* = 17.2, 1.6 Hz, 1H, =CH_{2a} in C(8) allyl), 5.16-5.24 (m, 3H, =CH_{2b} in C(8) allyl and = CH_2 in N(9) allyl), 5.90-6.12 (m, 2H, 2 x CH), 8.49 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 32.74 (C(8)$\underline{C}H_2$), 44.77 (N(9)CH_2), 54.18 (OCH_3), 117.71 (CH_2 in C(8) allyl), 118.64 (C-5), 120.63 (=CH_2 in N(9) allyl), 131.77 (CH= in N(9) allyl), 131.86 (CH= in C(8) allyl), 151.65 (C-8), 152.69 (C-4), 153.24 (C-2), 160.33 (C-6).

MS (EI) *m/z* (rel. %): 229/230 (87/100, M^+), 215 (6), 203 (9), 189 (23), 41(11).

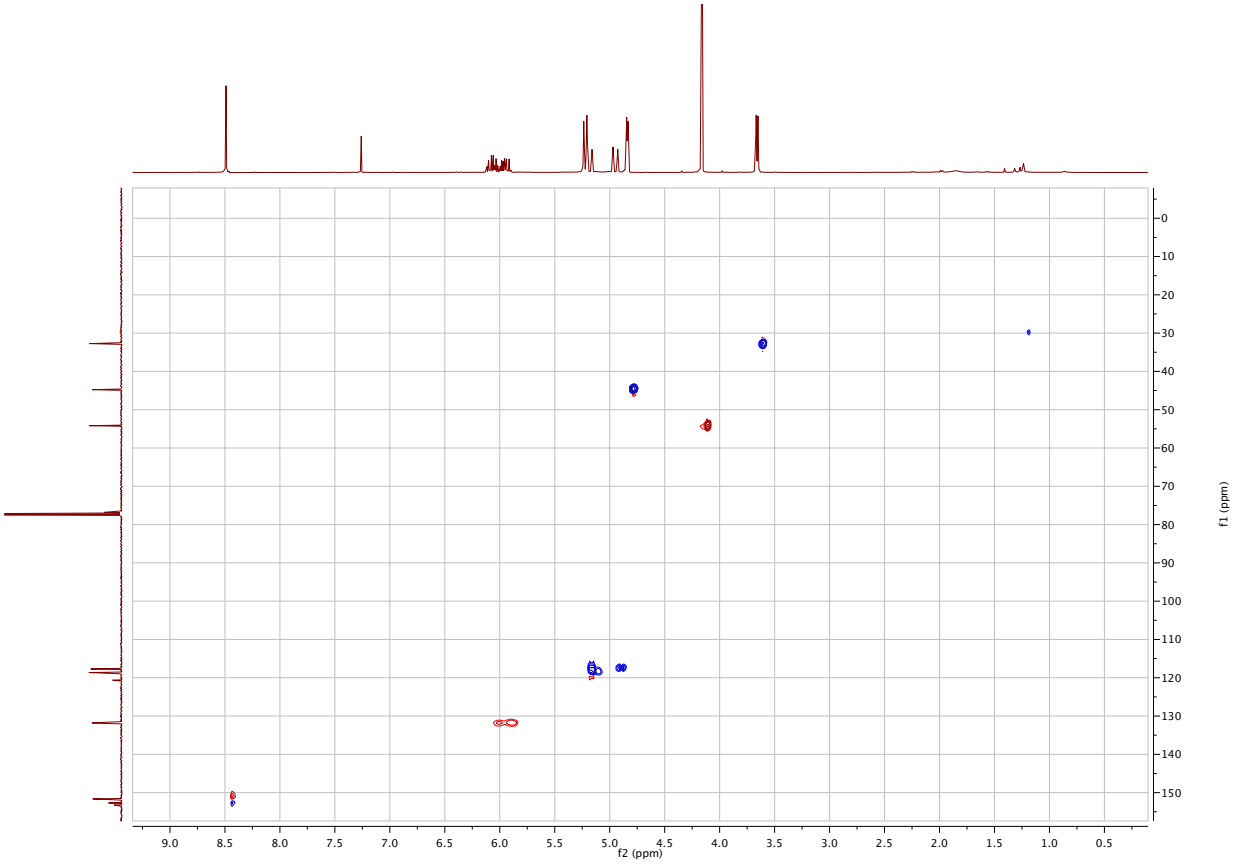
HRMS Found 230.1162 calculated for $C_{12}H_{14}N_4O$ 230.1167.

Spectrum 35. 400 MHz, $CDCl_3$, ^{1}H NMR of 8,9-diallyl-6-methoxy-9*H*-purine (**116**)

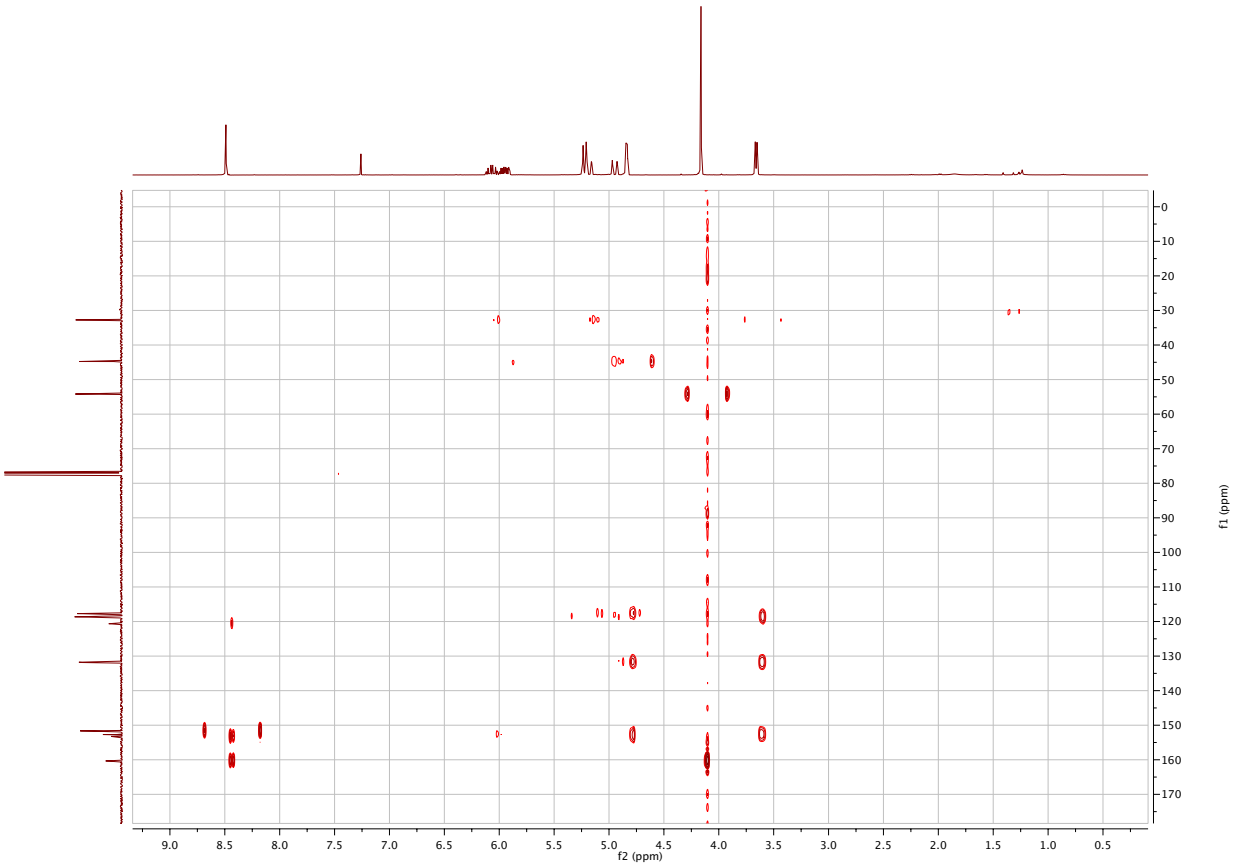


Spectrum 36. 100 MHz, $CDCl_3$, ^{13}C NMR of 8,9-diallyl-6-methoxy-9*H*-purine (**116**)

Spectrum 37. 400 MHz, $CDCl_3$, COSY of 8,9-diallyl-6-methoxy-9*H*-purine (**116**)

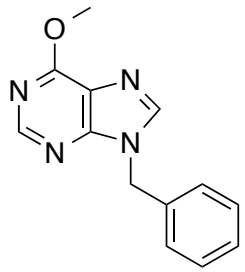


Spectrum 38. 400 MHz, $CDCl_3$, HSQC of 8,9-diallyl-6-methoxy-9*H*-purine (**116**)



Spectrum 39. 400 MHz, $CDCl_3$, HMBC of 8,9-diallyl-6-methoxy-9*H*-purine (**116**)

Synthesis of 9-benzyl-6-methoxy-9*H*-purine (117)



117

9-Benzyl-6-chloro-9*H*-purine **107** (250 mg, 1.02 mmol) was added to a stirred solution of sodium (90 mg, 3.9 mmol) in dry MeOH (10mL). The mixture was stirred for 28 hours at ambient temperature under Ar-atm. Water (20 mL) was added and the pH was adjusted to neutral by the addition of 1 M HCl. The mixture was extracted with EtOAc (100 mL, followed by 5 × 20 mL). The combined organic extracts were washed with brine (20 mL), dried ($MgSO_4$) and evaporated *in vacuo*. The product **117** was purified by flash chromatography on silica gel eluting with MeOH-DCM (1:49); yield 234 mg (96%) as a colorless solid.

9-Benzyl-6-methoxy-9*H*-purine (117)

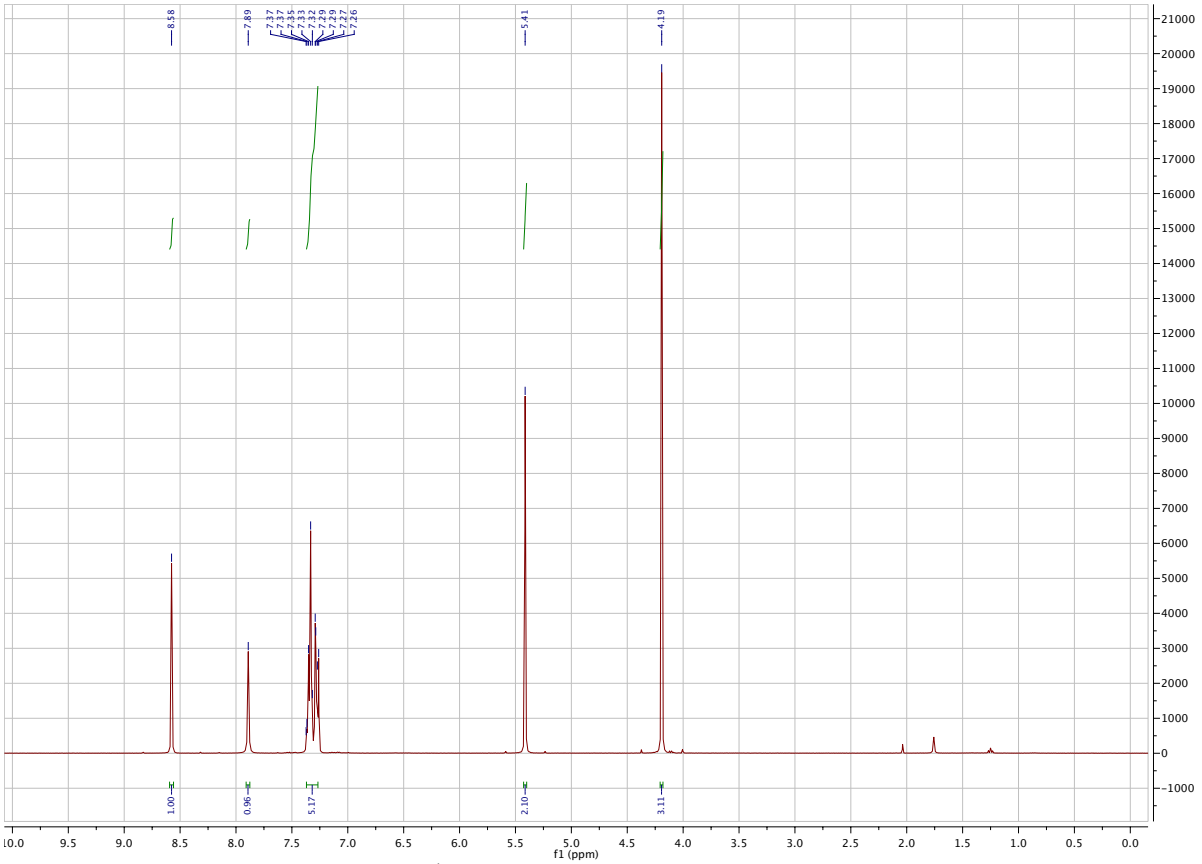
^{1}H NMR ($CDCl_3$, 400 MHz): δ 4.19 (s, 3H, CH_3O), 5.41 (s, 2H, NCH_2), 7.27-7.37 (m, 5H in Ph), 7.89 (s, 1H, H-8), 8.58 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz): δ 47.61 ($N(9)CH_2$), 54.36 (OCH_3), 121.58 (C-5), 127.92 (CH in Ph), 128.66 (CH in Ph), 129.24 (CH in Ph), 138.41 (C in Ph), 142.12 (C-8), 152.25 (C-4), 152.45 (C-2), 161.30 (C-6).

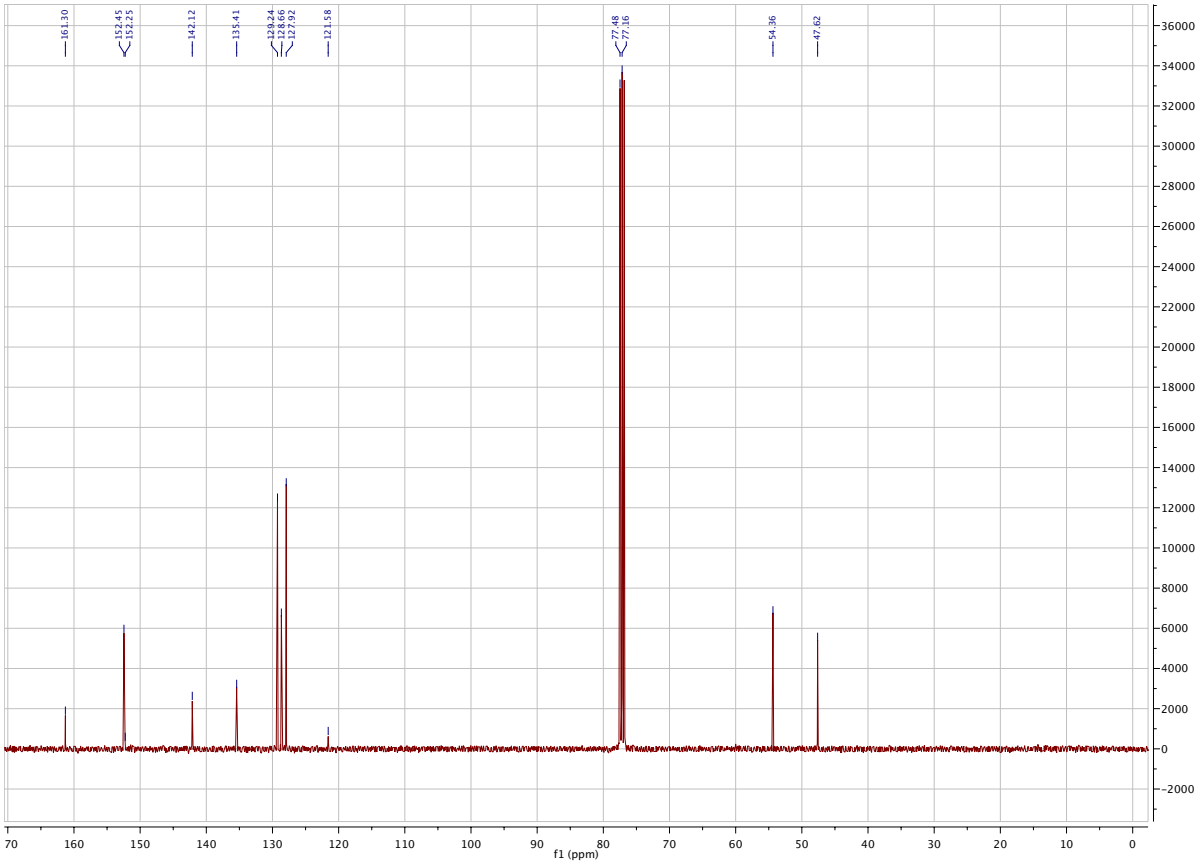
MS (EI) *m/z* (rel. %): 239/240 (88/85, M^+), 209 (6), 183 (11), 163 (9), 149 (7), 91 (100), 65 (18).

HRMS Found 240.1005 calculated for $C_{13}H_{14}N_4O$ 240.1011.

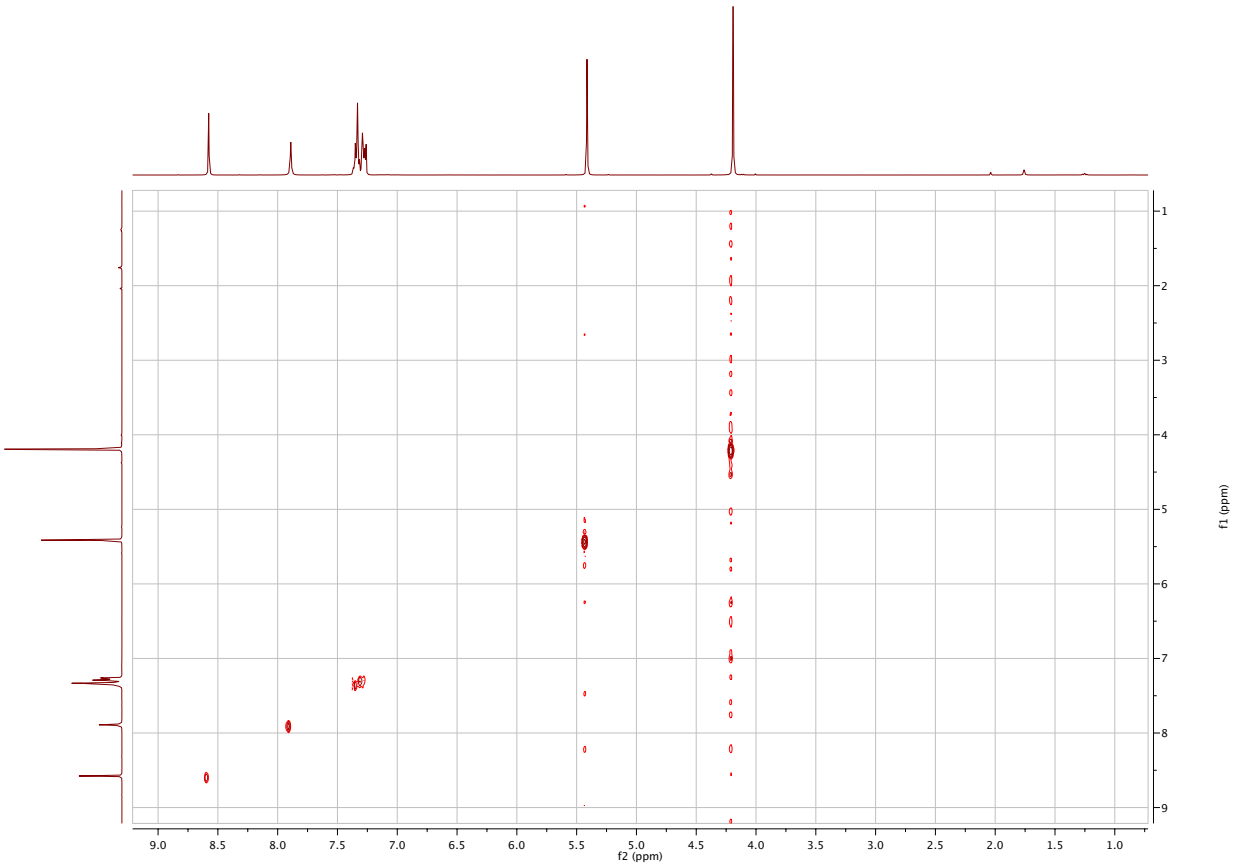
M.p: 116-117 ^oC.



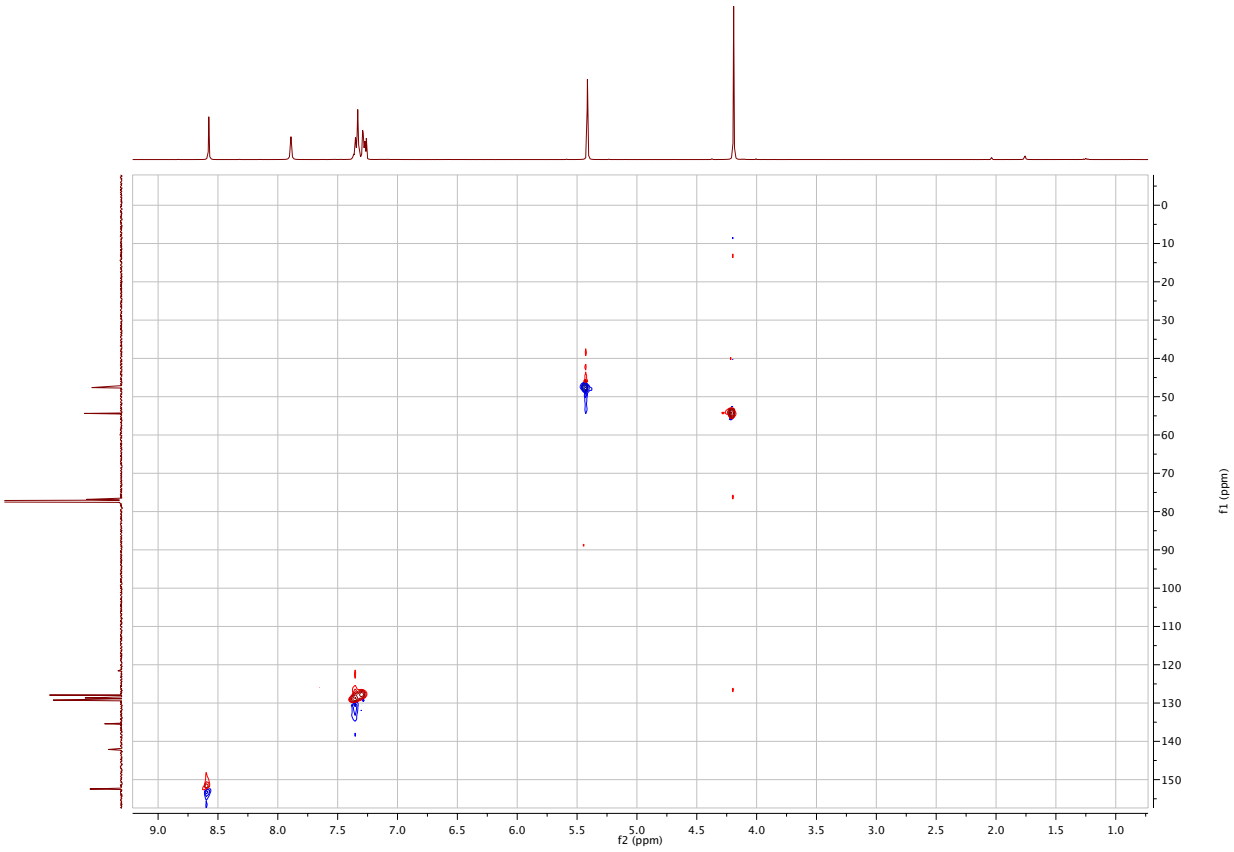
Spectrum 40. 400 MHz, $CDCl_3$, ^1H NMR of 9-benzyl-6-methoxy-9*H*-purine (**117)**



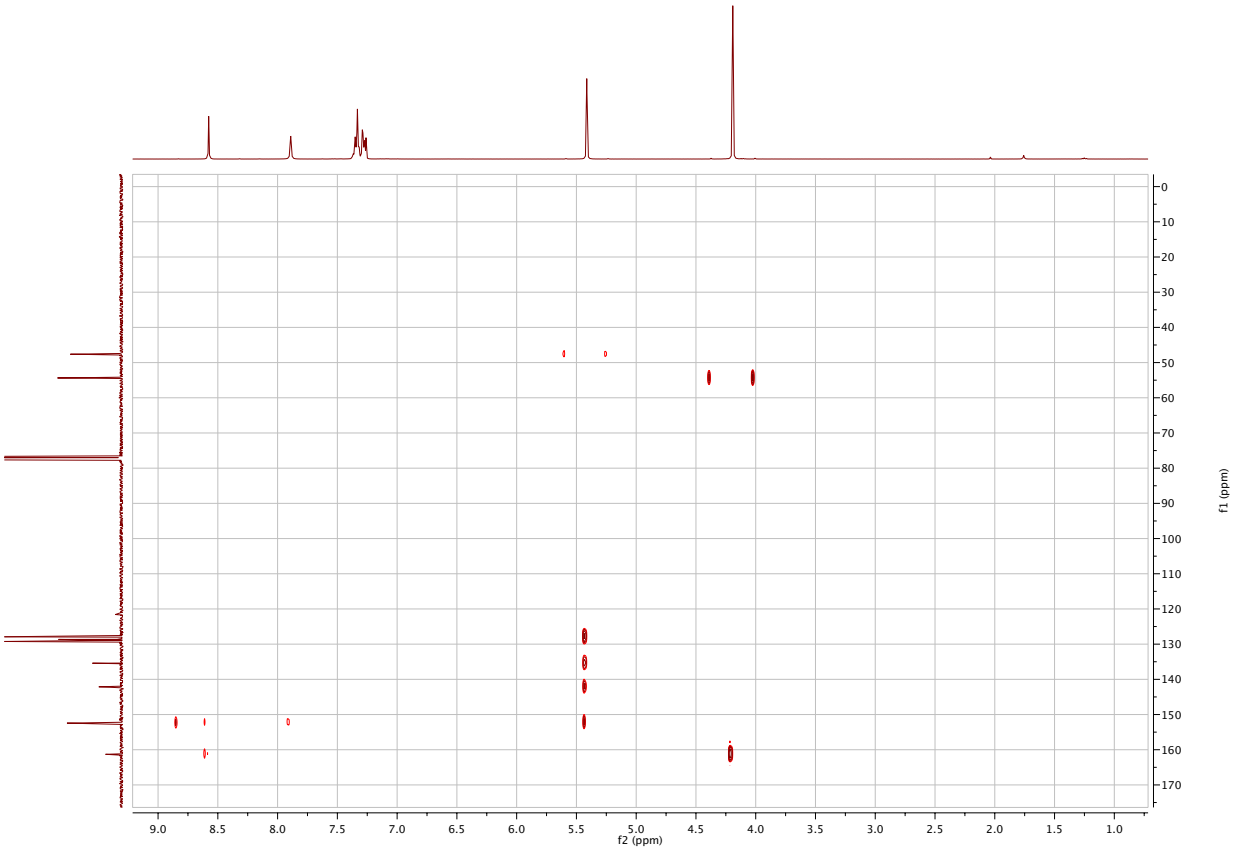
Spectrum 41. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-benzyl-6-methoxy-9*H*-purine (**117**)



Spectrum 42. 400 MHz, $CDCl_3$, COSY of 9-benzyl-6-methoxy-9*H*-purine (**117**)

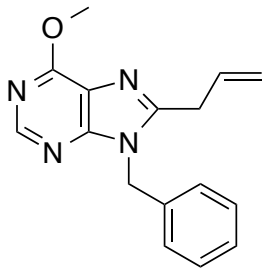


Spectrum 43. 400 MHz, $CDCl_3$, HSQC of 9-benzyl-6-methoxy-9*H*-purine (**117**)



Spectrum 44. 400 MHz, $CDCl_3$, HMBC of 9-benzyl-6-methoxy-9*H*-purine (**117**)

Synthesis of 8-allyl-9-benzyl-6-methoxy-9*H*-purine (118)



118

Allyl magnesium bromide (4.15 mL, 2.70 mmol of 0.65 M solution in diethyl ether) was added to a solution of compound **117** (221 mg, 0.896 mmol) in THF (10 mL) at 0 ºC under N_2-atm and the resulting mixture was stirred at 0 ºC for 4 hours. Sat. aq. NH_4Cl (20 mL) was added, the phases were separated and the water layer was extracted with EtOAc (2 x20 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The product was purified by flash chromatography eluting with acetone-EtOAc-hexane (1:1:8) to give 110 mg (44%) of 8-allyl-9-benzyl-6-methoxy-9*H*-purine **118** as a yellow oil.

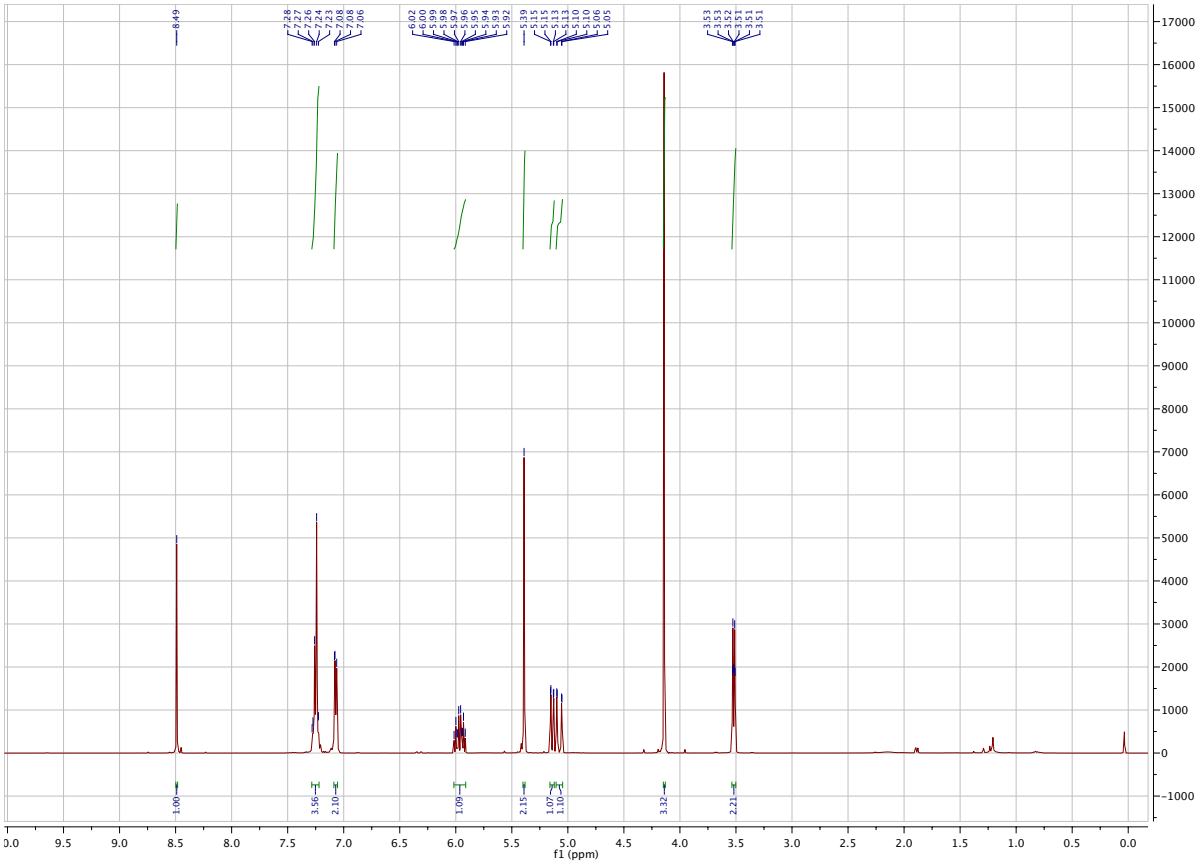
8-Allyl-9-benzyl-6-methoxy-9*H*-purine (118)

^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.52 (dt, *J* = 6.4, 1.6 Hz, 2H, C(8)CH_2), 4.14 (s, 3H, OCH_3), 5.08 (dd, *J* =17.2, 1.6 Hz, 1H, =CH_{2a} in C(8) allyl), 5.14 (dd, *J* =10.2, 1.6 Hz ,1H, =CH_{2b} in C(8) allyl), 5.39 (s, 2H, N(9)CH_2), 5.91-6.02 (m, 1H, CH in (C8) allyl), 7.06-7.08 (m, 2H, H in Ph), 7.22-7.28 (m, 3H, H in Ph), 8.49 (s, 1H, H-2).

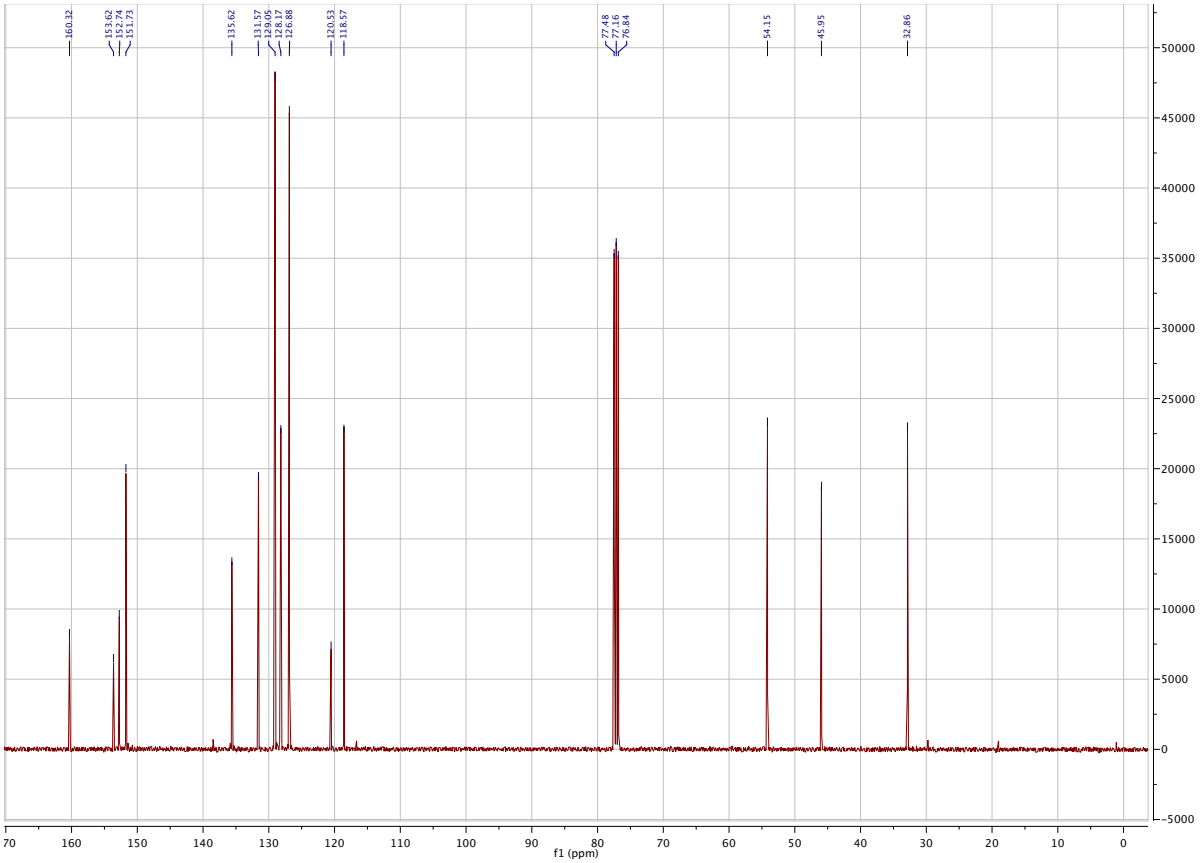
^{13}C NMR ($CDCl_3$, 100 MHz) δ 32.86 (C(8)$\underline{C}H_2$), 45.95 (N(9)CH_2), 54.15 (OCH_3), 118.57 (CH_2 in C(8) allyl), 120.53 (C-5), 126.88 (CH in Ph), 128.17 (CH in Ph), 129.05 (CH in Ph), 131.57 (CH= in C(8) allyl), 135.62 (C in Ph), 151.73 (C-8), 152.74 (C-4), 153.62 (C-2), 160.32 (C-6).

MS (EI) *m/z* (rel. %): 279/280 (61/100, M^+), 265 (6), 189 (27), 91 (67), 65(9).

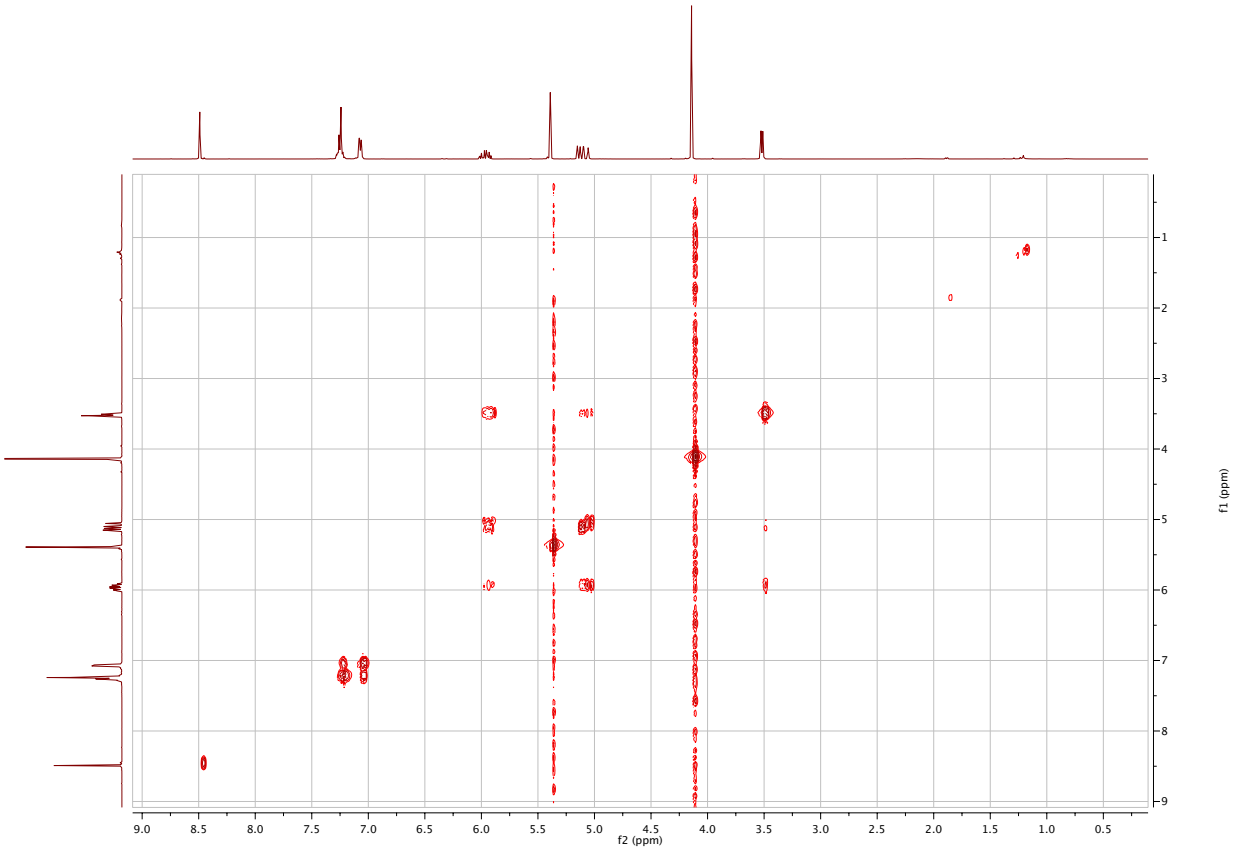
HRMS Found 280.1323 calculated for $C_{16}H_{16}N_4O$ 280.1324.



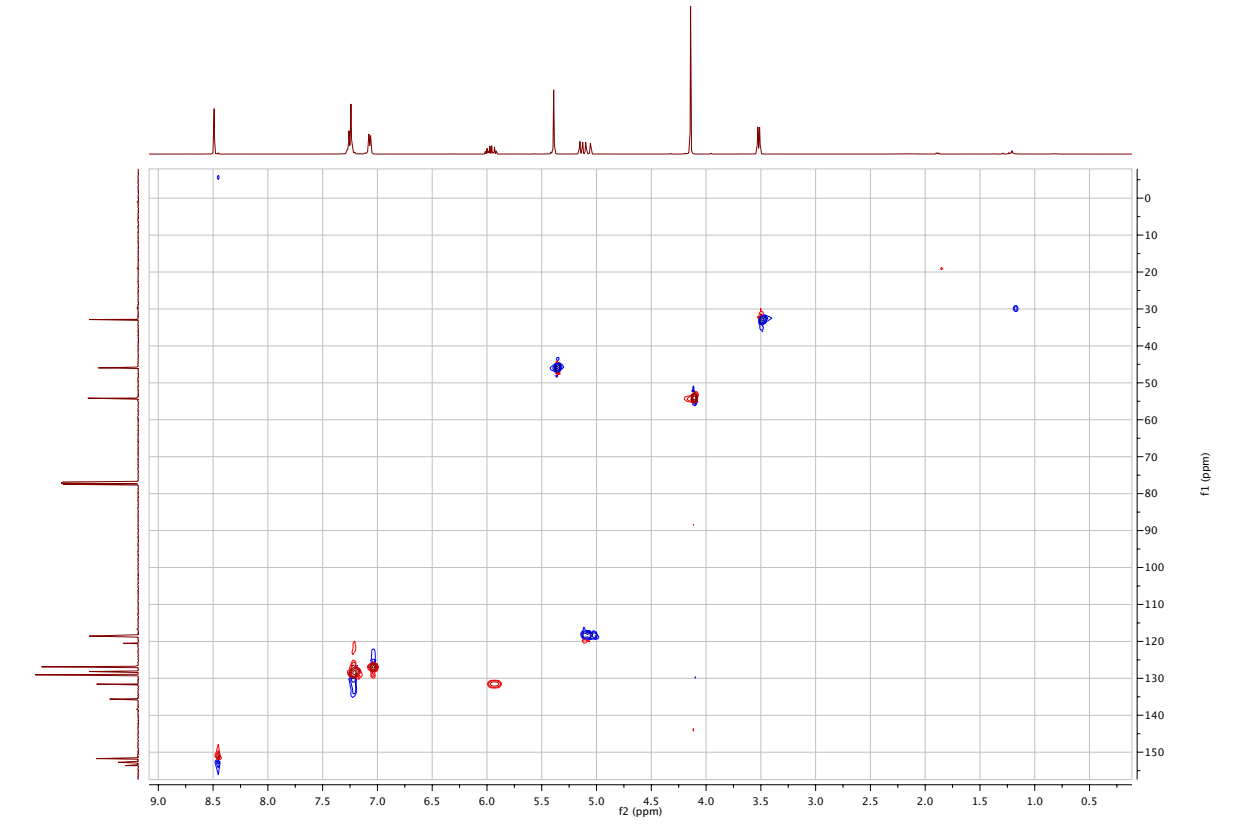
Spectrum 45. 400 MHz, $CDCl_3$, ^{1}H NMR of 8-allyl-9-benzyl-6-methoxy-9*H*-purine (**118**)



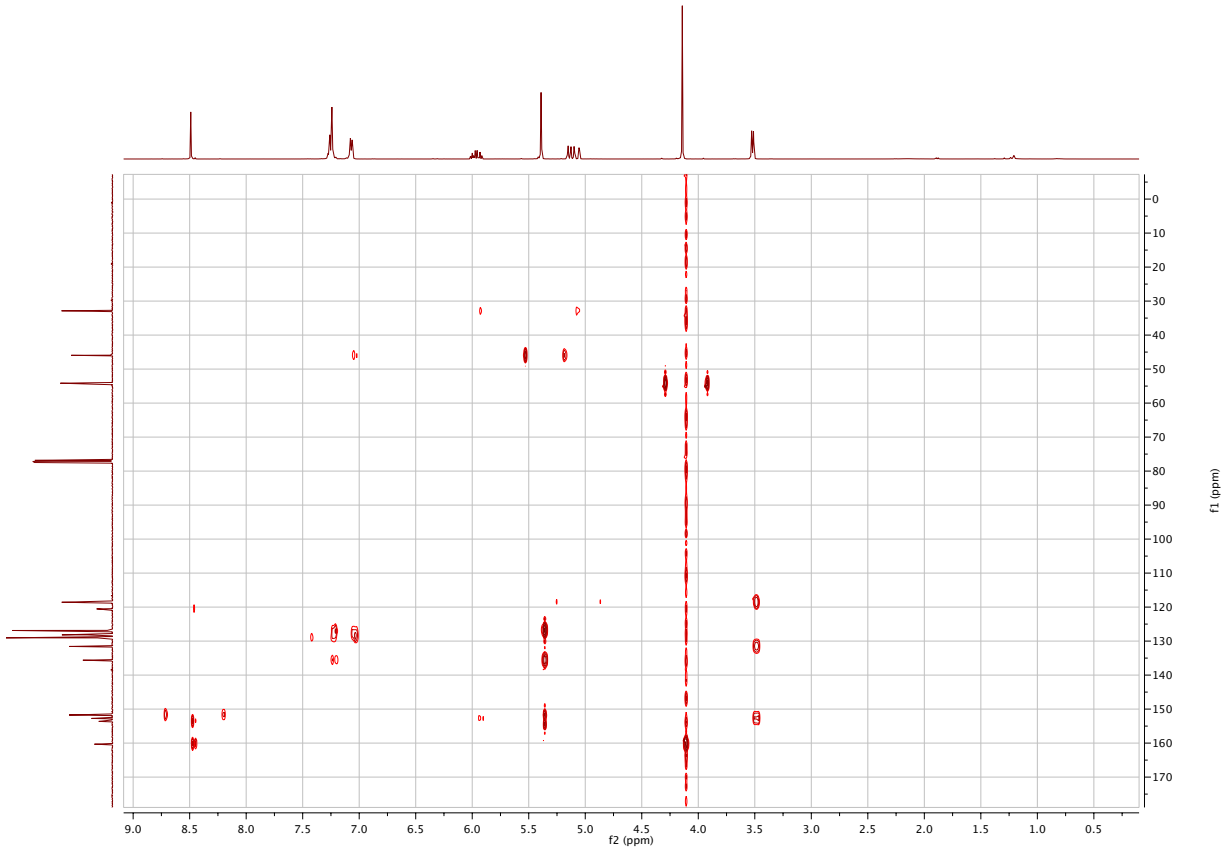
Spectrum 46. 100 MHz, $CDCl_3$, ^{13}C NMR of 8-allyl-9-benzyl-6-methoxy-9*H*-purine (**118**)



Spectrum 47. 400 MHz, $CDCl_3$, COSY of 8-allyl-9-benzyl-6-methoxy-9*H*-purine (**118**)

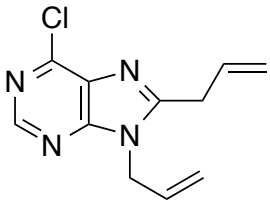


Spectrum 48. 400 MHz, $CDCl_3$, HSQC of 8-allyl-9-benzyl-6-methoxy-9*H*-purine (**118**)

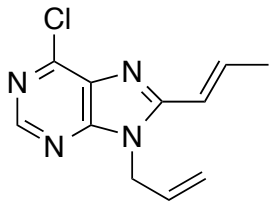


Spectrum 49. 400 MHz, $CDCl_3$, HMBC of 8-allyl-9-benzyl-6-methoxy-9*H*-purine (**118**)

Synthesis of 8,9-diallyl-6-chloro-9*H*-purine (106) and (*E*)-9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine (119)



106



119

Compound **103** (292 mg, 1.50 mmol) and indium powder (1.378 g, 12.00 mmol) were stirred in dry THF (9 mL). Allyl bromide (1.56 mL, 18.034 mmol) was added and the reaction was stirred at room temperature, saturated aqueous solution of NaCl (18 mL) was added, the phases were separated and the water layer was extracted with EtOAc (10 x 18 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated *in vacuo*. The crude product was dissolved in dry DCM (9 mL), MnO_2 (653 mg, 7.50 mmol) was added and the resulting mixture was stirred at room temperature for 2 h. The crude product was purified by flash chromatography on silica gel eluting with EtOAc-hexane (1:1) to give 220 mg (63%) as a mixture of of 8,9-diallyl-6-chloro-9*H*-purine **106** and 9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine **119** as a yellow oil.

The ratio of compounds **106**:**119** were 56:44, calculated from ^{1}H NMR.

8,9-Diallyl-6-chloro-*9H*-purine (106)

^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.76 (dt, J = 6.4, 1.6 Hz, 2H, C(8)CH_2), 4.88-4.92 (m, 2H, N(9)CH_2), 4.98-5.04 (m, 1H, CH_{2a} in C(8) allyl), 5.22-5.30 (m, 3H, CH_{2b} in C(8) allyl and =CH_2 in N(9) allyl), 5.90-6.11 (m, 2H, 2 x CH=), 8.69 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 32.97 (C(8)$\underline{C}H_2$), 44.73 (N(9)CH_2), 118.22 (=CH_2 in C(8) allyl), 119.34 (=CH_2 in N(9) allyl), 131.05 (CH= in N(9) allyl), 131.14 (CH= in C(8) allyl) 131.30 (C-5), 148.99 (C-4), 151.58 (C-2), 152.86 (C-6), 156.27 (C-8).

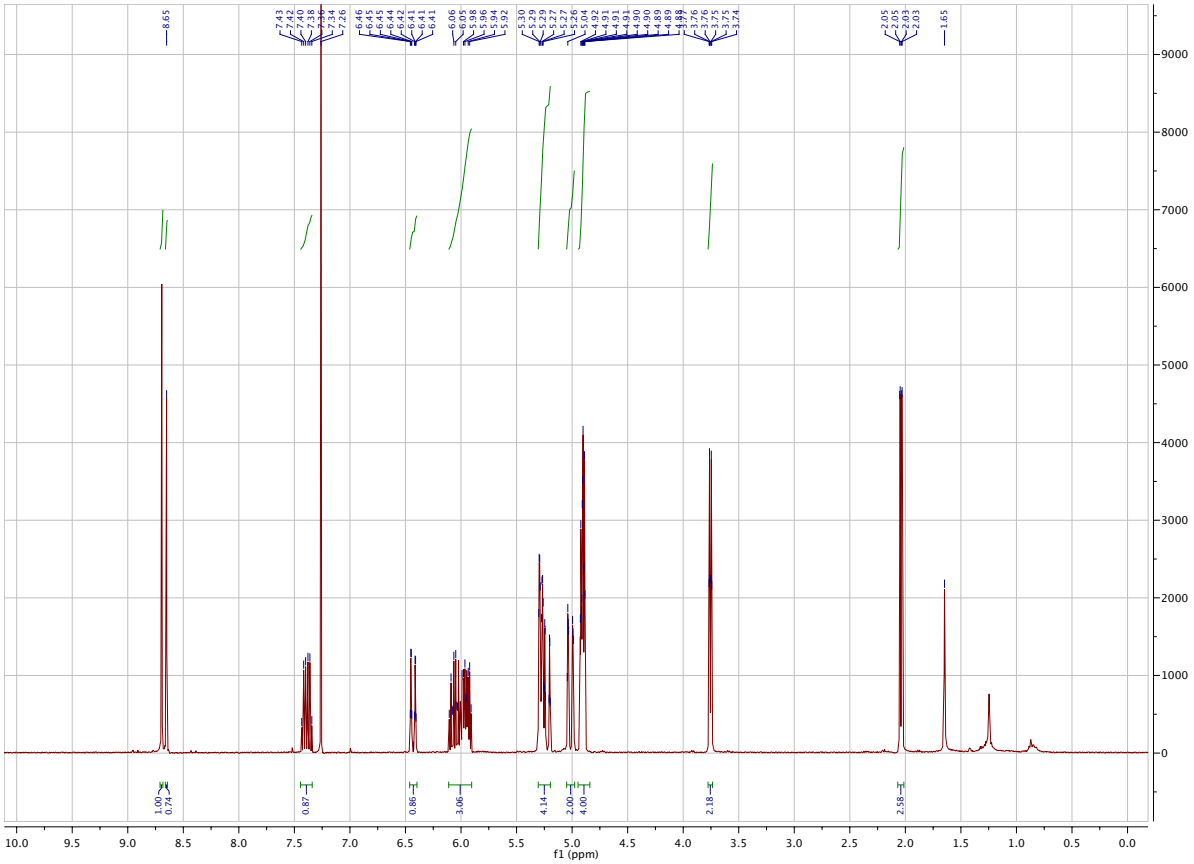
(*E*)-9-Allyl-6-chloro-8-(prop-1-en-1-yl)-9H-purine (119)

^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.04 (d, J = 6.8, 1.2 Hz, 3H, CH_3), 4.88-4.92 (m, 2H, N(9)CH_2), 4.98-5.04 (m, 1H, CH_{2a} in C(8) allyl), 5.22-5.30 (m, 1H, CH_{2b} in C(8) allyl), 6.43 (dq, J = 1.6, 15.6 Hz, 1H, C(8)CH=), 7.34-7.43 (m, 1H, C$\underline{H}CH_3$), 8.65 (s, 1H, H-2).

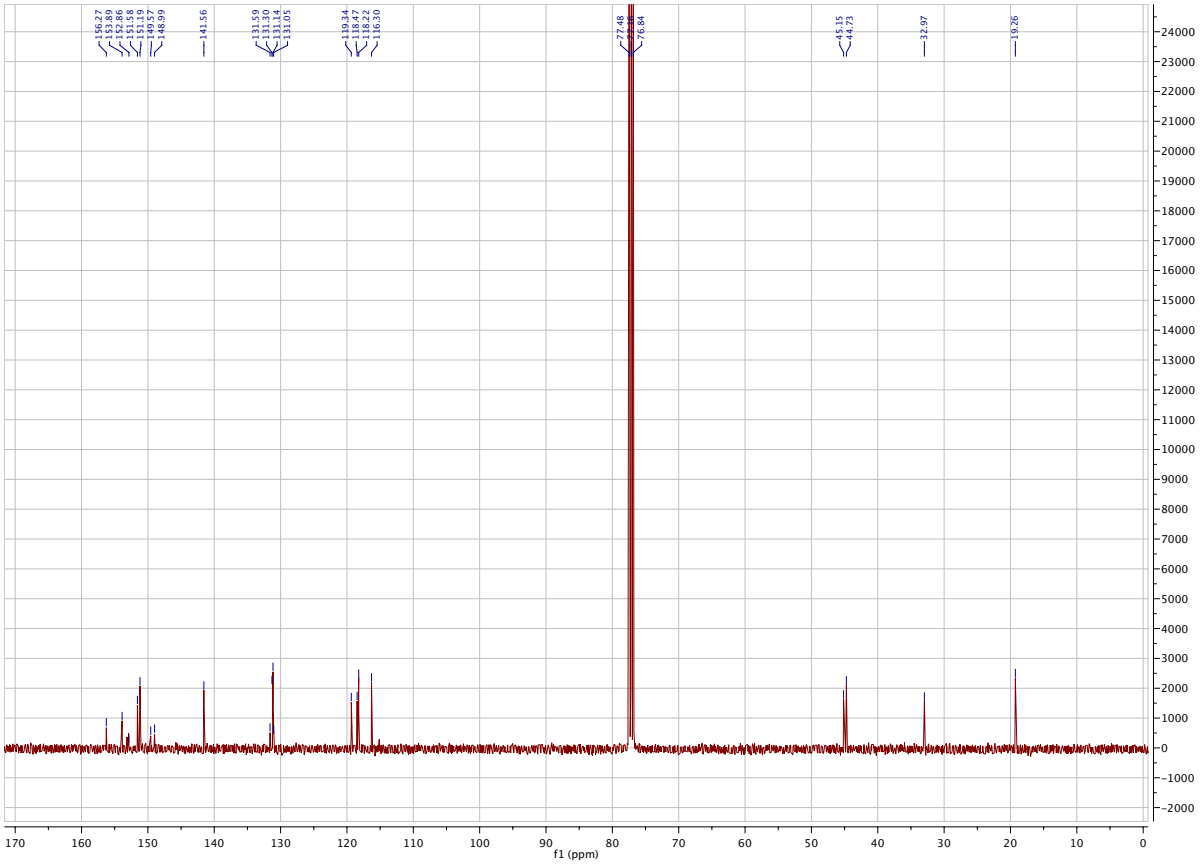
^{13}C NMR ($CDCl_3$, 100 MHz) δ 19.26 (CH_3), 45.15 (N(9)CH_2), 116.30 (C(8)$\underline{C}$H), 118.46 (=CH_2 in N(9) allyl), 131.05 (CH= in N(9) allyl), 131.59 (C-5), 141.56 ($\underline{C}HCH_3$), 149.57 (C-4), 151.19 (C-2), 153.16 (C-6), 153.88 (C-8).

MS (EI) m/z (rel. %): 236/234 (33/100, M^+), 219 (29), 207 (18), 193 (43), 168 (7), 157 (27).

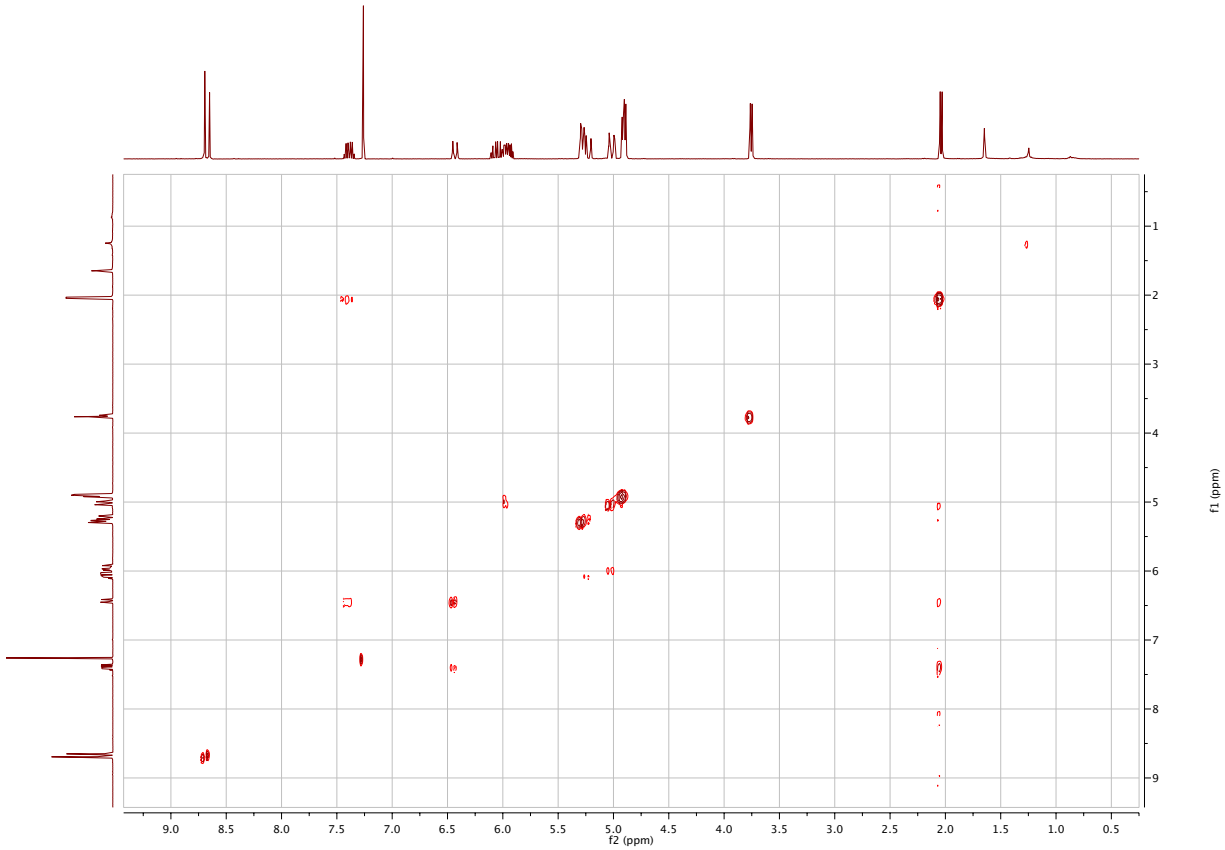
HRMS Found 234.0669 calculated for $C_{11}H_{11}N_4Cl$ 234.0672.



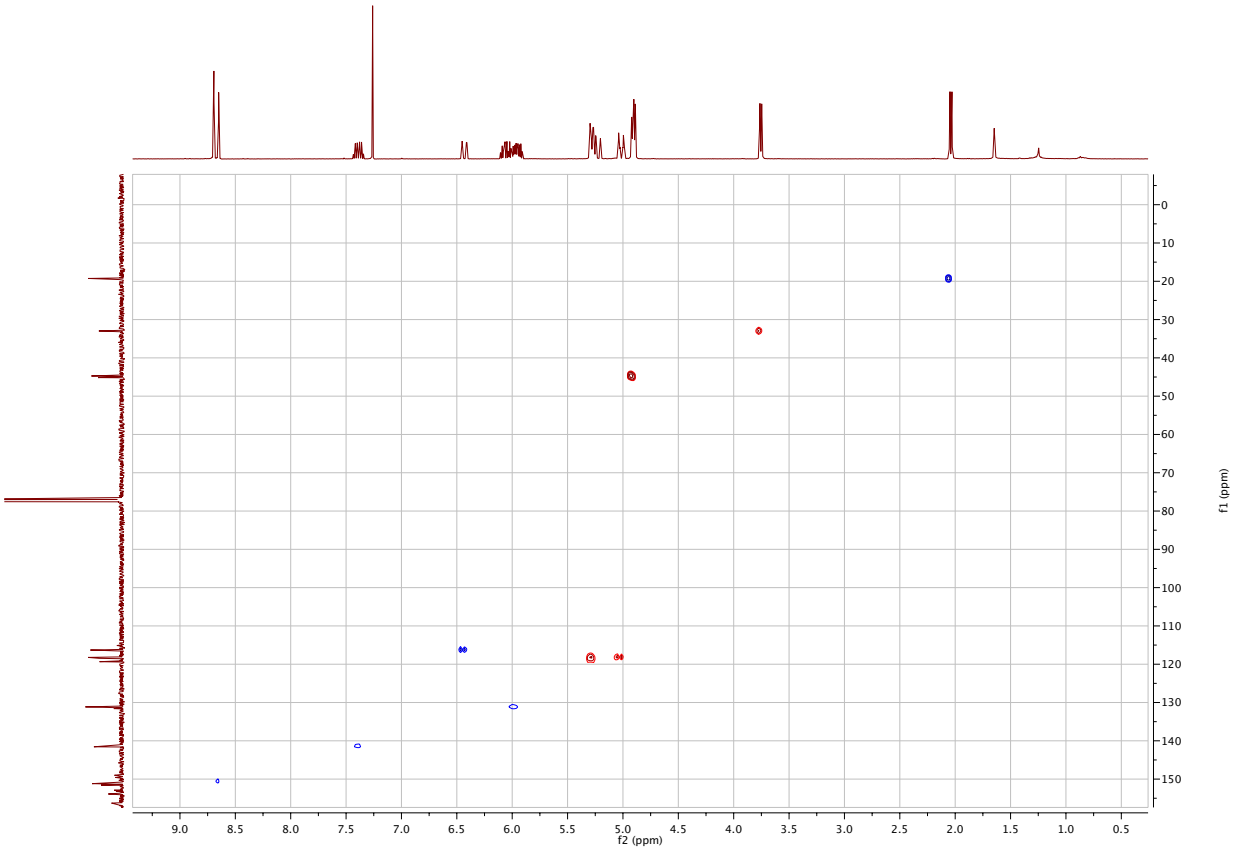
Spectrum 50. 400 MHz, $CDCl_3$, ^1H NMR of mixture 8,9-diallyl-6-chloro-9*H*-purine (**106**) and (*E*)-9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine (**119**)



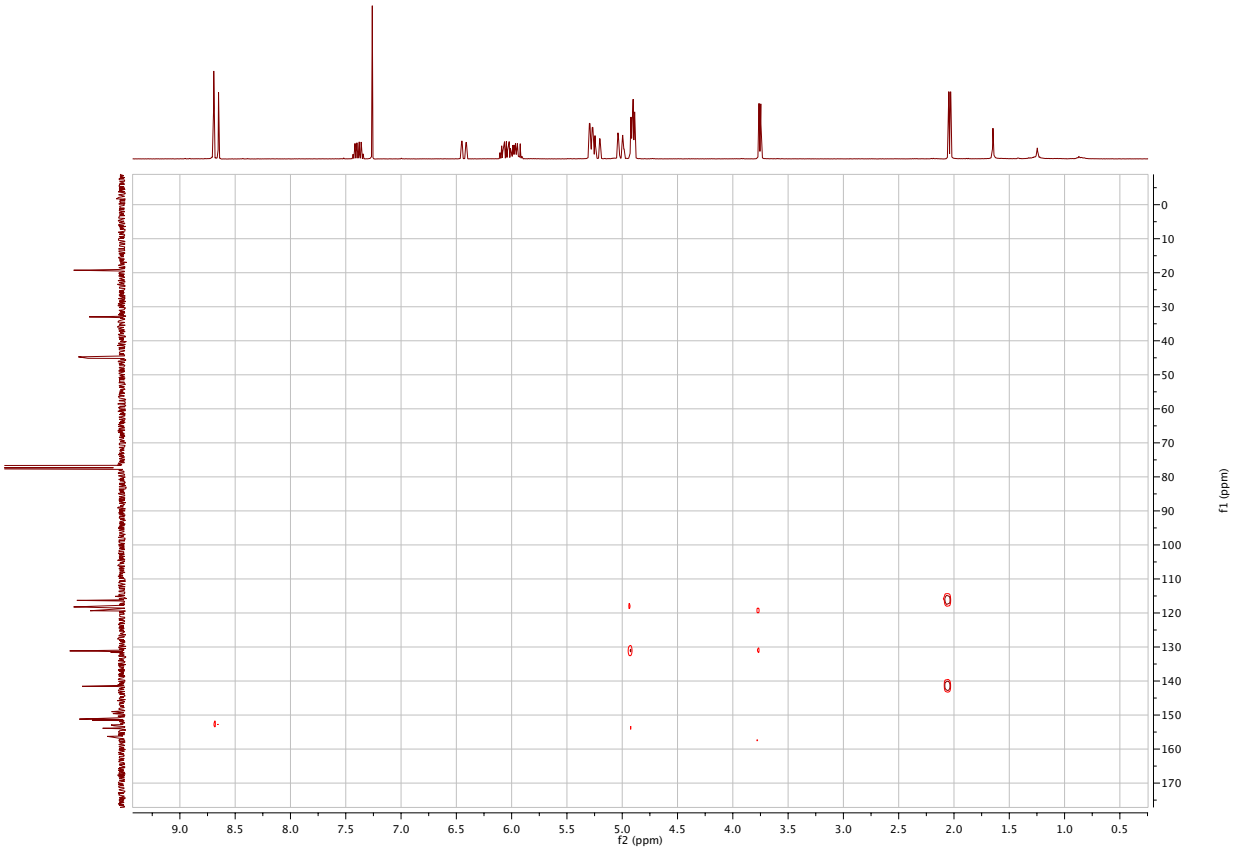
Spectrum 51. 100 MHz, $CDCl_3$, ^{13}C NMR of mixture 8,9-diallyl-6-chloro-9*H*-purine (**106**) and (*E*)-9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine (**119**)



Spectrum 52. 400 MHz, $CDCl_3$, COSY NMR of mixture 8,9-diallyl-6-chloro-9*H*-purine (**106**) and (*E*)-9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine (**119**)

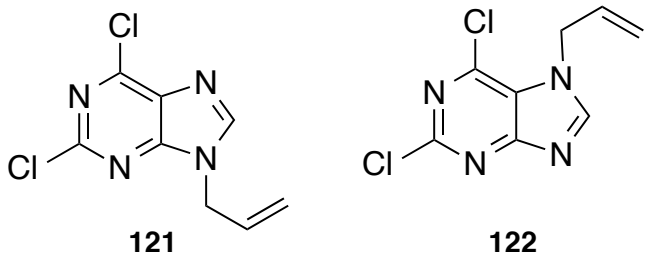


Spectrum 53. 400 MHz, $CDCl_3$, HSQC NMR of mixture 8,9-diallyl-6-chloro-9*H*-purine (**106**) and (*E*)-9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine (**119**)



Spectrum 54. 400 MHz, $CDCl_3$, HMBC NMR of mixture 8,9-diallyl-6-chloro-9*H*-purine (**106**) and (*E*)-9-allyl-6-chloro-8-(prop-1-en-1-yl)-9*H*-purine (**119**)

Synthesis of 9-allyl-2,6-dichloro-9*H*-purine (121) and 7-allyl-2,6-dichloro-7*H*-purine (122)



121 **122**

Potassium carbonate (4.15 g, 30.0 mmol) was added to a stirred solution of 2,6-dichloropurine **120** (1.58 g, 10.2 mmol) in dry DMF (40 mL) at ambient temperature under N_2-atm. After 20 min., allyl bromide (1.70 mL, 19.7 mmol) was added and the resulting mixture was stirred for 18 hours, filtered and evaporated *in vacuo*. The crude product was purified by flash chromatography on silica gel eluting first with EtOAc-hexane (3:7) followed by (2:1). This gave 1.50 g (65%) of 9-allyl-2,6-dichloro-9*H*-purine **121** as colorless solid and 614 mg (26%) of 7- allyl-2,6-dichloro-9*H*-purine **122** as pale yellow solid.

9-Allyl-2,6-dichloro-9*H*-purine (121)

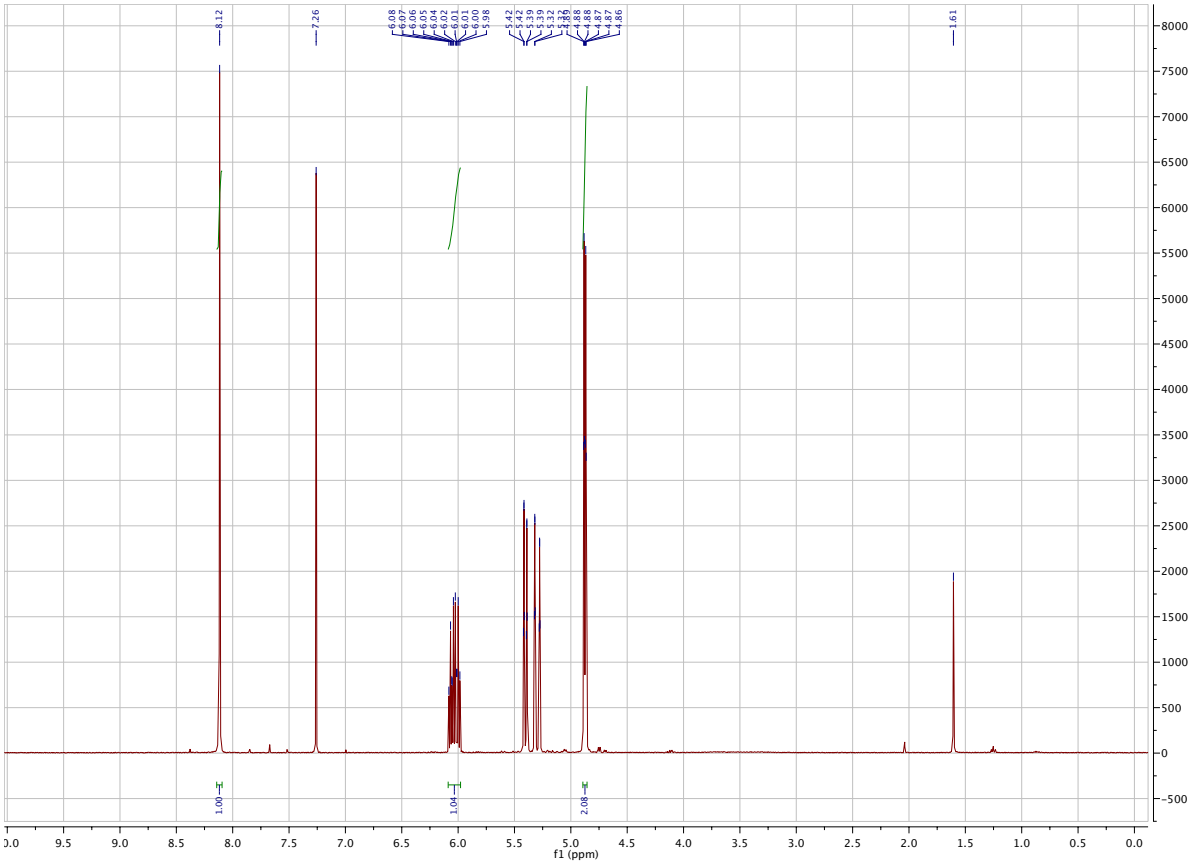
^{1}H NMR ($CDCl_3$, 400 MHz) δ 4.88 (dt, J = 6.0, 1.2Hz, 2H, N(9)CH_2), 5.29 (dt, J = 17.2, 1.2 Hz, 1H, =CH_{2a}), 5.40 (dt, J = 10.4, 1.2 Hz, 1H, =CH_{2b}), 5.98-6.08 (m, 1H, =CH), 8.12 (s, 1H, H- 8).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 46.60 (N(9)CH_2), 120.71 (=CH_2), 130.58 (=CH), 130.82 (C-5), 145.67 (C-8), 152.02 (C-4), 153.13 (C-6), 153.28 (C-2).

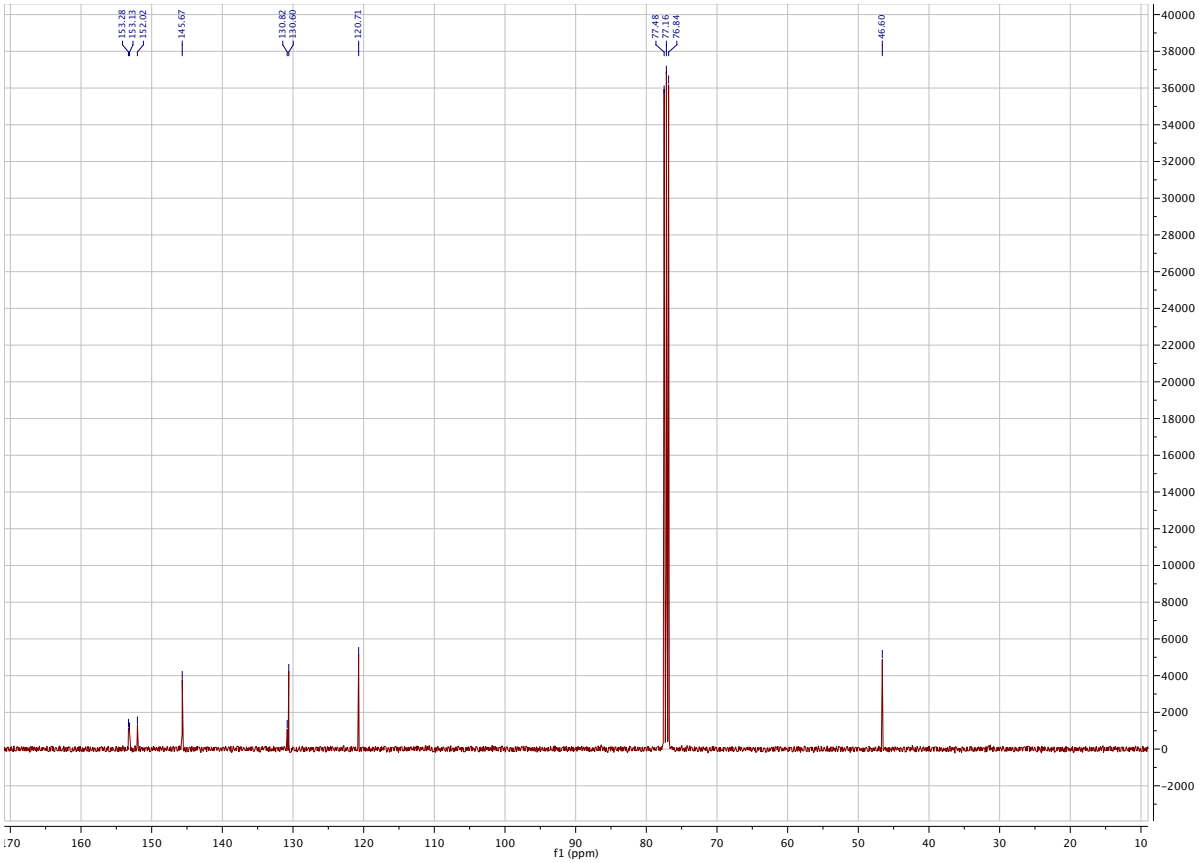
MS (EI) *m/z* (rel. %): 231/229/227 (15/73/100, M^+), 201 (18), 188 (13), 41 (51).

HRMS Found 227.9965 calculated for $C_8H_6N_4Cl_2$ 227.9969.

M.p. 87-88 ^{o}C (Lit.[94] 73-74 ^{o}C).



Spectrum 55. 400 MHz, $CDCl_3$, ^1H NMR of 9-allyl-2,6-dichloro-9*H*-purine (**121**)



Spectrum 56. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-allyl-2,6-dichloro-9*H*-purine (**121**)

7-Allyl-2,6-dichloro-7*H*-purine (122)

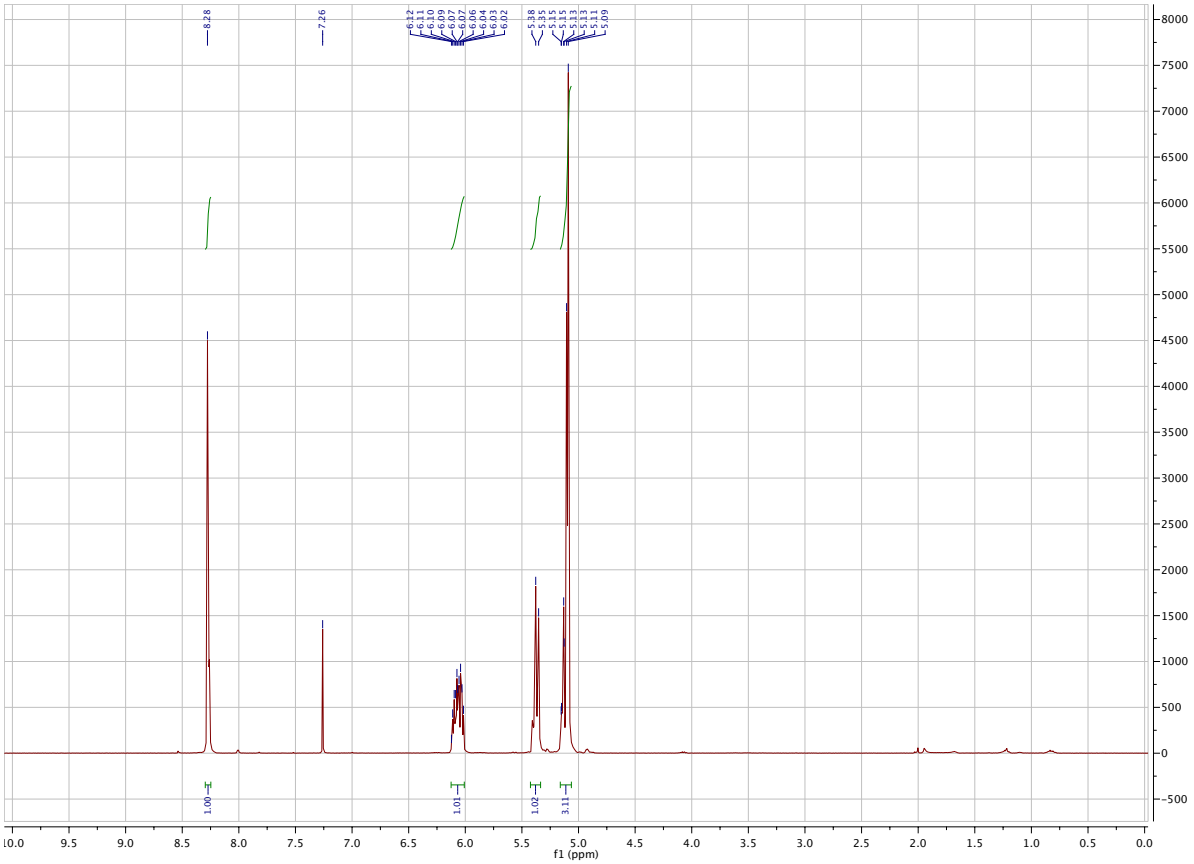
^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.09-5.17 (m, 3H, CH_2 and $=CH_{2a}$), 5.38 (d, J =14.0, 1.6 Hz, 1H, $=CH_{2b}$), 6.02-6.12 (m, 1H, =CH), 8.27 (s, 1H, H-8).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 49.51 ($N(7)CH_2$), 119.98 ($=CH_2$), 121.72 (C-5), 131.50 (=CH), 143.94 (C-6), 150.35 (C-2), 153.21 (C-8), 163.59 (C-4).

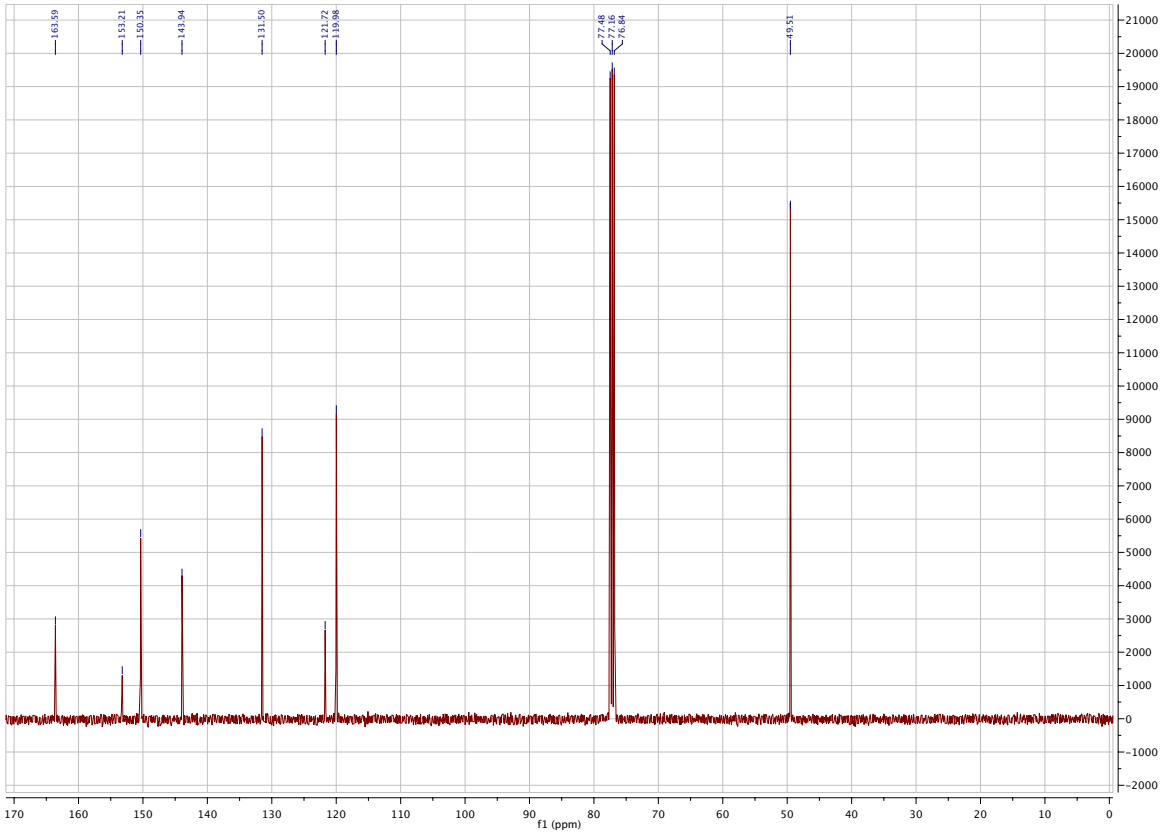
MS (EI) *m/z* (rel. %): 232/228/227 (10/100/27, M^+), 167 (10), 159 (8), 132 (19), 105 (6), 77 (5).

HRMS Found 227.9965 calculated for $C_8H_6N_4Cl_2$ 227.9969.

M.p. 75-76 °C (Lit.[94] 103-104 °C).

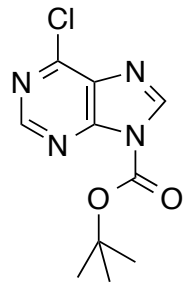


Spectrum 57. 400 MHz, $CDCl_3$, ^{1}H NMR of 9-allyl-2,6-dichloro-9*H*-purine (**122**)



Spectrum 58. 100 MHz, $CDCl_3$, ^{13}C NMR of 9-allyl-2,6-dichloro-9*H*-purine (**122**)

Synthesis of *tert*-butyl-6-chloro-*9H*- purine-9-carboxylate (125)



125

A suspension of 6-chloropurine **102** (1.55 g, 10.0 mmol), Boc_2O (3.10 g, 14.0 mmol) and DMAP (30 mg, 0.2 mmol) in dry DCM (15 mL) was stirred for 22 hours and evaporated *in vaccuo*. The crude product was purified by flash chromatography on silica gel eluting with 0.5% MeOH in DCM to give 2 400 mg (94%) of *tert*-butyl-6-chloro-*9H*-purine-9-carboxylate **125** as colorless solid.

***tert*-Butyl-6-chloro-*9H*- purine-9-carboxylate (125)**

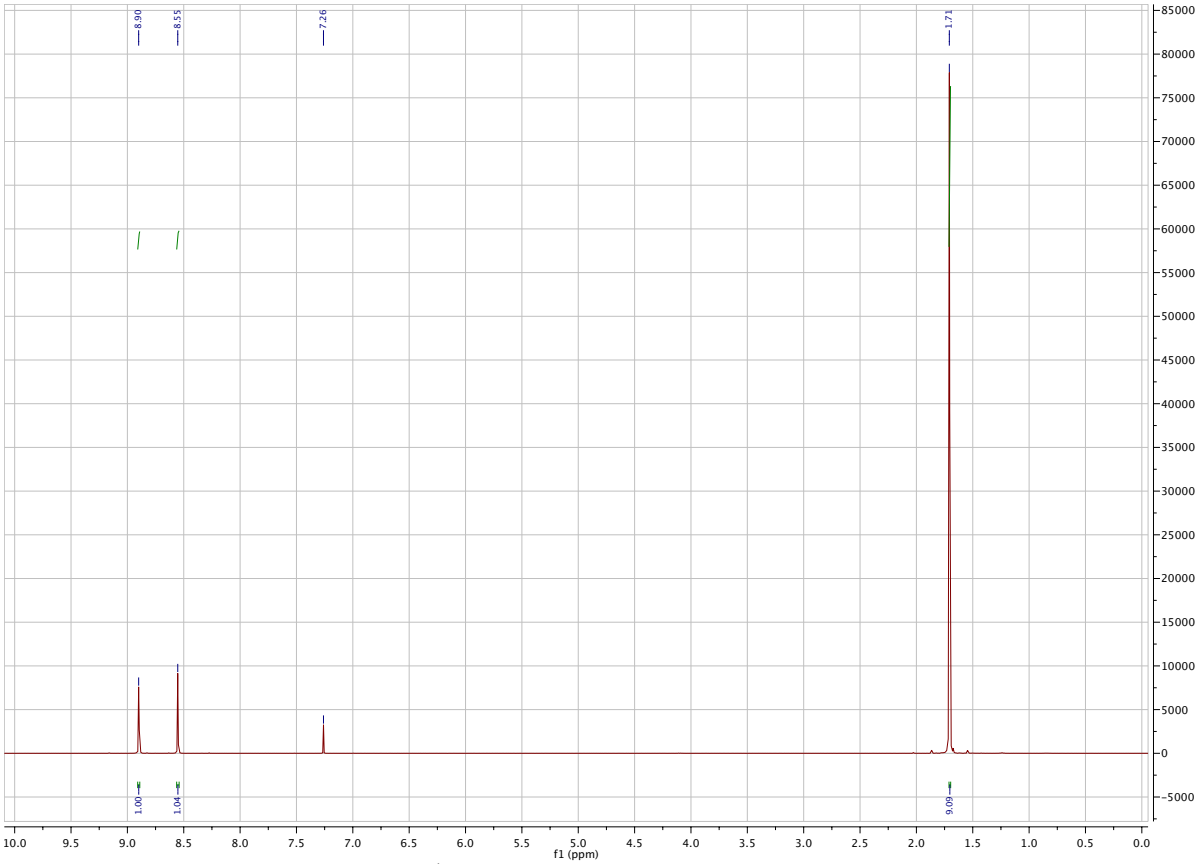
^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.71 (s, 9H, CCH_3), 8.55 (s, 1H, H-8), 8.90 (s, 1H, H-2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.05 (3xCH_3), 88.17 ($\underline{C}CH_3$), 132.60 (C-5), 143.97 (C-8), 145.48 (CO), 151.22 (C-4), 152.17 (C-6), 154.10 (C-2).

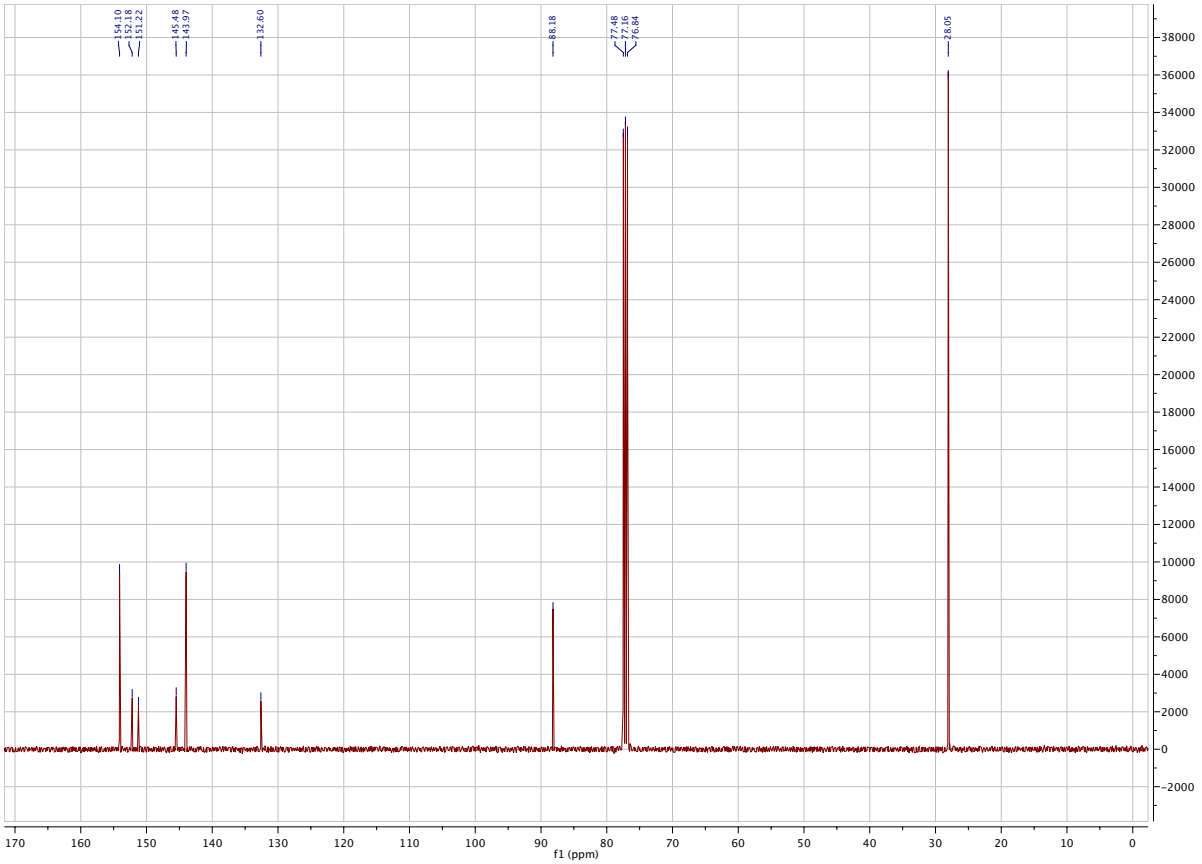
MS (EI) *m/z* (rel. %): 181 (8), 154 (36), 119 (19), 57 (100), 41 (26).

HRMS Found 254.0580 calculated for $C_{10}H_{11}ClN_4O_2$ 254.0570.

M.p. 121 -123 °C (Lit.[95] 111 °C).

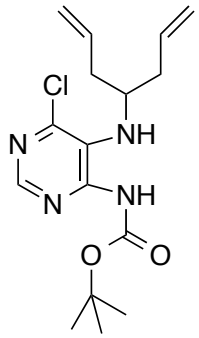


Spectrum 59. 400 MHz, $CDCl_3$, ^1H NMR of *tert*-butyl-6-chloro-*9H*- purine-9-carboxylate **(125)**

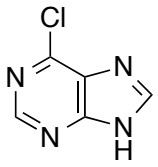


Spectrum 60. 100 MHz, $CDCl_3$, ^{13}C NMR of *tert*-butyl-6-chloro-*9H*- purine-9-carboxylate (**125**)

Synthesis of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate (126) and 6-chloro-*9H*- purine (102)



126



102

In powder (161 mg, 1.14 mmol) was stirred in dry THF (3 mL) under N_2-atm. Allyl bromide (0.15 mL, 1.71 mmol) was added in the reaction mixture having been sonicated for 30 minutes. Compound **125** (145 mg, 0.57 mmol) was added and the mixture was stirred for 28 hours (including 10 hours under the sonication). Sat. aq. NaCl (30 mL) was added and the aqueous phase was extracted with diethyl ether (10 x 20 mL). The combined organic layers were dried ($MgSO_4$) and evapourated *in vacuo*. The products were isolated by flash chromatography with silica gel eluting with acetone-EtOAc-hexane (1:1:18), followed by 1:1:6. This gave 64 mg (33%) of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate **126** as a yellow oil and 28 mg (32%) of 6-chloro-9*H*-purine **102** as a pale solid.

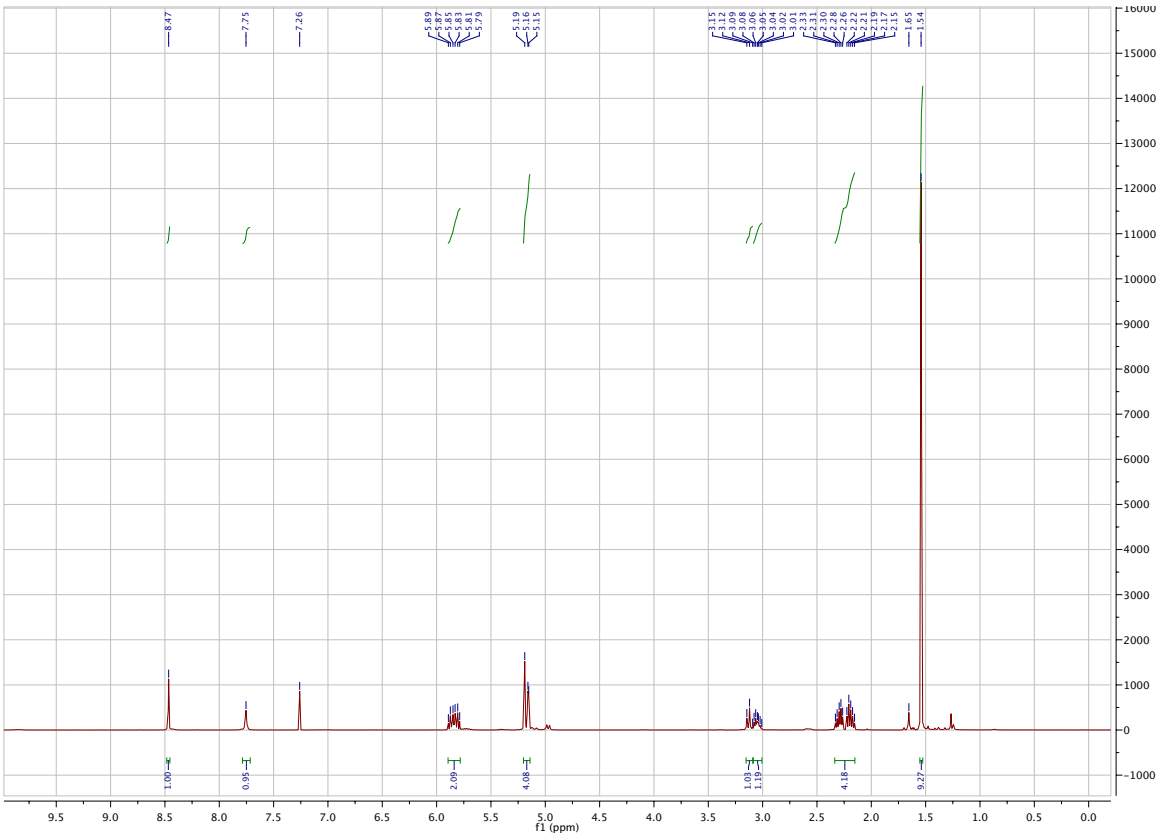
***tert*-Butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate (126)**

^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.54 (s, 9H, 3 x CH_3 in Boc), 2.15-2.33 (m, 4H, 2 x CH_2), 3.01-3.08 (m, 1H, NHC<u>H</u>), 3.09-3.15 (d, 1H, N<u>H</u>CH), 5.15-5.19 (m, 4H, 2 x CH_2=), 5.79-5.89 (m, 2H, 2 x CH=), 7.75 (brs, 1H, NHCO), 8.47 (s, 1H, H-2).

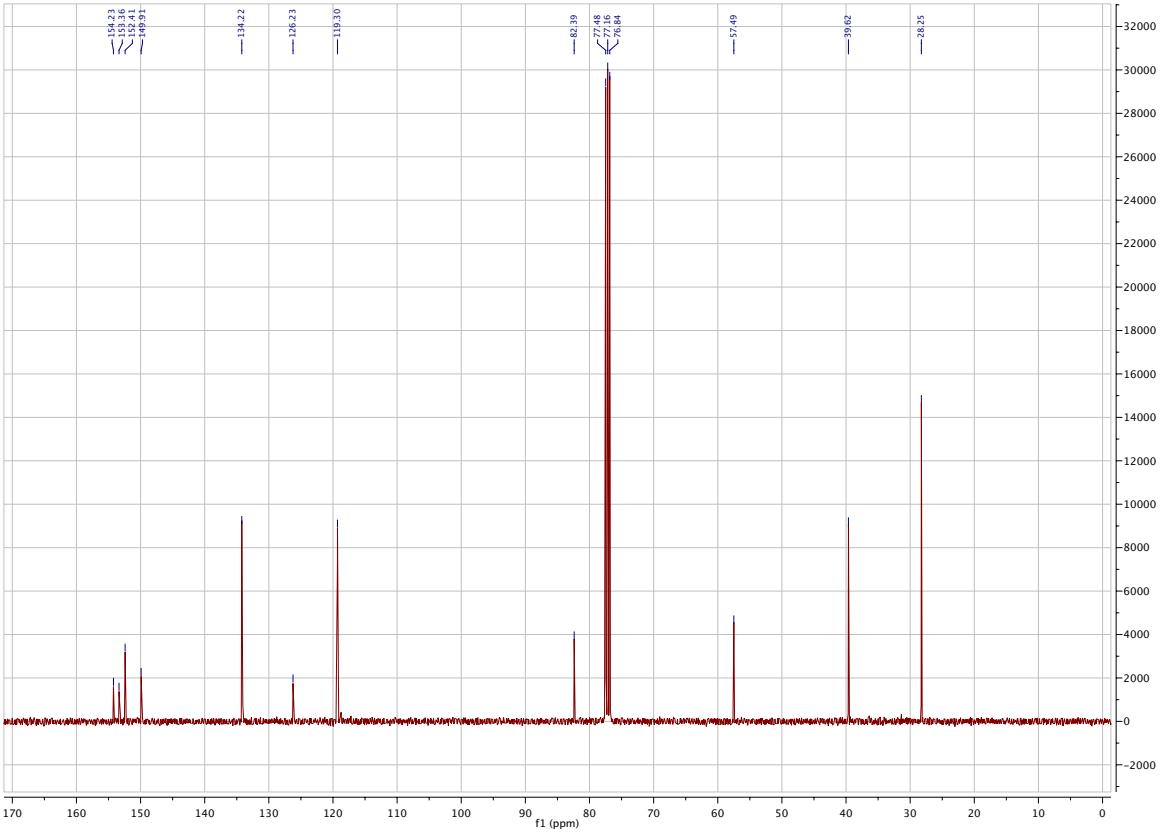
^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.24 (CH_3 in Boc), 39.60 (2 x <u>C</u>H_2CH=), 57.45 (NH<u>C</u>H), 82.38 (C in Boc), 119.25 (2 x=CH_2), 126.27 (C-5), 134.20 (2 x CH=), 149.93 (CO in Boc), 152.35 (C-6), 153.36 (C-4), 154.18 (C-2).

MS (EI) *m/z* (rel. %): 297 (5), 241 (22), 223 (59), 197 (100).

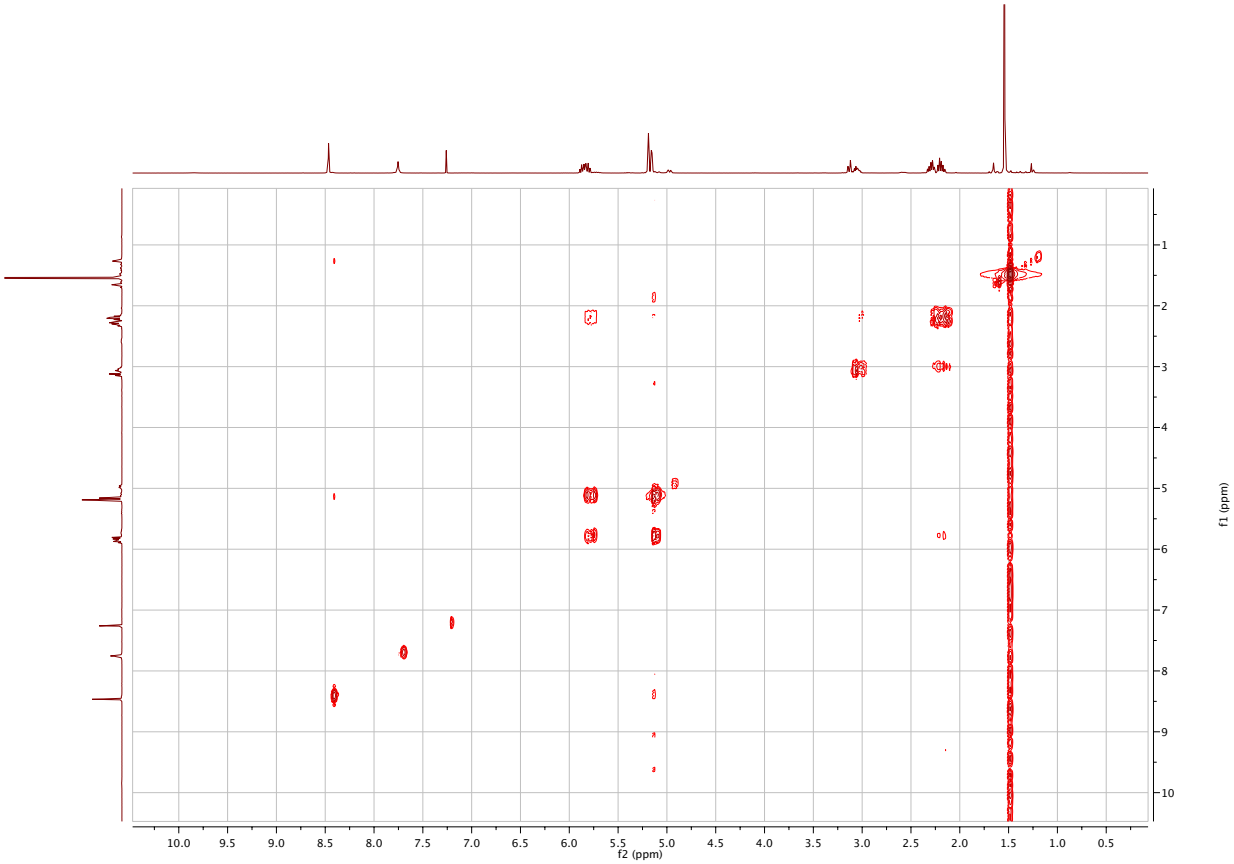
HRMS Found 338.1524 calculated for $C_{16}H_{23}N_4O_2Cl$ 338.1510.



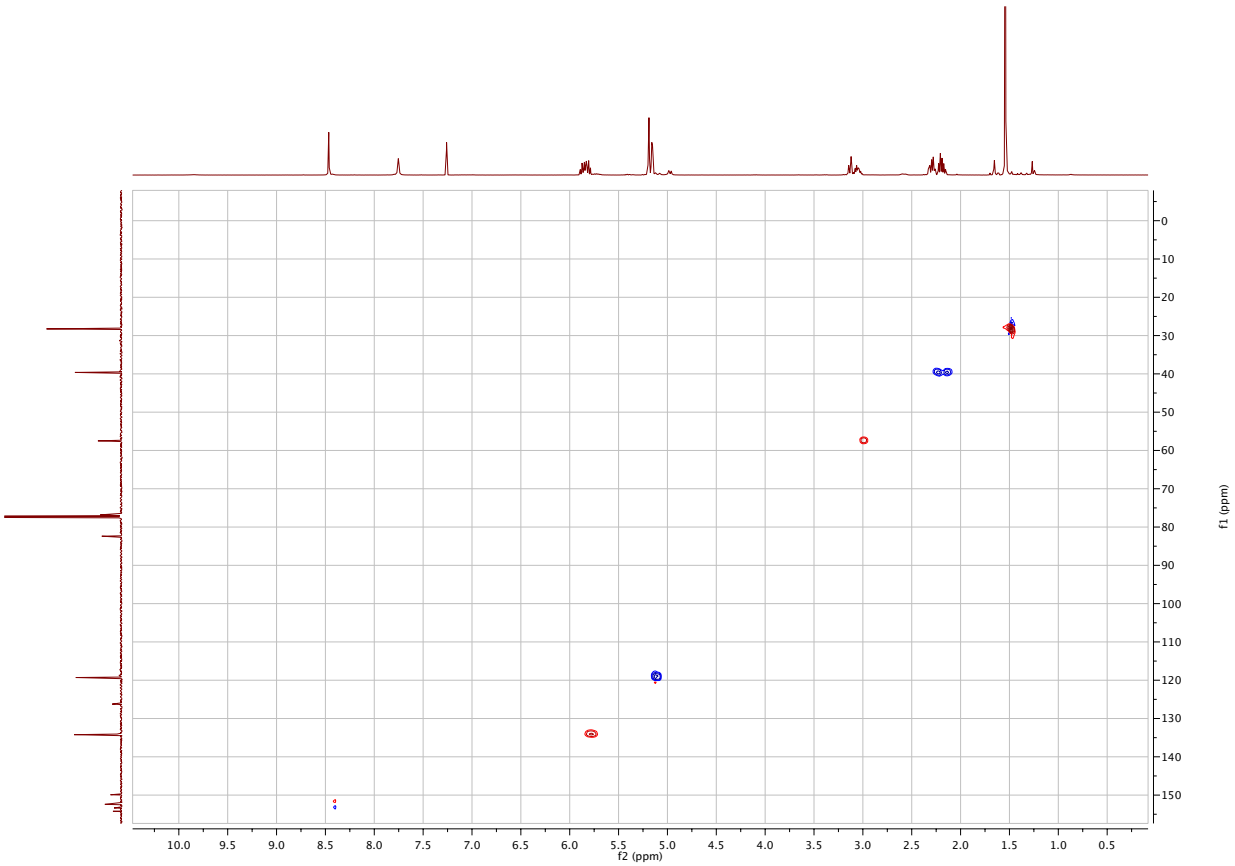
Spectrum 61. 400 MHz, $CDCl_3$, ^1H NMR of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate **(126)**



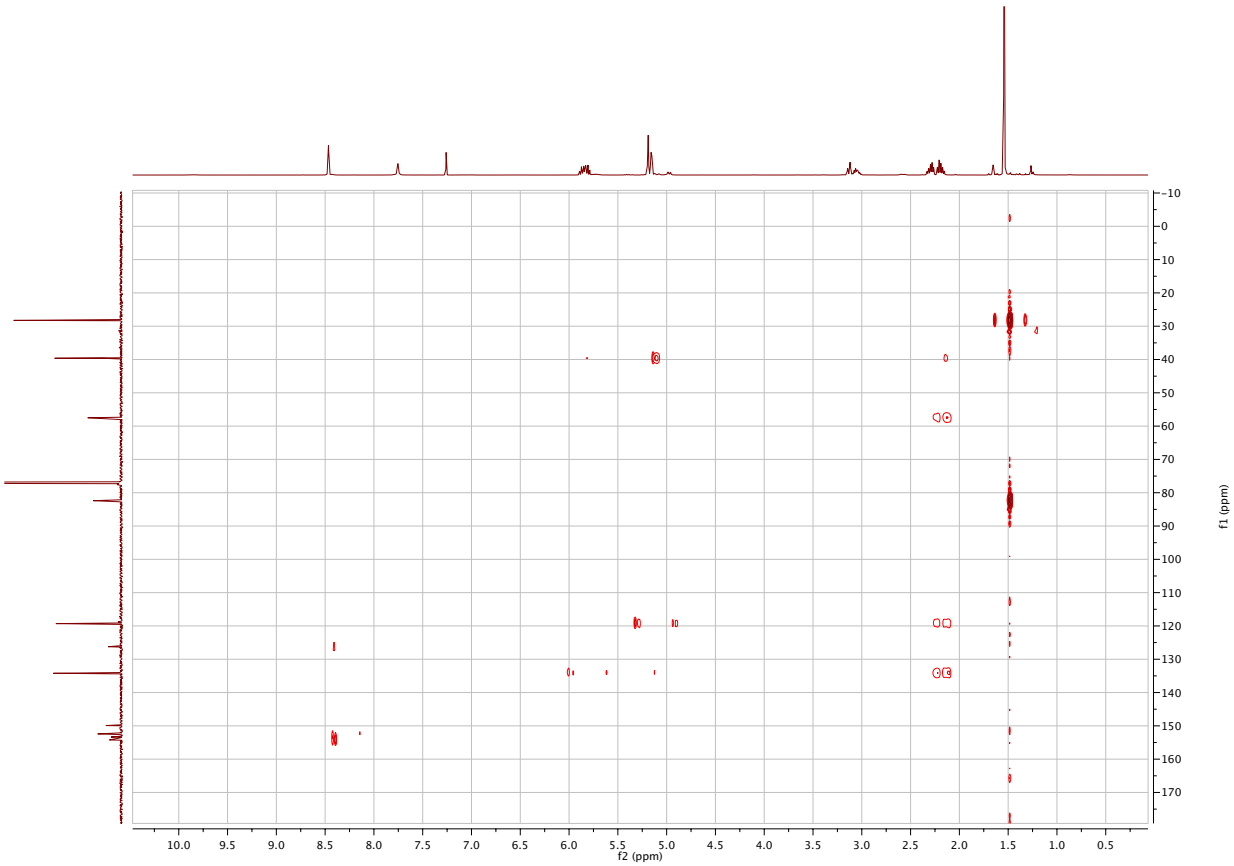
Spectrum 62. 100 MHz, $CDCl_3$, ^{13}C NMR of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate (**126**)



Spectrum 63. 100 MHz, $CDCl_3$, COSY NMR of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate (**126**)



Spectrum 64. 100 MHz, $CDCl_3$, HSQC NMR of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate (**126**)



Spectrum 65. 100 MHz, $CDCl_3$, HMBC NMR of *tert*-butyl (6-chloro-5-(hepta-1,6-dien-4-ylamino)pyrimidin-4-yl)carbamate (**126**)

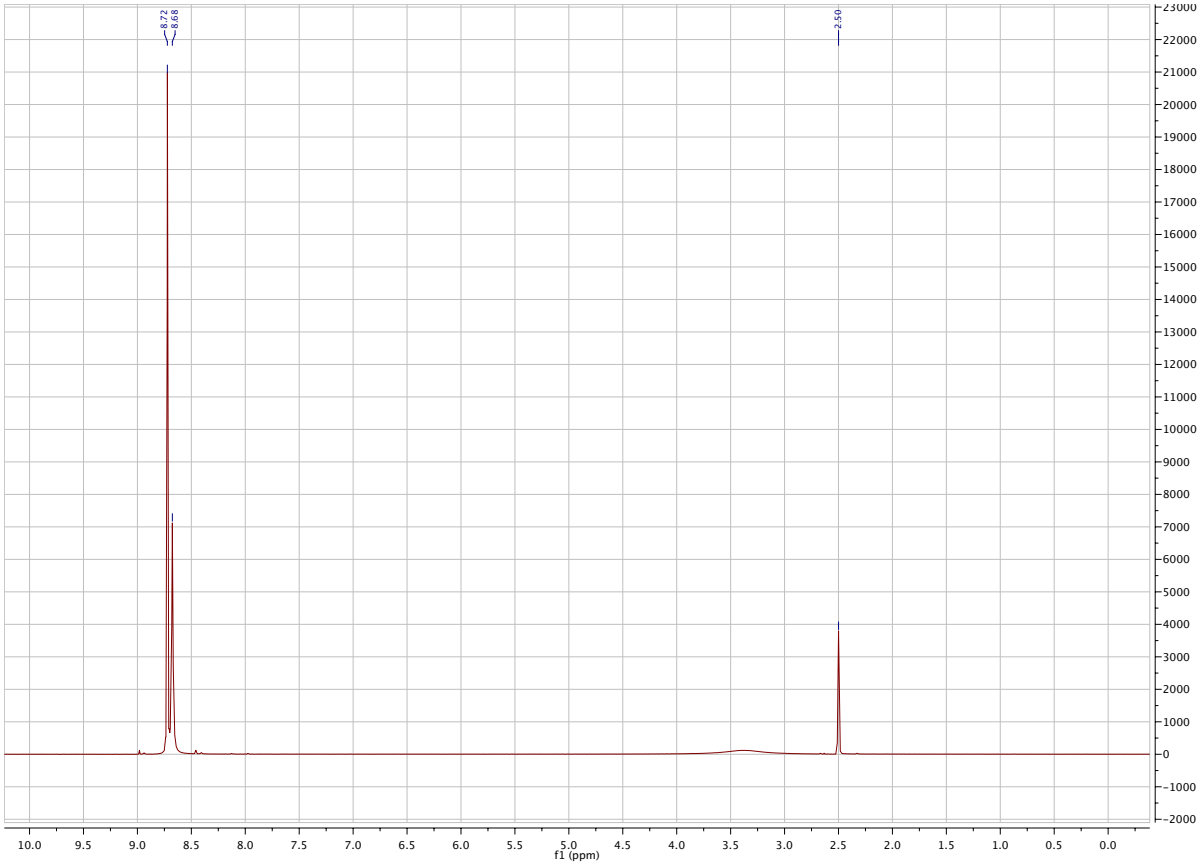
6-Chloro-*9H*-purine (102)

^{1}H NMR (DMSO-d_6, 400 MHz) δ 8.58 (s, 1H, H-8), 8.72 (s, 1H, H-2)

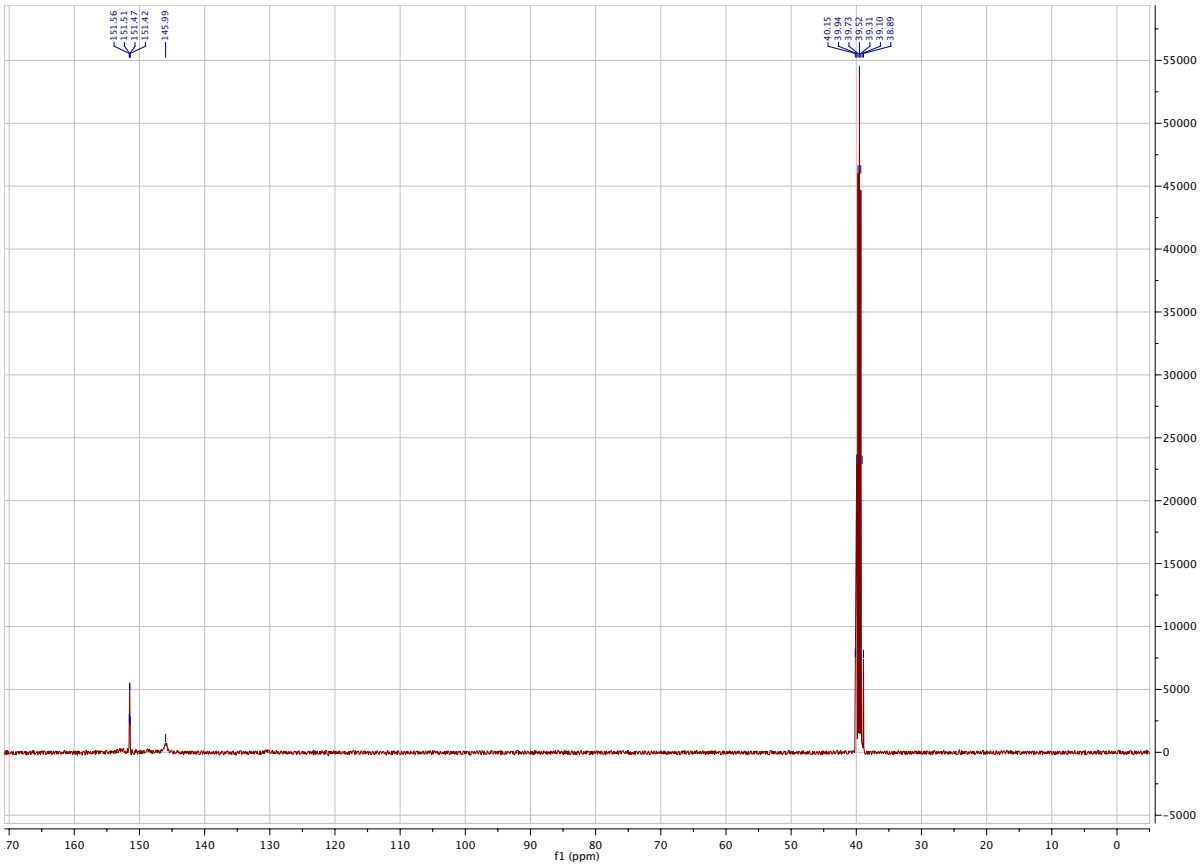
^{13}C NMR (DMSO-d_6, 100 MHz) δ 145.99 (C-5), 151.42 (C-8), 151.47 (C-4), 151.51 (C-2), 151.56 (C-6).

MS (EI) *m/z* (rel. %): 156/154 (32/100, M^+), 119 (58), 92 (14), 65 (9).

HRMS Found 154.0043 calculated for $C_5H_3ClN_4$ 154.0046.

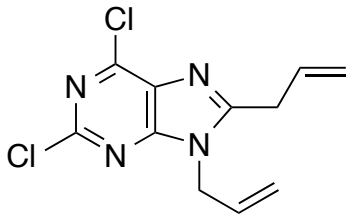


Spectrum 66. 400 MHz, DMSO-d_6, ^{1}H NMR of 6-chloro-*9H*-purine **(102)**



Spectrum 67. 100 MHz, DMSO-d_6, ^{13}C NMR of 6-chloro-*9H*-purine (**102**)

Synthesis of 8,9-diallyl-2,6-dichloro-*9H*- purine (124)



124

In powder (161 mg, 1.14 mmol) was stirred in dry THF (3 mL) under N_2-atm. Allyl bromide (0.15 mL, 1.71 mmol) was added and the reaction mixture having been sonicated for 30 minutes. Compound **121** (132 mg, 0.57 mmol) was added and the mixture was stirred in 28 hours (including 10 hours under the sonication). Sat. aq. NaCl (30 mL) was added and the aqueous phase was extracted with diethyl ether (10 x 20 mL). The combined organic layers were dried ($MgSO_4$) and evapourated *in vacuo*. The products were isolated by flash chromatography with silica gel eluting with acetone-EtOAc-hexane (1:1:10) to give 67 mg (44%) of 8,9-diallyl-2,6-dichloro-*9H*- purine **124** as yellow solid.

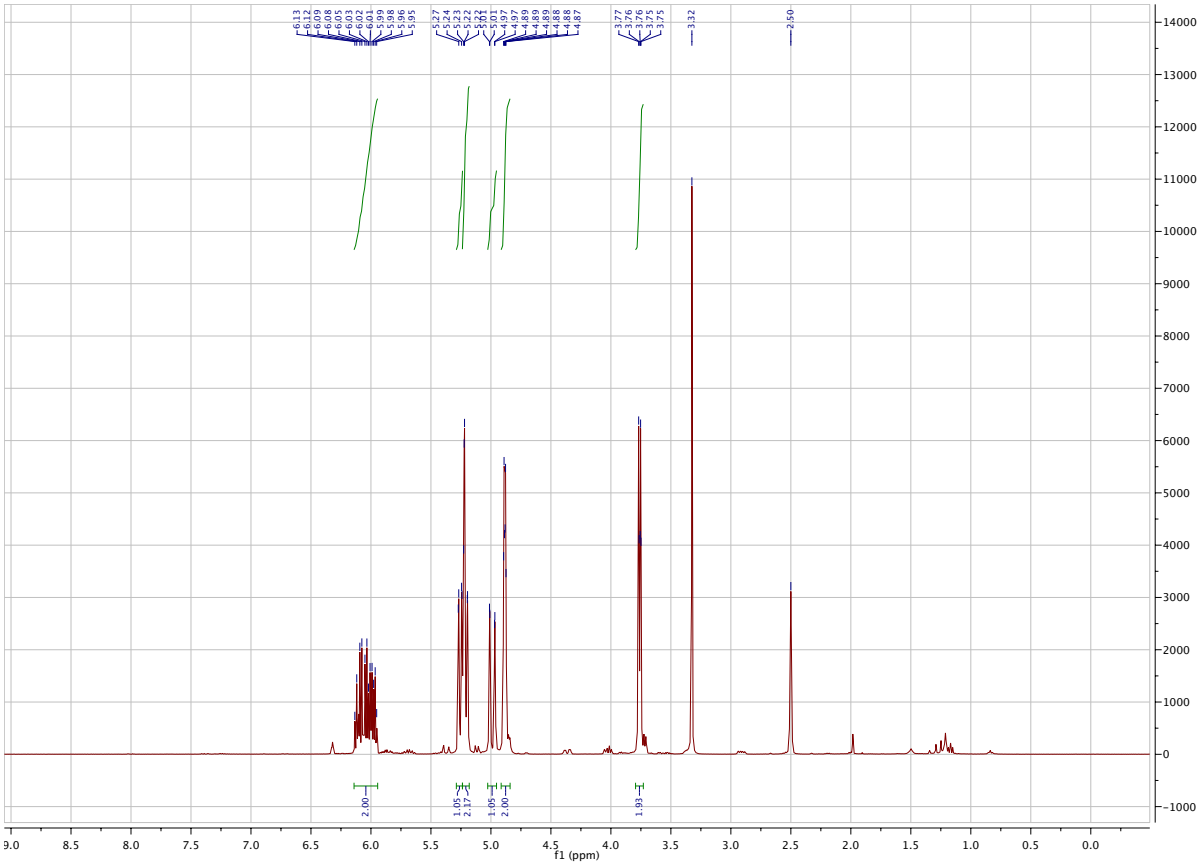
8,9-Diallyl-2,6-dichloro-*9H*- purine (124)

^{1}H NMR (DMSO-d_6, 400 MHz) δ 3.76 (dt, J = 6.8, 1.6 Hz, 2H, C(8)CH_2), 4.98 (dt, J = 4.8, 1.6 Hz, 2H, N(9)CH_2), 4.99 (dd, J = 16.8 Hz, 1H, =CH_{2a} in C(8) allyl), 5.19-5.22 (m, 2H, =CH_{2b} in C(8) allyl and =CH_{2a} in N(9) allyl), 5.25 (dd, J = 10.4 Hz, 1H, =CH_{2b} in N(9) allyl), 5.95-6.13 (m, 2H, 2 x CH=)

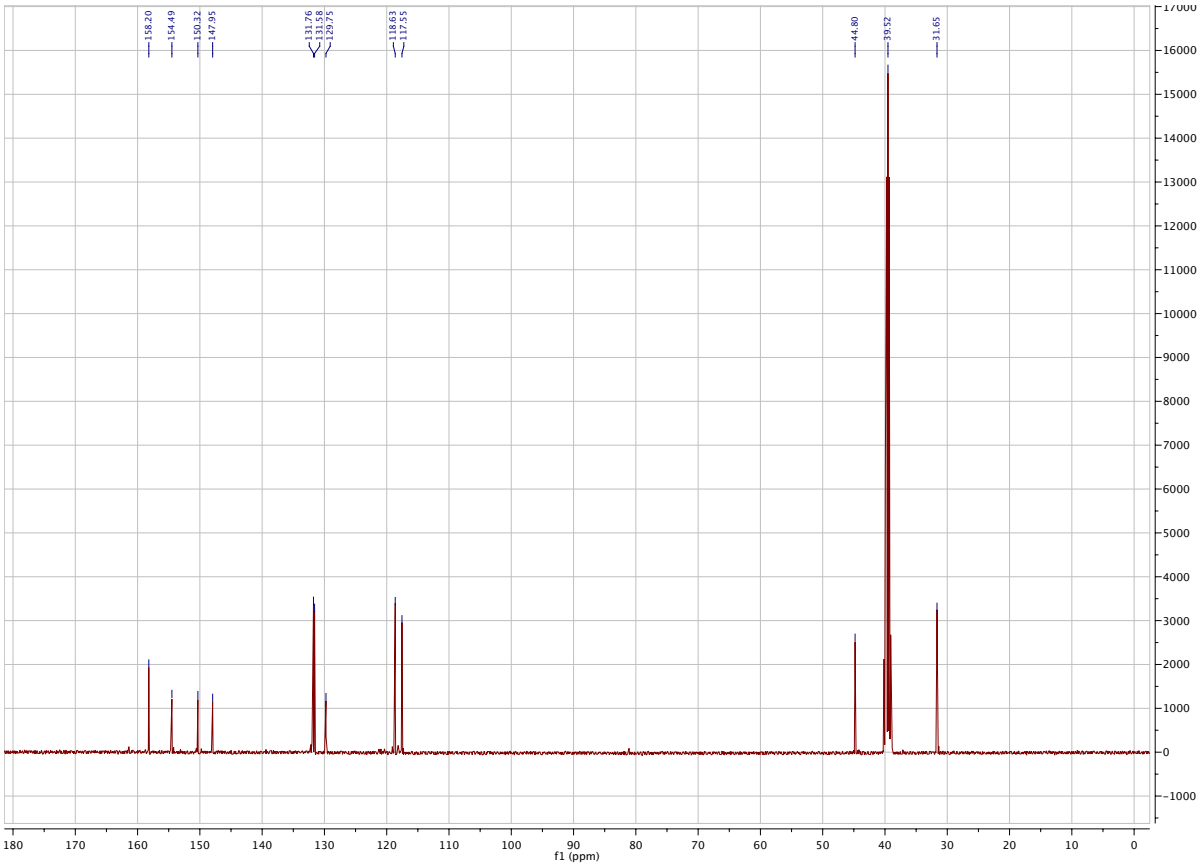
^{13}C NMR (DMSO-d_6, 100 MHz) δ 31.65 (C(8)$\underline{C}H_2$), 4.80 (N(9)CH_2), 117.55 (=CH_2 in C(8) allyl), 118.63 (=CH_2 in N(9) allyl), 129.75 (C-5), 131.58 (CH= in N(9) allyl), 131.76 (CH= in C(8) allyl), 147.93 (C-8), 150.32 (C-4), 154.49 (C-2), 158.20 (C-6).

MS (EI) *m/z* (rel. %): 267/268/269 (100/84/77), 241 (23), 227 (50), 191 (12).

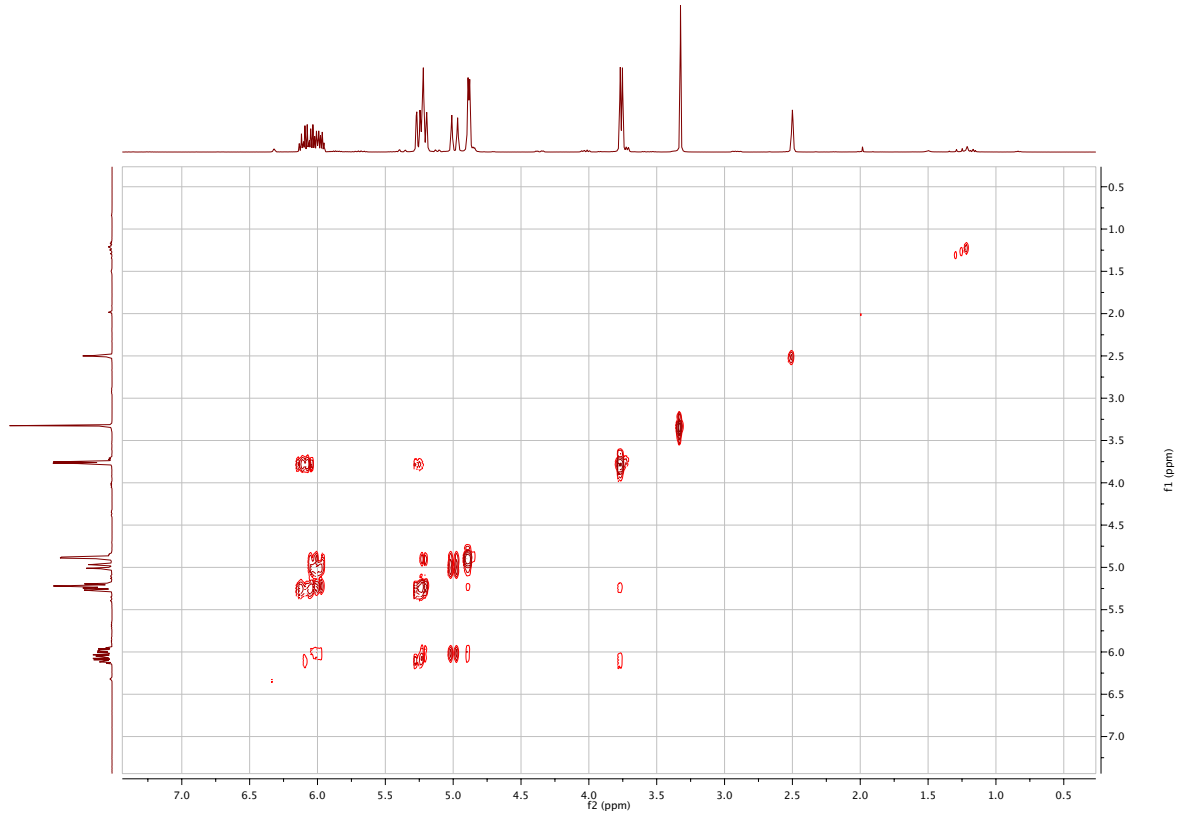
HRMS Found 268.0280 calculated for $C_{11}H_{10}Cl_2N_4$ 268.0283.



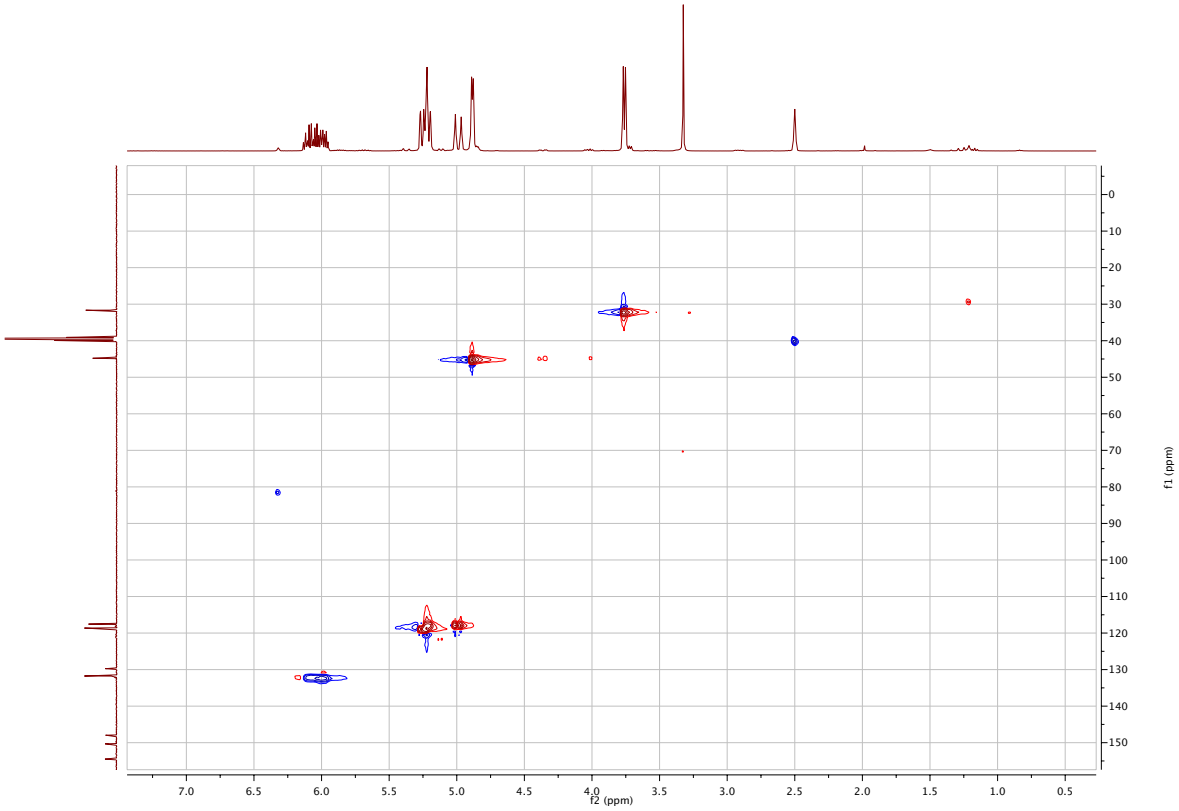
Spectrum 68. 400 MHz, DMSO-d_6, ^{1}H NMR of 8,9-diallyl-2,6-dichloro-*9H*-purine **(124)**



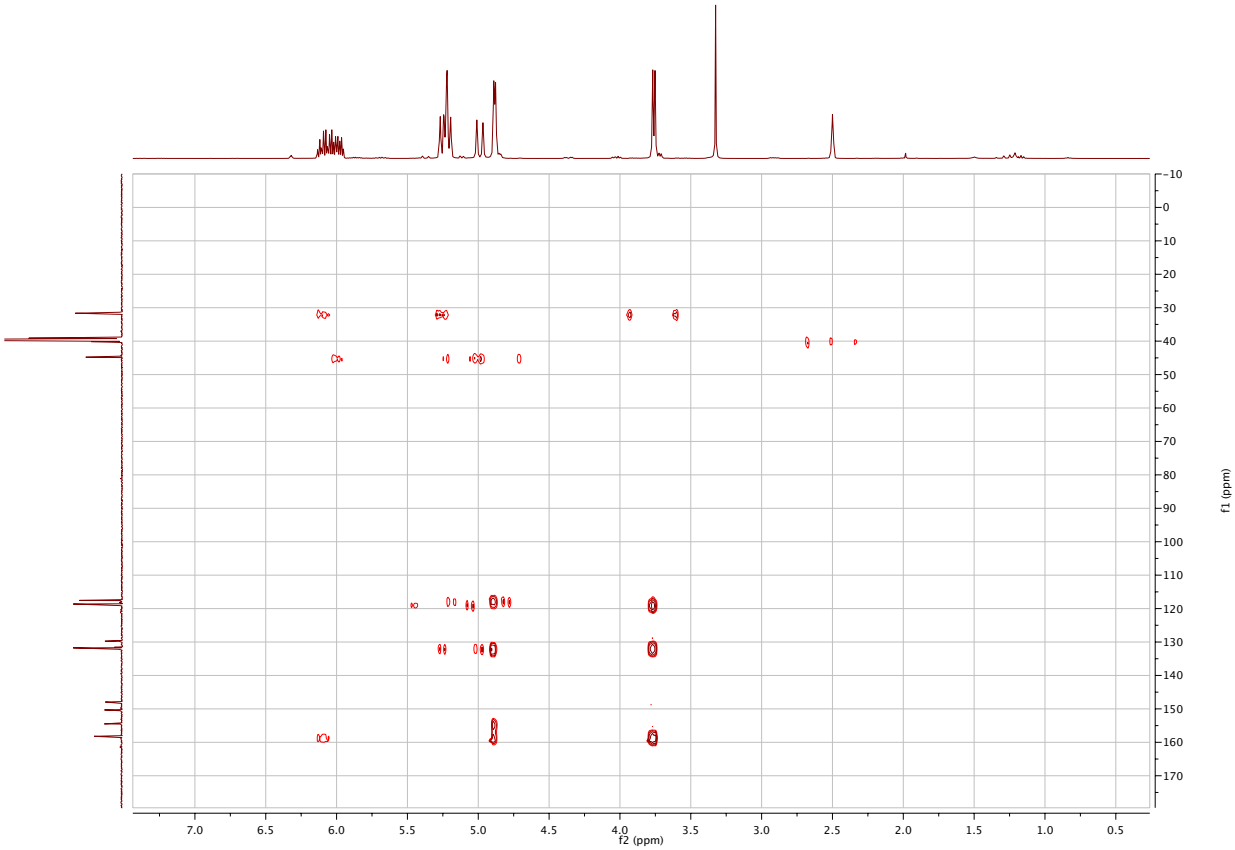
Spectrum 69. 100 MHz, DMSO-d_6, ^{13}C NMR of 8,9-diallyl-2,6-dichloro-*9H*-purine **(124)**



Spectrum 70. 400 MHz, DMSO-d_6, COSY NMR of 8,9-diallyl-2,6-dichloro-*9H*-purine **(124)**

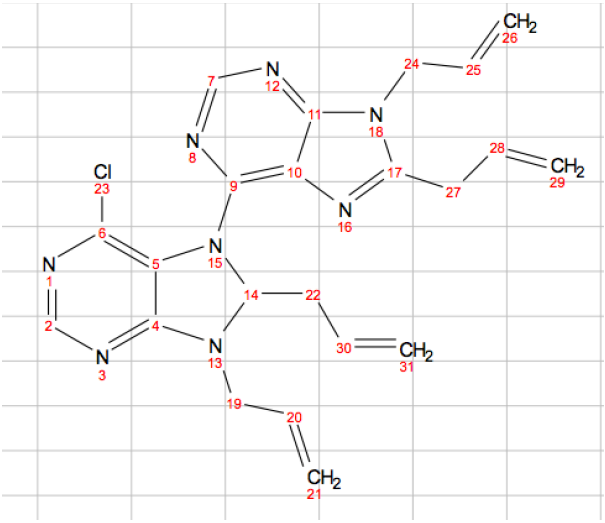


Spectrum 71. 400 MHz, DMSO-d_6, HSQC NMR of 8,9-diallyl-2,6-dichloro-*9H*-purine **(124)**



Spectrum 72. 400 MHz, DMSO-d_6, HMBC NMR of 8,9-diallyl-2,6-dichloro-*9H*-purine **(124)**

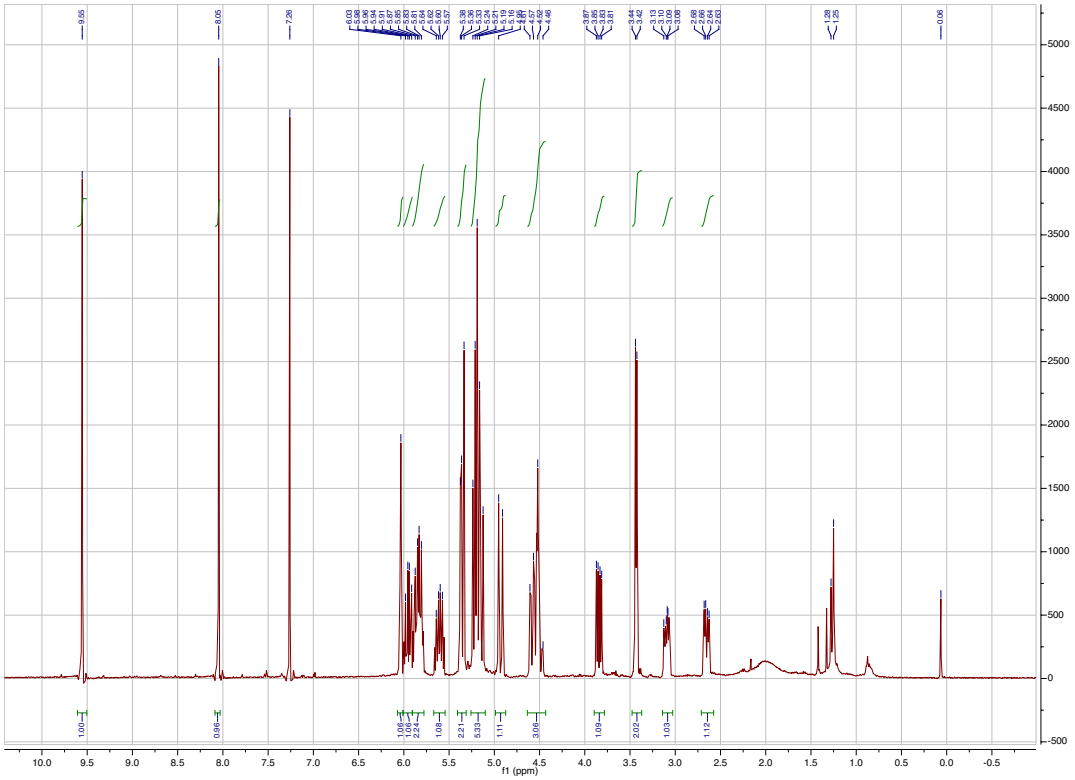
Appendix



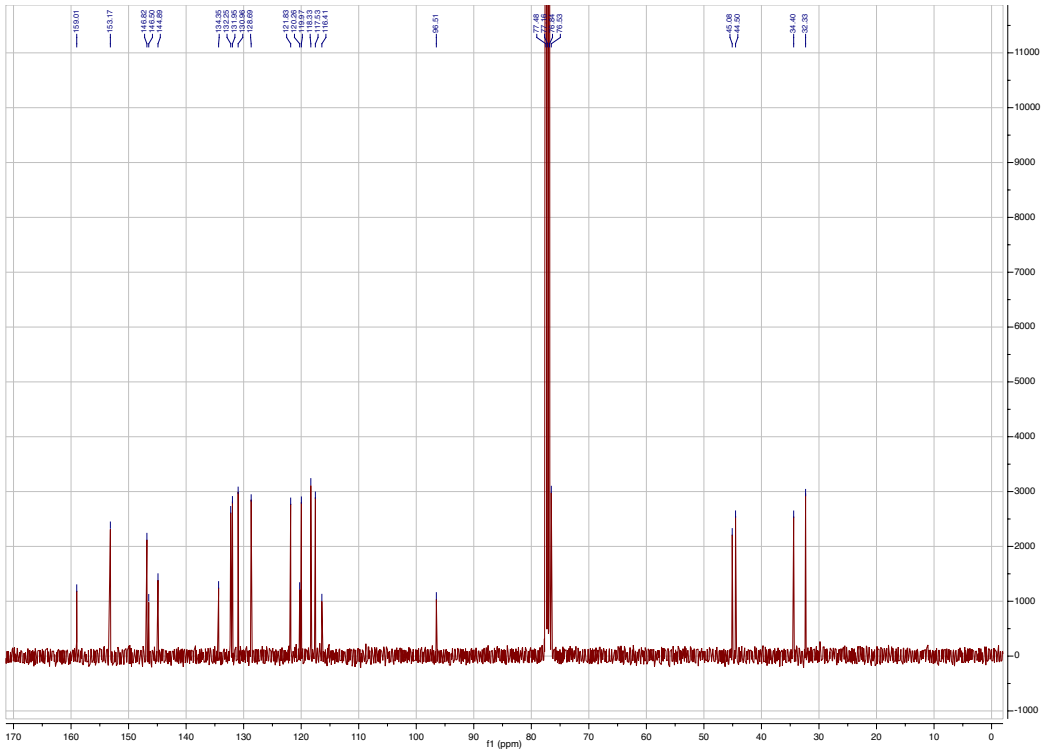
127

^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.63-2.68 (m, 1H, H_{22a}), 3.06-3.13 (m, 1H, H_{22b}), 3.43 (d, 2H, H_{27}), 3.81-3.87 (m, 1H, H_{19a}), 4.46-4.60 (m, 3H, H_{19b}, H_{24}), 4.93 (d, 1H, H_{26a}), 5.12-5-24 (m, 5H, H_{26a}, H_{31}, H_{29}), 5.33-5.37 (m, 2H, H_{21}), 5.78-6.00 (m, 3H, H_{20}, H_{25}, H_{30}), 6.02-6.03 (m, 1H, H_{28}), 8.05 (s, 1H, H_7), 9.55 (s, 1H, H_2).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 32.33 (C27), 34.40 (C22), 44.50 (C24), 45.08 (C19), C14 (76,53), 96.51 (C10), 116.41 (C11), 117.53 (C2673), 118.33 (C29), 119.97 (C21), 120.26 (C5), 121.83 (C31), 128.69 (C30), 130.96 (C20), 131.95 (C25), 132.25 (C28), 134.35 (C6), 144.89 (C17), 146.50 (C9), 146.82 (C7), 153.17 (C2), 159.01 (C4)



Spectrum 73. 400 MHz, $CDCl_3$, ^{1}H NMR of the predicted compound **127**



Spectrum 74. 100 MHz, $CDCl_3$, ^{13}C NMR of the predicted compound **127**

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