Fixation of Heterocumulenes, II[+]

A Study on the Reaction of Lithiated Allyl Systems with CO_2, Isocyanates and Isothiocyanates

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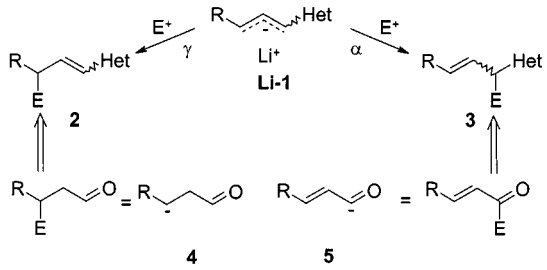
The regioselectivity of the reaction of 1-(thiophenyl)- (**Li-6**), 1-(phenylsulfinyl)- (**Li-12**), 1-(phenylsulfonyl)- (**Li-15**) and 1-(diethoxyphosphoryl)allyllithium (**Li-18**) with CO_2, PhNCO and PhNCS is investigated. Carboxylation of the allyl sulfide **6** and the allyl sulfoxide **12** proceeds with low regioselectivity. On the other hand, an exclusive γ-selectivity is achieved for reactions of CO_2 with **Li-15** and **Li-18**. *Both carboxylations are reversible and can be directed to give α-products by using low temperature workup (0 °C).* In contrast to CO_2, PhNCO reacts with the allylic compounds investigated here to give amides with a high degree of regioselectivity: α-Attack is found for the sulfide **6** and the sulfone **15** whereas the reaction occurs at the γ-terminus for the sulfoxide **12** and the phosphonate **18**. Exclusive α-attack is observed for all sulfur-substituted allyllithium compounds on reaction with PhNCS. In contrast to this, reaction of the phosphonate **18** with PhNCS yields exclusively the γ-product.

Introduction

We recently investigated the mechanism of the addition of CO_2 to 2-lithio-1,3-dithiane as an example for the transformation of CO_2 into useful organic compounds upon reaction with an organometallic reagent.[1] We further reported on the structure of sulfur-stabilized allyllithium compounds in solution.[2] Continuing our investigations, we are now exploring synthetic possibilities for the fixation of heterocumulenes by studying the reaction of hetero-substituted allyllithium species with CO_2, as well as with PhNCO and PhNCS, two additional heterocumulene representatives.

Heterosubstituted allyllithium compounds **Li-1** are extremely interesting from a synthetic point of view, due to their ability to serve either as homoenolates **4** or as acyl anion equivalents **5** (Scheme 1). Electrophilic attack at the α-position of such an ambident allyllithium species corresponds to the selection of the acyl anion equivalent **5** (also called a reversed polarity synthon) and results − after suitable synthetic workup − in a 1-substituted species **3**. Attack at the γ-position via the homoenolate **4** pathway leads to 3-substituted compounds **2**. Adducts obtained with aldehydes and ketones can be converted relatively easily into γ-lactols or γ-lactones.

The versatility and potential synthetic use of heterosubstituted allyllithium compounds has prompted numerous studies on these compounds.[3−12] Besides investigations into the structure in solution,[2,13] a great deal of effort has been made to investigate the regioselectivity of attack by various electrophiles, alkyl halides and carbonyl compounds such as aldehydes and ketones having mainly been employed in the past. Much less attention has been paid to electrophiles derived from the heterocumulene series (X=C=Z). Examples of such species are CO_2, CS_2, COS, PhNCO, PhNCS, etc. The products formed have wide synthetic applications.[14] As an example, thioamides[15] are valuable intermediates for the preparation of numerous aliphatic, aromatic and heterocyclic compounds. Among other applications, they serve as corrosion inhibitors and as accelerators for vulcanization additives, for lubricating oils, and are employed for plant protection.[16] Furthermore, they are potential backbone-modified peptide surrogates.[17] In addition to their use in peptide synthesis, amides are interesting synthons since they allow an extension of the carbon chain to take place via C-alkylation in addition to the possibility of *N*-alkylation.[18] The amide unit is part of the structure of many biologically active compounds, such as β-lactams.



Scheme 1

Continuing our investigations on lithiated compounds, we are now exploring synthetic possibilities for the fixation of heterocumulenes by studying the reaction of hetero-substituted allyllithium species with heterocumulenes. For this article, we employed CO_2 and also PhNCO and PhNCS as

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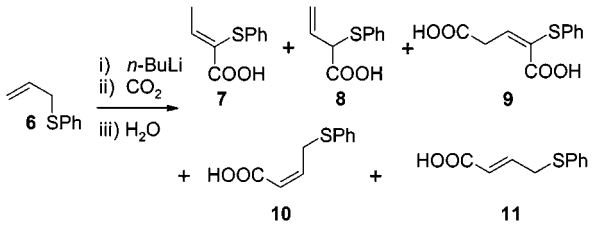
electrophiles and determined the regioselectivity of attack upon allyllithium compounds substituted with sulfur at the 1-position. Special interest was paid to the effect of the oxidation state of the sulfur atom upon the regioselectivity of heterocumulene addition, with lithiated allyl sulfides **Li-6**, sulfoxides **Li-12** and sulfones **Li-15** being included in the study. We furthermore investigated a related 1-(phosphonato)allyllithium compound **Li-18** in order to determine whether its behavior towards heterocumulenes can be directly compared to the corresponding lithiated allyl sulfone. All lithiated allylic compounds were synthesized according to modified procedures taken from the literature.[19,26−32]

Results and Discussion

Several factors can directly influence the observed ratio of α- versus γ-attack. Among them are the type of the heteroatom, its attached substituents, the nature of the electrophile, the solvent, additives, the temperature, aggregation and, of course, the identity of the counter-ion. We therefore performed all reactions under comparable experimental conditions (−78 °C, *n*BuLi, THF, workup at room temperature). In this article, aggregational effects can be neglected since we recently succeeded in showing that the sulfur-stabilized allyllithium compounds considered here are monomeric in THF at −108 °C and, in addition, exist exclusively in an *endo*-conformation.[2,20,21] Furthermore, the sulfur heteroanalogues are substituted by the same group (phenyl) in order to permit direct comparison of the effect of the sulfur oxidation state upon the regioselectivity. Since the substituents on the phosphorus atom may have a steric influence on the course of the reaction, the ethyl derivative of allyl phosphonate was chosen throughout.

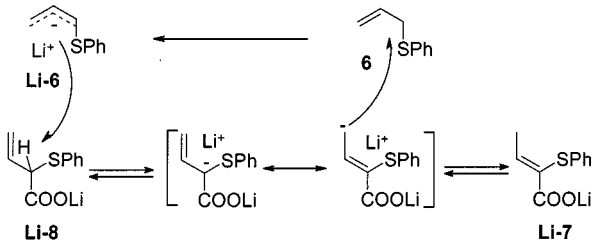
Carboxylation Reactions

Lithiated allyl phenyl sulfide (**Li-6**) shows very poor regioselectivity towards CO_2. A mixture of α- and γ-attack, as well as disubstitution (e.g. compound **9**), occurs (Scheme 2). The main product **7** is a rearranged isomer of the α-adduct **8**. The corresponding *E* isomer of **7** was detected only in traces. Furthermore, two γ-adducts, (*Z*)- (**10**) and (*E*)-phenylsulfanylbut-2-enoic acid (**11**) were obtained.



Scheme 2

We assume that the main product, 2-phenylsulfanyl-but-2-enoic acid (**7**), originates from the lithium derivative **Li-8**. The acidified proton in **Li-8** is most probably removed with the assistance of another molecule of lithiated **Li-6** (Scheme 3). A [1,3] shift followed by reprotonation at the 3-position then yields lithiated **Li-7**. Support for this mechanism was found when *n*-butyl iodide was employed as a competing electrophile. The expected 3-phenylsulfanylhept-1-ene was obtained as well as the α-carboxylic acid **8** (the main product), together with the γ-isomers **10** and **11**. No isomerization of **8** to **7** was observed. Obviously, *n*-butyl iodide trapped the remaining lithiated allyl phenyl sulfide (**Li-6**), which could no longer act as a base to deprotonate **Li-8**. The formation of **7** could also be avoided by trapping the lithium intermediate **Li-8** with DCl. No isomerization product **7** was observed (see Table 1).



Scheme 3. Proposed mechanism for the rearrangement of the α-product **8**

Table 1. Product ratio of the phenylsulfanylcarboxylic acid relative to **11**

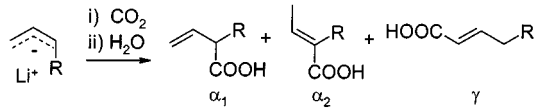
CO_2	α-isomer **7**	α **8**	α, γ **9**	γ-*Z* **10**	γ-*E* **11**
dry ice[a]	2.7	−	1	1	1
CO_2 gas[a]	1.6	0.9	3.7	1.3	1
dry ice[b]	0.3	1	0.4	1.1	1
dry ice, DCl[a]	−	1.6	0.9	1.2	1

[a] Workup at room temperature. − [b] Workup at 0 °C.

The experimental conditions were then varied in order to determine whether the reaction is thermodynamically or kinetically controlled. After a workup from 0 °C, a product distribution slightly different to that found at room temperature was observed. A workup at low temperatures obviously hinders the isomerization reaction that yields compound **7**. The amount of α-adduct **8** increases accordingly. In addition to the kinetic lability observed, ab inito calculations indicate that compound **Li-7** is thermodynamically more stable [4.2 kcal/mol at the HF/6−31+G(d) level of theory] than compound **Li-8**. The product ratios found also reveal a difference between the behavior of dry ice and that of gaseous CO_2. Although variation of the reaction conditions does change the α/γ ratio slightly, the predominate formation of one particular adduct could not be achieved.

Reaction of the lithiated sulfoxide **Li-12** with CO_2 results in a 1:1 mixture of the rearranged α-isomer (α_2) and the γ-isomer (**13** and **14**, Scheme 4). If the workup is carried out at 0 °C instead of at room temperature, a dramatic change in the regioselectivity results. Only γ-addition takes place, forming **17** in 47% yield (Table 2). In direct contrast to the

lithiated sulfide, disubstitution is not observed for the sulfoxide.



R	Li	α_1	α_2	γ
S(O)Ph	**Li-12**		**13**	**14**
SO_2Ph	**Li-15**	**16**		**17**
$P(O)(OEt)_2$	**Li-18**	**19**		**20**

Scheme 4

Table 2. Product distribution and chemical yields of the carboxylic acids

R	Compound	Yield [%]	Workup temp.	Product ratios α_1	α_2	γ
SOPh	**12**	42	room temp.	—[a]	1.3	1
	12	47	0 °C	—[a]	—[a]	1
SO_2Ph	**15**	57	room temp.	—[a]	—[a]	1
	15	65	0 °C	1	—[a]	—[a]
$P(O)(OEt)_2$	**18**	53	room temp.	—[a]	—[a]	1
	18	59	0 °C	1	—[a]	—[a]

[a] Product not detected.

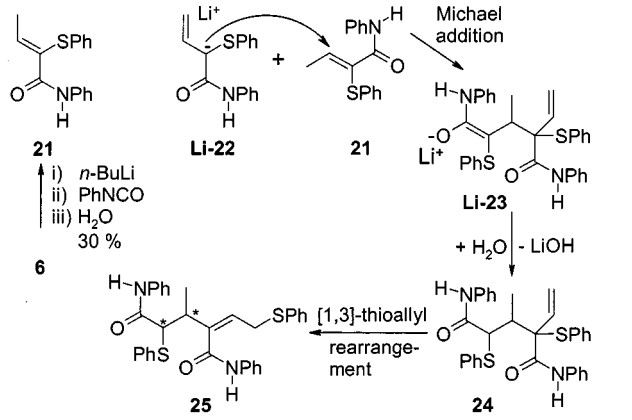
Regiospecific γ-attack occurs when CO_2 reacts with either the lithiated sulfone **Li-15** or the phosphonate **Li-18** to yield compounds **17** and **20**,[22] respectively (Scheme 4 and Table 2). The yields are higher than that observed for the sulfoxide **Li-12**. If the temperature of the workup is decreased to 0 °C, complete α-regioselectivity is achieved, to yield compounds **16** and **19**, respectively. By deprotonating the α-substituted acids **16** and **19** at −78 °C, we succeeded in showing that the carboxylic acids obtained by γ-attack (**17** and **20**) are the thermodynamically more stable structures. The lithiated species thus generated were allowed to equilibrate at room temperature before being reprotonated. After this treatment, only the γ-products **17** and **20** were found. The stabilization of the γ-adducts **17/20** as compared to the α-substituted acids **16/19** can be attributed to the stabilization gained because of the conjugation of the double bond of the allylic backbone with the double bond of the carboxylic unit.

These investigations show that *the carboxylation reaction is reversible* for sulfonyl- and phosphoryl-substituted allyllithium compounds and that the regioselectivity can be controlled by the workup temperature. This is an interesting fact, since reversible CO_2 fixation by organolithium compounds is quite rare. α-Attack by CO_2 at low temperatures has, however, been reported for lithiated (2*Z*)-3,7-dimethyl-1-(*p*-tolylsulfonyl)-2,6-octadiene, resulting in (3*Z*)-4,8-dimethyl-2-(*p*-tolylsulfonyl)-3,7-nonadienoic acid.[23,24]

All experimental data allow the conclusion that increasing the oxidation state of the sulfur atom promotes γ-selectivity (valid for carboxylic acids, the initially generated carboxylate salts of which were allowed to reach thermal equilibrium). However, if an excess of CO_2 is employed, disubstitution results for 1-(thiophenyl)allyllithium (**Li-6**). In addition to the carboxylic acids, starting material was also recovered for all allyl derivatives. This could possibly be due to reprotonation of the lithium intermediates by traces of H_3O^+, even though the CO_2 employed was dried with concentrated sulfuric acid.

Syntheses of Amides

Replacing CO_2 with PhNCO resulted in a considerable improvement in the regioselectivity. Only one major product was obtained for all lithiated allyl compounds investigated here. Reaction of lithiated allyl phenyl sulfide **Li-6** with PhNCO proceeds with high α-selectivity to give **21** (Scheme 5, Table 3). In addition to the 1:1 adduct, a small quantity of the 2:2 compound **25** was found. The formation of the latter can be explained by a Michael addition of lithiated amide **Li-22** to the β-carbon atom of the allylic



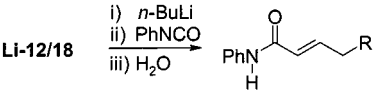
Scheme 5

Table 3. Product distribution obtained for the amidation reaction

R	Compound	Product	Yield [%]	PhNCO
SPh	**6**	**21** + **(25)**	30	1
SOPh	**12**	**26**	66	1
SO_2Ph	**15**	**28**	78	1
	15	**30**	37	0.4
$P(O)(OEt)_2$	**18**	**27**	67	0.5

backbone of already protonated amide **21**, followed by a [1,3]-thioallyl rearrangement to give **25**. A racemic pair of diastereomers was isolated, thus providing evidence for a diastereoselective reaction. The asymmetric centers could be assigned by employing (*S*)-(+)-2,2,2,-trifluoro-1-(9-anthryl)ethanol as a chiral shift reagent.

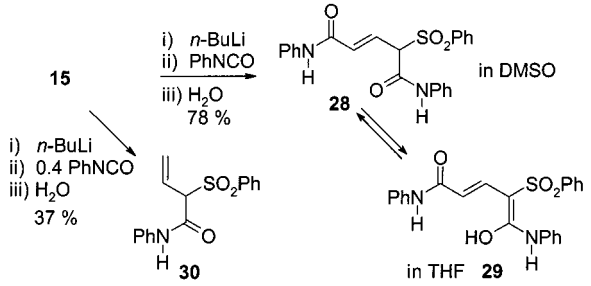
In direct contrast to the lithiated thioether **Li-6**, reaction of **Li-12** with PhNCO occurred by γ-attack to yield the amide **26** (Scheme 6). The temperature of the workup did not influence the regioselectivity.



R = S(O)Ph **26**
R = $P(O)(OEt)_2$ **27**
(0.5 PhNCO)

Scheme 6

In the case of the sulfone, it was necessary to employ an excess of the lithiated species **Li-15**, since reaction with an equimolar amount resulted in the diamide **28** instead of the monoamide **30** (Scheme 7). The amide function acidifies the proton at the α-carbon atom, which facilitates a second deprotonation. Steric effects probably increase the preference for γ-attack by the second equivalent of PhNCO, thus resulting in the α,γ-diamide **28**. NMR investigations show that the diamide is present in DMSO, while in THF the enol tautomer **29** is observed.



Scheme 7

In analogy to the sulfone **15**, half an equivalent of PhNCO was necessary in order to obtain the monoamide **27** of the lithiated phosphonate **Li-18** (Table 3). In direct contrast to the α-attack observed for the sulfone, the reaction occurred exclusively at the γ-carbon atom (Scheme 6).

Syntheses of Thioamides

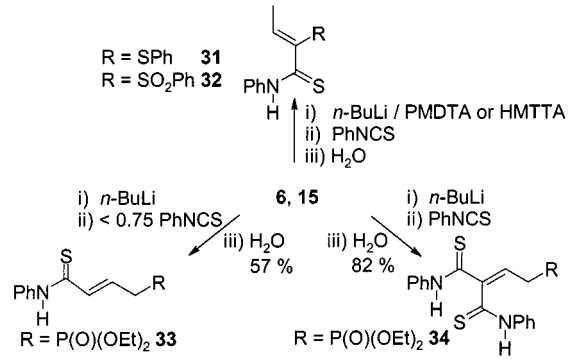
Reaction of the lithiated allyl compounds with PhNCS also results in highly selective or regiospecific product formation. All sulfur-containing species were substituted at the α-carbon atom next to the heteroatom, whereas the phosphonate **Li-18** was attacked at the γ-terminus.

Similarly to PhNCO, PhNCS reacts to give (*Z*)-*N*-phenyl-2-(phenylsulfanyl)but-2-enethioamide (**31**), a crotyl or acrylamide (Table 4, Scheme 8). Because of the reduced reactivity of PhNCS as compared to PhNCO, it proved necessary to employ *N*,*N*,*N*′,*N*′′,*N*′′′,*N*′′′-hexamethyltriethylenetetramine (HMTTA) as a cosolvent. In contrast to the lithiated thioether **Li-6**, treatment of the lithiated sulfoxide **Li-12** with PhNCS in the presence of a cosolvent [TMEDA (*N*,*N*,*N*′,*N*′-tetramethylethylenediamine), PMDTA (*N*,*N*,*N*′,*N*′′,*N*′′-pentamethyldiethylenetriamine), etc.] did not result in thioamide formation. Two equivalents of both *n*BuLi and PhNCS had to be employed in order to obtain the α-substituted sulfoxide **35**. Under these conditions, 9% of the dithioamide **36** was formed (Scheme 9). The excess of PhNCS reacted with *n*BuLi to give *n*-butylphenylthioamide **37**. Compound **36** is most probably generated through the reaction of traces of allyllithium (**Li-39**) [resulting from deprotonation of allyl phenyl sulfoxide (**12**) by *n*BuLi] with the isothiocyanate to give **41**. *n*-Butyl sulfoxide (**38**), formed in the first step of the reaction, is deprotonated by an excess of *n*BuLi to give the lithiosulfoxide **Li-40**. Compounds **Li-40** and **41** then react with each other by Michael addition to yield the dithioamide **36** as the by-product (Scheme 10).

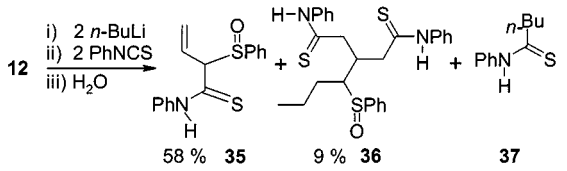
Table 4. Product distribution obtained for the thioamidation reaction

R	Compound	Product	Yield [%]	PhNCS	Cosolvent
SPh	**6**	**31**	58	1	HMTTA
SOPh	**12**	**35**[a]	58	2[b]	–
SO_2Ph	**15**	**32**	46	1	PMDTA
$P(O)(OEt)_2$	**18**	**33**	57	> 0.75	–
	18	**34**	82	1	–

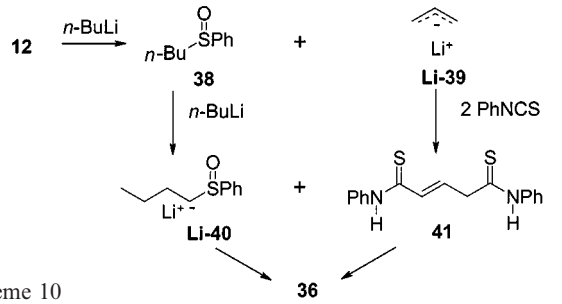
[a] By-product **36** was obtained in 9% yield. – [b] Two equivalents of *n*BuLi were necessary.



Scheme 8



Scheme 9



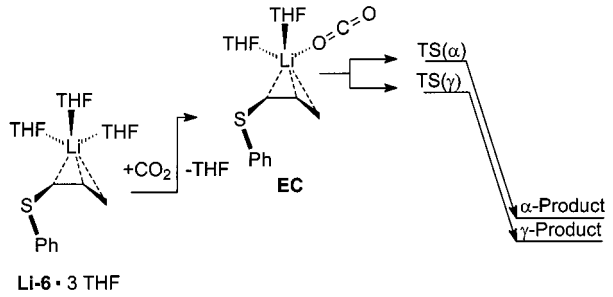
Scheme 10

For the reaction of lithiated allyl phenyl sulfone (**Li-15**) with PhNCS, PMDTA turned out to be the appropriate cosolvent (Table 4, Scheme 8). In the absence of PMDTA, the reaction forming the α-substituted thioamide **32** was not observed. The reaction between the lithiated allylphosphonate **Li-18** and PhNCS could be achieved without the addition of a cosolvent. An excess of **Li-18** had to be employed in order to obtain the monothioamide **33**.[22] Disubstitution with formation of the γ,γ-product **34**[22] is obtained otherwise. In contrast to the lithiated sulfur compounds, which

are attacked in the α-position, the lithiated phosphoryl species **Li-18** undergoes regiospecific γ-substitution. A change of the workup temperature to 0 °C had no effect upon the regioselectivity of the electrophilic fixation, in contrast to the carboxylation reaction.

Mechanistic Considerations

A combined experimental and theoretical study of the lithiated species **Li-6**, **Li-12** and **Li-15** recently succeeded in assigning three-dimensional *solution state structures* for these lithiated species in THF at low temperatures.[2] As a concrete example, **Li-6** exists exclusively in an *endo* conformation and is a monomer in THF under the experimental conditions applied in this article. $^{1}H,^{6}Li$-HOESY experiments show the presence of an η^3 contact of the lithium ion with the allyl system. The η^3 bridging present is not exactly symmetrical; the carbanion-stabilizing capability of the SPh substituent causes the lithium ion to favor a $C_\alpha-Li$ contact ion pair structure, a fact that could be shown both in experiment and in an extensive computational study which included microsolvation[2] (the first solvation sphere of **Li-6** most probably contains three THF molecules cf. **Li-6**·3THF, Scheme 11).



Scheme 11. Proposed mechanism for the carboxylation of **Li-6**

Combining our knowledge of the solution structure of **Li-6** with the results of an extensive ab initio study (which again included microsolvation) of the carboxylation reaction of a lithiated dithiane[1] (2-lithio-2-phenyl-1,3-dithiane·THF·TMEDA[25]) provides us with a strong foundation for speculation on the probable carboxylation mechanism of **Li-6**. The THF-solvated allyllithium compound most probably reacts with CO_2 to form an encounter complex **EC** (or encounter complexes, since the allyl substrate is not symmetrical) in which one THF molecule is pushed out of the first coordination sphere of the lithium cation (Scheme 11). As could be shown for the dithiane, CO_2 is a worse donor ligand than THF, which indicates that the replacement of THF by CO_2 will be slightly endothermic (ca. 3−5 kcal/mol would be expected). Formation of the encounter complex will further polarize the CO_2 molecule, thus facilitating the subsequent reaction via (at least) two transition structures, one for α- and one for γ-attack, both of which can be expected to lie ca. 15−20 kcal/mol above the energy of the separated reactants. Model calculations at the B3LYP/6−31+G(d) level of theory on 1-thioallyllithium, neglecting microsolvation, indicate that both transition structures are expected to be practically isoenergetic, which correlates satisfactorily with the product mixture found experimentally (Table 5). Progressing further along the reaction path, product formation will be quite exothermic, thus providing the overall driving force for the reaction. A detailed ab inito study, including microsolvation, on the mechanism of this carboxylation reaction is currently in progress and will be reported on in a forthcoming article. In addition, the effect of the substituent (SPh, SOPh and SO_2Ph) on the reaction mechanism − in particular the question of whether carboxylation takes place preferentially in a C−Li or in an Li−O contact ion pair in the case of SOPh and SO_2Ph − will be addressed.

Table 5. Relative energies [kcal/mol] for the reaction of CO_2 with sulfur-substituted allyllithium compounds, calculated at the B3LYP/6−31+G(d) level of theory

Substituents	SH	SOH	SO_2H
ΔE(reactants)	0.0	0.0	0.0
ΔE(**EC**)	−7.2	−3.2	−7.7
ΔE(**TS$_\alpha$**)	−6.3	−2.3	−2.8
ΔE(**TS$_\gamma$**)	−6.2	−3.2	−1.9
ΔE(α-product)[a]	−30.0	−8.1	−9.2
ΔE(γ-product)[a]	−32.8	−10.0	−12.4

[a] Lithiated adduct.

Conclusions

Addition of CO_2 to lithiated allyl phenyl sulfone (**Li-15**) and lithiated diethyl allylphosphonate (**Li-18**) is reversible and can be controlled by the temperature of the workup. An extra stabilization of the γ- over the α-substituted carboxylic acids, due to conjugation of the allylic double bond with a carboxylic function, is gained in this case.

In contrast to the carboxylation reactions, treatment of the lithiated species with either PhNCO or PhNCS proceeds with high regioselectivity. A reason for this might be found in energy differences between the encounter complex and/or the transition structures calculated for CO_2 and PhNCO/PhNCS, with the former obviously being symmetrical with respect to the electrophilic reaction center.

While variation of the oxidation state of the sulfur atom results in no general tendency for either α- or γ-attack in amide formation, exclusive α-attack is observed for all sulfur-substituted allyllithium compounds on reaction with PhNCS. Only the reaction with lithiated phosphonate **Li-18** gives a γ-adduct for the thioamide. Changing the temperature of the workup to 0 °C did not affect the regioselectivity of the electrophilic fixation of PhNCO and PhNCS as observed for CO_2.

Experimental Section

General Remarks: All NMR spectra were recorded with either a Bruker AC250 spectrometer or a Bruker DRX400 spectrometer. All measurements were carried out in $CDCl_3$ (δ_H = 7.24, δ_C = 77.0) except for **28** ([D$_6$]DMSO, δ_H = 2.49, δ_C = 39.7). These solv-

ents were also used as internal standards (ppm). The mass spectra were obtained using Finnigan quadrupole mass spectrometers SSQ-710 MAT and 900 XL TRAP. Infrared spectra (KBR) were obtained using a NICOLET Impact 400 spectrometer. The elemental analyses were performed with a LECO CHNS 932 combuster. All reactions were carried out under argon (dried with phosphorus pentoxide and potassium hydroxide). THF was distilled from sodium/benzophenone prior to use. CO_2 was dried, if necessary, by passing it through a solution of concentrated sulfuric acid. The melting points were measured in a copper capillary block and are not corrected. PhNCO and PhNCS were obtained from Aldrich. The allylic substrates (**6**,[26] **13**,[27] **16**,[28] **17**[29]) were prepared according to modified literature procedures.[30,31] The side reaction of *n*BuLi with the heterocumulenes should, under favorable conditions, occur only in small quantities, since the allylic species chosen contain carbanion-stabilizing groups. The deprotonation reaction appeared to be quantitative. However, a small excess of *n*BuLi might be present in the reaction mixtures, since 1.1 equivalents of *n*BuLi, with respect to the allylic species, were generally applied. This was done in order to compensate for deactivation of the lithium base by traces of moisture in the THF. In the case of carboxylations, the organolithium compound was added from a syringe onto the CO_2 in order to avoid the presence of carboxylate and *n*BuLi at the same time.

Synthesis of Allylic Acids. − General Procedure: *n*-Butyllithium (5.5 mmol, 1.6 M in hexane) was added to a stirred solution of the allyl compound (5 mmol) in tetrahydrofuran (10 mL) at −78 °C under argon. The resulting yellow solution was kept at this temperature for 1 h before being poured onto solid CO_2. (Dry, solid CO_2 was obtained by passing the gas through concentrated sulfuric acid and condensing it with liquid nitrogen. If gaseous CO_2 was employed, it was bubbled through the lithiated solution for about 3−4 h.) The reaction mixture was stirred for additional 2 h and the temperature was allowed to rise. The mixture was then hydrolyzed with 2 M aqueous HCl to form the allylic acid. Purification was achieved by addition of 5% aqueous NaOH and removal of the impurities with diethyl ether. Addition of 2 M aqueous hydrochloric acid gave the acid, which was then extracted with diethyl ether (3 × 15 mL). The combined extracts were dried with $MgSO_4$ and the solvent was removed. Deviations from this procedure include performing the hydrolysis and the subsequent workup at 0 °C; the hydrolysis with DCl, or application of 1 equiv. of *n*-butyl iodide as an additional electrophile. The product ratios of the (phenylsulfanyl)carboxylic acids **7−11** can be found in Table 1. They were taken from the relative signal intensities in the ^{1}H NMR spectra.

(Phenylsulfanyl)carboxylic Acids: The total yield of the (phenylsulfanyl)butenoic acids was 71.0%.

(*Z*)-2-(Phenylsulfanyl)but-2-enoic Acid (7): ^{1}H NMR: δ = 2.11 (d, 3 H, CH_3), 7.10−7.27 (m, 5 H, Ph), 7.69 (m, 1 H, CH), 11.67 (s, 1 H, COOH). − ^{13}C NMR: δ = 17.2 (CH_3), 126.2 (Ph, C-*o*,*o*′), 126,6 (C-α), 127.9 (Ph, C-*m*,*m*′), 129.1 (Ph, C-*p*), 135.1 (Ph, C-*i*), 152.8 (C-β), 169.5 (C=O). − $C_{10}H_{10}O_2S$ (194.2): calcd. C 61.86, H 5.15, S 16.49; found C 61.70, H 5.19, S 16.49. − MS; *m*/*z*: 194. − M.p. 86 °C. − IR [cm^{-1}]: ṽ = 1676 (C=O), 2825 (OH).

2-(Phenylsulfanyl)but-3-enoic Acid (8): ^{1}H NMR: δ = 4.25 (d, 1 H, CH-α), 5.22 (d, 2 H, CH_2-γ), 5.94 (m, 1 H, CH-β), 7.18−7.54 (m, 5 H, Ph), 10.91 (s, 1 H, COOH). − $C_{10}H_{10}O_2S$ (194.2)^{13}C NMR: δ = 54.3 (C-α), 119.6 (C-γ), 122.6 (C-β), 128.6 (Ph, C-*o*,*o*′), 129.1 (Ph, C-*m*,*m*′), 133.7 (Ph, C-*p*), 146.0 (Ph, C-*i*), 176.5 (C=O).

4-(Phenylsulfanyl)pent-2-enedioic Acid (9): ^{1}H NMR: δ = 3.63 (d, $^3J_{H\text{-}H}$ = 6.96 Hz, 2 H, CH_2-γ), 7.14−7.32 (m, 5 H, Ph), 7.69 (m, 1 H, CH-β), 9.35 (s, 2 H, 2 COOH). − ^{13}C NMR: δ = 35.8 (C-γ), 126.1 (Ph, C-*o*,*o*′), 127.8 (C-α), 129.0 (Ph, C-*m*,*m*′), 134.0 (Ph, C-*p*), 135.2 (Ph, C-*i*), 145.6 (C-β), 175.3 (C=O), 177.1 (C=O).

4-(Phenylsulfanyl)but-2-enoic Acids. − *Z* Isomer 10: ^{1}H NMR: δ = 3.35 (d, 2 H, CH_2-α), 5.93 (m, 1 H, CH-β), 6.42 (d, $^3J_{H\text{-}H}$ = 9.34 Hz, 1 H, CH-γ), 7.14−7.32 (m, 5 H, Ph), 9.35 (s, 1 H, COOH). − ^{13}C NMR: δ = 31.0 (C-α), 124.1 (C-β), 125.3 (Ph, C-*o*,*o*′), 127.4 (C-γ), 128.2 (Ph, C-*m*,*m*′), 129.0 (Ph, C-*p*), 137.6 (Ph, C-*i*), 169.0 (C=O). − ***E* Isomer 11:** ^{1}H NMR: δ = 3.19 (d, 2 H, CH_2-α), 5.88 (m, 1 H, CH-β), 6.31 (m, $^3J_{H\text{-}H}$= 15.09 Hz, 1 H, CH-γ), 7.14−7.32 (m, 5 H, Ph), 9.35 (s, 1 H, COOH). − ^{13}C NMR: δ = 34.4 (C-α), 123.8 (C-β), 125.3 (Ph, C-*o*,*o*′), 128.2 (C-γ), 129.0 (Ph, C-*m*,*m*′), 130.0 (Ph, C-*p*), 137.8 (Ph, C-*i*), 169.0.

(Phenylsulfinyl)carboxylic Acids: A mixture of (*Z*)-2-(phenylsulfinyl)but-2-enoic acid (**13**) (α-product) and (*E*)-4-(phenylsulfinyl)but-2-enoic acid (**14**) (γ-product) in a ratio of 1.3:1 (from the ^{1}H NMR spectrum) was obtained [total yield 42% (0.5 g)]. (*Z*)-2-(Phenylsulfinyl)but-2-enoic acid (**13**) partially precipitated from the mixture.

(*Z*)-2-(Phenylsulfinyl)but-2-enoic Acid (13): ^{1}H NMR: δ = 2.31 (d, 3 H, CH_3), 7.24 (m, 1 H, CH-β), 7.75−7.88 (m, 5 H, Ph), 8.87 (s, 1 H, COOH). − ^{13}C NMR: δ = 16.0 (CH_3), 124.3 (Ph, C-*o*,*o*′), 129.4 (Ph, C-*m*,*m*′), 131.7 (Ph, C-*p*), 135.5 (C-α), 142.2 (Ph, C-*i*), 147.1 (C-β), 164.8 (C=O). − $C_{10}H_{10}O_3S$ (210.2): calcd. C 57.13, H 4.79, S 15.25; found C 57.11, H 4.75, S 15.17. − MS; *m*/*z*: 210. − M.p. 135 °C. − IR [cm^{-1}]: ṽ = 1699 (C=O), 2933 (OH).

(*E*)-4-(Phenylsulfinyl)but-2-enoic Acid (14): Hydrolysis followed by workup at 0 °C produced 47% (*E*)-4-(phenylsulfinyl)but-2-enoic acid (**14**). − ^{1}H NMR: δ = 3.70 (m, 2 H, CH_2-α), 5.84 (d, $^3J_{H\text{-}H}$ = 15.61 Hz, 1 H, CH-γ), 6.72 (m, 1 H, CH-β), 7.24−7.66 (m, 5 H, Ph), 9.06 (s, 1 H, COOH). − ^{13}C NMR: δ = 58.2 (CH_2-α), 124.3 (Ph, C-*o*,*o*′), 128.2 (C-γ), 129.4 (Ph, C-*m*,*m*′), 131.8 (Ph, C-*p*), 136.0 (C-β), 142.5 (Ph, C-*i*), 170.9 (C=O). − $C_{10}H_{10}O_3S$ (210.2): calcd. C 57.13, H 4.79, S 15.25; found C 56.22, H 4.85, S 15.39. − MS; *m*/*z*: 210. − IR [cm^{-1}]: ṽ = 1710 (C=O), 2961 (OH).

(Phenylsulfonyl)carboxylic Acids

(*E*)-4-(Phenylsulfonyl)but-2-enoic Acid (17): Stirring the yellow liquid with diethyl ether caused the product to solidify. The yield was 57% (0.6 g). − ^{1}H NMR: δ = 4.30 (d, 2 H, CH_2-α), 5.85 (d, $^3J_{H\text{-}H}$ = 15.53 Hz, 1 H, CH-γ), 6.51 (m, 1 H, CH-β), 7.60−8.22 (m, 5 H, Ph), 12.53 (s, 1 H, COOH). − ^{13}C NMR: δ = 55.5 (C-α), 125.9 (C-β), 127.2 (Ph, C-*o*,*o*′), 127.8 (C-γ), 131.4 (Ph, C-*m*,*m*′), 132.1 (Ph, C-*p*), 136.5 (Ph, C-*i*), 164.0 (C=O). − $C_{10}H_{10}O_4S$ (226.2): calcd. C 53.09, H 4.46, S 14.17; found C 53.13, H 4.49, S 13.91. − MS; *m*/*z*: 227 [M + 1]. − M.p. 145 °C. − IR [cm^{-1}]: ṽ = 1704 (C=O), 2938 (OH).

2-(Phenylsulfonyl)but-3-enoic Acid (16): The α-adduct was obtained in 65% yield (1.2 g) when the workup was carried out at 0 °C. − ^{1}H NMR: δ = 4.53 (d, 1 H, CH-α), 5.23 (d, 1 H, CH-γ), 5.40 (d, 1 H, CH-γ), 5.82 (m, 1 H, CH-β), 7.50 (t, 2 H, Ph-*m*,*m*′), 7.63 (t, 1 H, Ph-*p*), 7.80 (d, 2 H, Ph-*o*,*o*′), 9.42 (s, 1 H, COOH). − ^{13}C NMR: δ = 74.6 (C-α), 125.1 (C-β), 126.2 (C-γ), 129.1 (Ph, C-*o*,*o*′), 129.7 (Ph, C-*m*,*m*′), 134.7 (Ph, C-*p*), 135.7 (Ph, C-*i*), 167.9 (C=O). − $C_{10}H_{10}O_4S$ (226.2): calcd. C 53.09, H 4.46, S 14.17; found C 52.80, H 4.58, S 13.61. − MS; *m*/*z*: 227 [M + 1]. − M.p. 92 °C. − IR [cm^{-1}]: ṽ = 1733 (C=O), 2957 (OH).

(Diethoxyphosphoryl)carboxylic Acids

(*E*)-4-(Diethoxyphosphoryl)but-2-enoic Acid (20): The colorless liquid (*E*)-4-(diethoxyphosphoryl)but-2-enoic acid (**20**) was purified by column chromatography with ethyl acetate/hexane (1:10 followed by 1:5). White crystals suitable for X-ray crystallography were formed.[22] The yield was 53% (3.3 g). Alternatively, purification could be achieved by means of distillation at 0.87 mbar and 160 °C. − ^{1}H NMR: δ = 1.30 (m, 6 H, 2 CH_3), 2.76 (dd, $^2J_{P-H}$ = 23.15 Hz, 2 H, CH_2-α), 4.11 (m, 4 H, 2 OCH_2), 5.94 (dd, $^3J_{H-H}$ = 15.58 Hz, $^4J_{P-H}$ = 5.03 Hz, 1 H, CH-γ), 6.91 (m, 1 H, CH-β), 8.82 (s, 1 H, COOH). − ^{13}C NMR: δ = 16.3 (CH_3), 29.5 and 26.2 ($^1J_{C-P}$ = 207.0 Hz, C-α), 62.6 (OCH_2), 125.7 ($^3J_{C-P}$ = 13.7 Hz, C-γ), 139.0 ($^2J_{C-P}$ = 11.1 Hz, C-β), 169.2 (C=O). − ^{31}P NMR: δ = 25.80. − $C_8H_{15}O_5P$ (222.1): calcd. C 43.25, H 6.80; found C 43.39, H 6.96. − MS; *m*/*z*: 223 [M + 1]. − M.p. 85 °C. − IR [cm^{-1}]: ṽ = 1708 (C=O), 2909 (OH).

2-(Diethoxyphosphoryl)but-3-enoic Acid (19): If the workup was carried out at 0 °C, 59% (0.9 g) of 2-(diethoxyphosphoryl)but-3-enoic acid (**19**) was isolated. − ^{1}H NMR (OH signal not detectable): δ = 1.28 (m, 6 H, 2 CH_3), 2.59 (dd, $^2J_{P-H}$ = 21.09 Hz, 1 H, CH-α), 4.10 (m, 4 H, 2 OCH_2), 5.20 (m, 2 H, CH-γ), 5.75 (m, 1 H, CH-β). − ^{13}C NMR: δ = 16.2 (CH_3), 32.2 and 30.8 ($^1J_{C-P}$ = 139.7 Hz, C-α), 61.9 (OCH_2), 120.2 ($^3J_{C-P}$ = 14.6 Hz, C-γ), 127.1 ($^2J_{C-P}$ = 11.37 Hz, C-β), 169.0 ($^2J_{C-P}$ = 5.6 Hz, C=O). − ^{31}P NMR: δ = 28.69. − $C_8H_{15}O_5P$ (221.1): calcd. C 43.25, H 6.80; found C 42.61, H 7.12. − MS; *m*/*z*: 223 [M + 1]. − IR [cm^{-1}]: ṽ = 1724 (C=O), 2983 (OH).

Phenylsulfanyl Amides

(*Z*)-*N*-Phenyl-2-(phenylsulfanyl)but-2-enamide (21): Allyl phenyl sulfide (6.0 g, 40 mmol) and TMEDA (4.7 g, 40 mmol) in THF (50 mL) were cooled to −78 °C, and *n*BuLi in hexane (27.5 mL, 44 mmol) was added. The yellow solution was stirred for 1 h at this temperature, followed by the slow addition of a solution of PhNCO (4.4 mL, 40 mmol) and HMTTA, 7.0 mL, 40 mmol) in THF. The reaction mixture was then kept for additional 1 h at −78 °C and then allowed to warm up to room temperature overnight. Water (10 mL) and saturated aqueous NH_4Cl (10 mL) were then added to the red brown solution. The organic layer was extracted with diethyl ether (3 × 25 mL), dried with $MgSO_4$ and the solvent removed. Column chromatography with hexane/ethyl acetate (5:1) gave **21**, which could be recrystallized from hexane/acetone. The yield was 3.2 g of amide, corresponding to 30%. In addition, 33% of allyl phenyl sulfide and 36% of 1-propenyl phenyl sulfide (rearranged starting material) were recovered. − ^{1}H NMR: δ = 2.12 (d, 3 H, CH_3), 7.03−7.50 (m, 10 H, 2 Ph), 7.84 (q, 1 H, CH-β), 8.56 (s, 1 H, NH). − ^{13}C NMR: δ = 17.0 (C-γ), 120.0 (Ph, C-*o*,*o*′), 124.5 (Ph, C-*o*,*o*′), 126.4 (Ph, C-*m*,*m*′), 126.9 (Ph, C-*m*,*m*′), 127.2 (Ph, C-*p*), 128.9 (Ph, C-*p*), 129.5 (C-α), 134.4 (Ph, C-*i*), 137.6 (Ph, C-*i*), 149.3 (C-β), 162.3 (C=O). − $C_{16}H_{15}NOS$ (269.4): calcd. C 71.34, H 5.61, N 5.20, S 11.90; found C 71.47, H 5.61, N 5.20, S 12.16. − MS; *m*/*z*: 269. − M.p. 117−119 °C . − IR [cm^{-1}]: ṽ = 1657 (OCNH, I), 1508 (OCNH, II), 1250 (OCNH, III), 685 (OCNH, δ).

(*Z*)-3-Methyl-*N*,*N*′-diphenyl-2-(phenylsulfanyl)-4-[2-(phenylsulfanyl)ethylidene]pentanediamide (25): If the reaction described above was carried out in the absence of TMEDA, **25** was obtained as a by-product (2% as referenced to 1 equiv. of PhNCO). − ^{1}H NMR: δ = 1.21 (d, $^3J_{H-H}$ = 6.76 Hz, 3 H, CH_3), 2.58 (m, 1 H, CH-β′), 2.67−2.75 (m, 1 H, CH-α), 2.85−2.92 (m, 1 H, CH-α), 3.74 (d, $^3J_{H-H}$ = 5.97 Hz, 1 H, CH-α′), 7.06−7.43 (m, 20 H, 4 Ph), 7.70 (t, $^3J_{H-H}$ = 7.21 Hz, 1 H, CH-β), 8.51 (s, 1 H, NH), 8.75 (s, 1 H, NH). − ^{13}C NMR: δ = 18.4 (C-γ′), 35.5 (C-α), 36.1 (C-β′), 60.4 (C-α′), 120.0 (Ph, C-*o*,*o*′), 124.6 (Ph, C-*o*,*o*′), 124.7 (Ph, C-*o*,*o*′), 126.6 (Ph, C-*o*,*o*′), 127.1 (Ph, C-*m*,*m*′), 127.1 (Ph, C-*m*,*m*′), 127.7 (Ph, C-*m*,*m*′), 128.5 (C-γ), 128.9 (Ph, C-*m*,*m*′), 129.0 (Ph, C-*p*), 129.4 (Ph, C-*p*), 129.5 (Ph, C-*p*), 130.7 (Ph, C-*p*), 133.6 (Ph, C-*i*), 134.2 (Ph, C-*i*), 137.2 (Ph, C-*i*), 137.5 (Ph, C-*i*), 150.5 (C-β), 162.0 (C=O), 168.3 (C=O). − $C_{32}H_{30}O_2N_2S_2$ (538.7): calcd. C 71.34, H 5.61, N 5.20, S 11.90; found C 71.18, H 5.70, N 5.32, S 12.04. − MS; *m*/*z*: 538. − M.p. 156−158 °C. − IR [cm^{-1}]: ṽ = 1651/1600 (OCNH, I), 1538 (OCNH, II), 1264 (OCNH, III), 688 (OCNH, δ).

Phenylsulfinyl Amides

(*E*)-*N*-Phenyl-4-(phenylsulfinyl)but-2-enamide (26): Allyl phenyl sulfoxide (2.4 g, 14.3 mmol) in THF (20 mL) at −78 °C was added to *n*BuLi in hexane (9.8 mL, 15.8 mmol). The mixture was stirred for 1 h, and PhNCO (2.6 g, 21.5 mmol) was added. After stirring overnight, the workup of the orange solution was performed analogously to that for compound **21**. Purification was achieved by dissolving the amide **26** in CH_2Cl_2 and precipitating with hexane, and also by washing through silica gel with hexane/ethyl acetate (2:1) as the eluents. The yield was 2.7 g, corresponding to 66% with respect to the allyl phenyl sulfoxide. − ^{1}H NMR: δ = 3.56−3.69 (m, 2 H, CH_2-α), 6.22 (d, $^3J_{H-H}$ = 15.20 Hz, 1 H, CH-γ), 6.58 (m, 1 H, CH-β), 7.06−7.54 (m, 10 H, 2 Ph), 8.34 (s, 1 H, NH). − ^{13}C NMR: δ = 58.4 (C-α), 119.6 (Ph, C-*o*,*o*′), 120.3 (Ph, C-*o*,*o*′), 124.3 (Ph, C-*m*,*m*′), 128.9 (Ph, C-*m*,*m*′), 129.3 (Ph, C-*p*), 129.7 (Ph, C-*p*), 131.5 (C-β), 132.6 (Ph, C-*i*), 137.9 (C-γ), 141.7 (Ph, C-*i*), 162.4 (C=O). − MS; *m*/*z*: 285. − M.p. 116 °C. − IR [cm^{-1}]: ṽ = 1679 (OCNH, I), 1545 (OCNH, II), 1248 (OCNH, III), 693 (OCNH, δ) $C_{16}H_{15}NO_2S$ (285.3).

Phenylsulfonyl Amides

(*E*)-*N*,*N*′-Diphenyl-4-(phenylsulfonyl)pent-2-enediamide (28): Allyl phenyl sulfone (0.5 g, 2.7 mmol) in THF (5 mL) was cooled to −78 °C. After deprotonation with *n*BuLi in hexane (2.0 mL, 3.2 mmol), the solution was stirred for 1 h, after which PhNCO (0.3 g, 2.7 mmol) was added. The reaction mixture was then stirred overnight and water (5 mL) and 1 M HCl were added. Addition of diethyl ether caused the precipitation of the product as a white solid. After storing in a refrigerator and filtering, 0.4 g of product was obtained. This corresponds to a yield of 78% with respect to PhNCO. − ^{1}H NMR ([D_6]DMSO): δ = 5.22 (d, $^3J_{H-H}$ = 9.20 Hz, 1 H, CH_2-α), 6.38 (d, $^3J_{H-H}$ = 15.38 Hz, 1 H, CH-γ), 6.74 (m, 1 H, CH-β), 7.04−7.82 (m, 15 H, 3 Ph), 10.25 (s, 1 H, NH), 10.44 (s, 1 H, NH). − ^{13}C NMR: δ = 72.6 (C-α), 119.3 (Ph, C-*o*,*o*′), 119.5 (Ph, C-*o*,*o*′), 123.7 (Ph, C-*o*,*o*′), 124.4 (Ph, C-*m*,*m*′), 128.8 (Ph, C-*m*,*m*′), 128.9 (Ph, C-*m*,*m*′), 129.2 (Ph, C-*p*), 129.2 (Ph, C-*p*), 130.3 (Ph, C-*p*), 132.1 (C-β), 134.7 (C-γ), 136.6 (Ph, C-*i*), 137.8 (Ph, C-*i*), 138.7 (Ph, C-*i*), 160.8 (C=O), 161.6 (C=O). − $C_{23}H_{20}N_2O_4S$ (420.5): calcd. C 65.70, H 4.79, N 6.66, S 7.63, found C 65.58, H 4.80, N 6.78, S 6.97. − MS; *m*/*z*: 421 [M + 1]. − M.p. 228 °C (decomp.). − IR [cm^{-1}]: ṽ = 1662/1638 (OCNH, I), 1542 (OCNH, II), 1256 (OCNH, III), 686 (OCNH, δ). − The enol tautomer **29** in THF [^{1}H NMR: δ = 6.02 (d, $^2J_{H-H}$ = 14.68 Hz, 1 H, CH-β), 6.78−7.83 (m, 15 H, Ph), 8.08 (d, $^2J_{H-H}$ = 14.68 Hz, 1 H, CH-γ), 8.76 (s, 1 H, NH), 10.09 (s, 1 H, NH)] was confirmed by a selective TOCSY experiment. A single coupling to the proton signal at δ = 8.08 was observed on irradiation at δ = 6.02.

***N*-Phenyl-2-(phenylsulfonyl)but-3-enamide (30):** *n*BuLi in hexane (7.2 mL, 11.4 mmol) was added at −78 °C to allyl phenyl sulfone (2.1 g, 11.4 mmol) in THF (50 mL). The yellow solution was stirred for 1 h at this temperature, after which PhNCO (0.5 g, 4.8 mmol)

in THF (5 mL) was slowly added. The workup was carried out analogously to that of **21**. The oil was dissolved in CH_2Cl_2. A sticky product was precipitated with hexane; on stirring in hexane it became powder-like. The yield was 37.0% with respect to PhNCO (0.5 g). − ^{1}H NMR: δ = 4.67 (d, 1 H, CH-α), 5.39 (dd, 2 H, CH_2-γ), 5.93 (m, 1 H, CH-β), 7.03−7.84 (m, 10 H, 2 Ph), 8.66 (s, 1 H, NH). − ^{13}C NMR: δ = 75.6 (C-α), 125.5 (C-γ), 125.8 (C-β), 128.4 (Ph, C-*o*,*o*′), 128.7 (Ph, C-*o*,*o*′), 128.9 (Ph, C-*m*,*m*′), 129.1 (Ph, C-*m*,*m*′), 129.4 (Ph, C-*p*), 129.5 (Ph, C-*p*), 136.2 (Ph, C-*i*), 137.2 (Ph, C-*i*), 162.5 (C=O). − MS; *m*/*z*: 301. − M.p. 134 °C. − IR [cm^{-1}]: ṽ = 1688 (OCNH, I), 1543 (OCNH, II), 1247 (OCNH, III), 691 (OCNH, δ) $C_{16}H_{15}NO_2S$ (301.3).

Diethoxyphosphoryl Amides

(*E*)-4-(Diethoxyphosphoryl)-*N*-phenylbut-2-enamide (27): Diethyl allylphosphonate (2.1 g, 11.7 mmol) in THF (30 mL) was added to *n*BuLi in hexane (7.3 mL, 11.7 mmol) at −78 °C. The reaction mixture was stirred for 45 min at −78 °C, after which PhNCO (0.7 g, 5.8 mmol) was added to the nearly colorless solution, which promptly turned yellow. The solution was kept overnight and then protonated with a saturated solution of NH_4Cl. The THF was evaporated. The residue was extracted with $CHCl_3$ and dried with $MgSO_4$. The product was only slightly contaminated and was purified by column chromatography [silica gel, hexane/ethyl acetate (1:1, later 2:1)]. The total yield of amide was 67.0% (1.2 g). − ^{1}H NMR: δ = 1.29 (m, 6 H, 2 CH_3), 2.72 (dd, $^3J_{H\text{-}H}$ = 7.73 Hz, $^2J_{P\text{-}H}$ = 22.81 Hz, 2 H, CH_2-α), 4.07 (m, 4 H, 2 OCH_2), 6.25 (dd, $^3J_{H\text{-}H}$= 15.34 Hz, $^4J_{P\text{-}H}$ = 5.00 Hz, allylic coupling: $^4J_{H\text{-}H}$ = 1.40 Hz, 1 H, CH-γ), 6.83 (m, 1 H, CH-β), 7.05 (t, 1 H, Ph-*p*), 7.27 (t, 2 H, Ph-*m*,*m*′), 7.63 (d, 2 H, Ph-*o*,*o*′), 8.89 (s, 1 H, NH). − ^{13}C NMR: δ = 16.3 ($^3J_{C\text{-}P}$= 5.9 Hz, CH_3), 30.0 ($^1J_{C\text{-}P}$ = 138.6 Hz, C-α), 62.4 ($^2J_{C\text{-}P}$ = 6.9 Hz, OCH_2), 120.0 (Ph, C-*o*,*o*′), 124.0 (Ph, C-*m*,*m*′), 128.7 (Ph, C-*p*), 129.2 ($^3J_{C\text{-}P}$ = 13.6 Hz, C-γ), 133.1 ($^2J_{C\text{-}P}$ = 11.4 Hz, C-β), 138.3 (Ph, C-*i*), 163.3 (C=O). − ^{31}P NMR: δ = 26.21. − $C_{14}H_{20}NO_4S$ (297.3): calcd. C 56.56, H 6.78, N 4.71, found C 56.15, H 7.09, N 4.35. − MS; *m*/*z*: 297. − M.p. 88 °C. − IR [cm^{-1}]: ṽ = 1679 (OCNH, I), 1543 (OCNH, II), 1222 (OCNH, III), 688 (OCNH, δ).

Phenylsulfanyl Thioamides

(*Z*)-*N*-Phenyl-2-(phenylsulfanyl)but-2-enethioamide (31): Allyl phenyl sulfide (0.8 g, 5.5 mmol) and HMTTA (1.3 g, 6.0 mmol) in THF (50 mL) were treated with *n*BuLi in hexane (3.8 mL, 6.0 mmol) at −78 °C. The yellow solution was stirred for 1 h at −78 °C, followed by the addition of PhNCS (0.7 g, 5.5 mmol) in THF (5 mL). The color changed to orange. After stirring overnight, the workup was carried out analogously to that reported for the amide **21**. The column chromatography was performed with hexane/ethyl acetate (10:1). The yield was 58% (0.9 g). − ^{1}H NMR: δ = 2.18 (d, 3 H, CH_3), 7.16−7.70 (m, 10 H, 2 Ph), 8.17 (q, 1 H, CH-β), 10.30 (s, 1 H, NH). − ^{13}C NMR: δ = 18.1 (C-γ), 124.0, 124.7 (Ph, C-*o*,*o*′), 126.5 (Ph, C-*m*,*m*′), 127.1 (Ph, C-*m*,*m*′), 128.8 (Ph, C-*p*), 129.5 (Ph, C-*p*), 133.4 (C-α), 135.8 (Ph, C-*i*), 138.6 (Ph, C-*i*), 151.8 (C-β), 192.3 (C=S). − $C_{16}H_{15}NS_2$ (285.4): calcd. C 65.51, H 5.47, N 4.78, S 21.70; found C 67.33, H 5.30, N 4.91, S 22.47. − MS; *m*/*z*: 285. − M.p. 132−135 °C. − IR [cm^{-1}]: ṽ = 1082 (C=S), 1362, 1525.

Phenylsulfinyl Thioamides

***N*-Phenyl-2-(phenylsulfinyl)but-3-enethioamide (35):** *n*BuLi in hexane (6.7 mL, 10.8 mmol) was added to allyl phenyl sulfoxide (0.9 g, 5.4 mmol) at −78 °C. After approximately 1 h, PhNCS (1.5 g, 10.8 mmol) in THF (20 mL) was added, upon which the yellow solution turned orange. The workup was accomplished as for **21**. Recrystallization of the oil from 2-propanol gave a beige solid, the by-product **36**. The α-adduct **35** was found in the filtrate; the 2-propanol was removed and the residue was washed with hexane. The yield was 58% (0.9 g) with respect to the sulfoxide. − ^{1}H NMR: δ = 4.92 (td, 1 H, CH-α), 5.25 (td, $^3J_{C\text{-}H}$ = 10.29 Hz, 1 H, CH-γ), 5.59 (td, $^3J_{C\text{-}H}$ = 17.14 Hz, 1 H, CH-γ), 6.10 (m, 1 H, CH-β), 7.21−7.97 (m, 10 H, 2 Ph), 8.95 (s, 1 H, NH). − ^{13}C NMR: δ = 79.0 (C-α), 117.2 (C-γ), 124.8 (Ph, C-*o*,*o*′), 125.0 (Ph, C-*o*,*o*′), 127.1 (Ph, C-*m*,*m*′), 127.3 (Ph, C-*m*,*m*′), 129.6 (Ph, C-*p*), 130.0 (Ph, C-*p*),136.2 (Ph, C-*i*), 136.9 (Ph, C-*i*), 137.8 (C-β), 200.8 (C=S). − MS; *m*/*z*: 302 [M + 1]. − IR [cm^{-1}]: ṽ = 1082 (C=S), 1362, 1525.

***N*,*N*′-Diphenyl-3-[1-(phenylsulfinyl)butyl]pentanedithiodiamide (36):** The yield of the by-product was 9% (0.2 g). − ^{1}H NMR: δ = 0.70 (t, 3 H, CH_3-δ′′), 0.78 and 1.75 (2 m, 2 H, CH_2-γ′′), 0.95 and 1.20 (2 m, 2 H, CH_2-β′′),2.51 (m, 1 H, CH-α), 3.15 (m, 2 H, CH_2-γ), 3.28 (m, 2 H, CH_2-γ′), 3.39 (m, 1 H, CH-β), 7.23−7.54 (m, 11 H, Ph), 7.85 (d, 2 H, Ph-*o*,*o*′), 7.92 (d, 2 H, Ph-*o*,*o*′), 10.39 (s, 1 H, NH), 10.88 (s, 1 H, NH). − ^{13}C NMR: δ = 14.0 (C-δ′′), 20.3 (C-γ′′), 35.3 (C-β′′), 38.7 (C-α), 50.8 (C-γ), 54.5 (C-γ′), 55.4 (C-β), 122.5 (Ph, C-*o*,*o*′), 123.4 (Ph, C-*o*,*o*′), 124.0 (Ph, C-*o*,*o*′), 126.7 (Ph, C-*m*,*m*′), 126.8 (Ph, C-*m*,*m*′), 128.8 (Ph, C-*m*,*m*′), 128.9 (Ph, C-*p*), 129.4 (Ph, C-*p*), 131.2 (Ph, C-*p*), 138.6 (Ph, C-*i*), 139.0 (Ph, C-*i*), 141.9 (Ph, C-*i*), 201.2 (C=S), 203.6 (C=S). − $C_{27}H_{30}N_2OS_3$ (494.7): calcd. C 65.55, H 6.11, N 5.66, S 19.44; found C 65.11, H 6.12, N 5.57, S 19.72. − MS (FAB); *m*/*z*: 495 [M + 1]. − M.p. 154 °C. − IR [cm^{-1}]: ṽ = 1080/1130 (C=S), 1316, 1495.

Phenylsulfonyl Thioamides

***N*-Phenyl-2-(phenylsulfonyl)but-2-enethioamide (32):** Allyl phenyl sulfone (2.1 g, 11.4 mmol) and PMDTA (2.2 g, 12.5 mmol) in THF (50 mL) were cooled to −78 °C, deprotonated with *n*BuLi in hexane (7.8 mL, 12.5 mmol) and stirred for 1 h. PhNCS (1.5 g, 11.4 mmol) in THF (5 mL) was added, causing the yellow solution to change to orange. After stirring overnight, the workup was carried out as for **21**. Purification was achieved as follows: The oil was poured on top of a silica gel column, washed with hexane and the fraction eluted with acetone was subjected to column chromatography with hexane/ethyl acetate (20:1), resulting in1.7 g of a yellow solid (46%). − ^{1}H NMR: δ = 2.07 (d, 3 H, CH_3), 7.22 (q, 1 H, CH-β), 7.26−7.62 (m, 6 H, 2 Ph-*m*,*m*′, *p*), 7.71 (d, 2 H, Ph-*o*,*o*′), 7.85 (d, 2 H, Ph-*o*,*o*′), 9.83 (s, 1 H, NH). − ^{13}C NMR: δ = 15.6 (C-γ), 122.9 (Ph, C-*o*,*o*′), 127.2 (Ph, C-*o*,*o*′), 128.5 (Ph, C-*m*,*m*′), 129.0 (Ph, C-*m*,*m*′), 129.4 (Ph, C-*p*), 133.9 (Ph, C-*p*), 134.7 (Ph, C-*i*), 138.0 (Ph, C-*i*), 141.3 (C-β), 144.5 (C-α), 186.4 (C=S). − $C_{16}H_{15}NO_2S_2$ (317.4): calcd. C 60.57, H 4.73, N 4.45, S 20.19, found C 60.00, H 4.88, N 4.48, S 19.74. − MS; *m*/*z*: 317 [M + 1]. − M.p. 140 °C. − IR [cm^{-1}]: ṽ = 1082 (C=S), 1380, 1549.

Diethoxyphosphoryl Thioamides

2-[2-(Diethoxyphosphoryl)ethylidene]-*N*,*N*′-diphenyldithiomalonamide (34): Diethyl allylphosphonate (1.4 g, 7.8 mmol) in THF (25 mL) was treated at −78 °C with *n*BuLi in hexane (5.4 mL, 8.6 mmol). After stirring for 1 h, PhNCS (1.1 g, 7.8 mmol) was added slowly. The previously pale yellow solution became lemon yellowish. After standing overnight, the now orange solution was subjected to a workup similar to that of **21**. During the evaporation of the solvent, the yellow product crystallized. After recrystallization from 2-propanol, crystals suitable for X-ray crystallography were obtained.[22] Yield: 1.4 g (83% with respect to PhNCS). − ^{1}H NMR: δ = 1.35 (t, $^3J_{H\text{-}H}$ = 7.05 Hz, 6 H, 2 CH_3), 2.83 (dd, $^3J_{H\text{-}H}$ = 9.05 Hz, $^2J_{P\text{-}H}$ = 23.09 Hz, 2 H, CH_2-α), 4.16 (m, 4 H, 2

OCH_2), 6.88 (m, 1 H, CH-β), 7.20−7.44 (m, 6 H, 2 Ph-*m*,*m*′, *p*), 7.81 (d, $^3J_{H-H}$ = 7.88 Hz, 2 H, Ph-*o*,*o*′), 8.01 (d, 2 H, Ph-*o*,*o*′), 11.40 (s, 1 H, NH), 11.58 (s, 1 H, NH). − ^{13}C NMR: δ = 16.5 (CH_3), 27.8 and 29.9 ($^1J_{P-C}$ = 132.96 Hz, C-α), 63.4 (OCH_2), 122.0 (Ph, C-*o*,*o*′), 123.2 (Ph, C-*o*,*o*′), 126.8 (Ph, C-*m*,*m*′), 127.3 (C-β), 127.4 (Ph, C-*m*,*m*′), 128.8 (Ph, C-*p*), 128.9 (Ph, C-*p*), 138.3 (Ph, C-*i*), 139.0 (Ph, C-*i*), 149.0 and 149.2 ($^3J_{C-P}$ = 14.5 Hz, C-γ), 190.5 (C=S), 191.6 (C=S). − ^{31}P NMR: δ = 27.49. − $C_{21}H_{25}N_2O_3PS_2$ (448.5): calcd. C 56.23, H 5, S 14.30; found C 55.94, H 5.60, S 14.51. − MS; *m*/*z*: 448. − M.p. 125 °C. − IR [cm^{-1}]: ṽ = 1096/1123 (C=S), 1345/1383, 1493/1522.

(*E*)-4-(Diethoxyphosphoryl)-*N*-phenylbut-2-enethioamide (33): Diethyl allylphosphonate (9.6 g, 54.1 mmol) in THF (85 mL) was added at −78 °C to *n*BuLi in hexane (34 mL, 54.4 mmol). After 1 h, PhNCS (1.5 g, 10.8 mmol) in THF (23 mL) was slowly added. The workup was performed analogously to **21**. The orange oil was dissolved in THF and hexane was added until the solution became cloudy. The flask was kept in the refrigerator and the sticky precipitate was then stirred with ethyl acetate/hexane (2:1). The product (1.9 g, 57% with respect to PhNCO) was obtained as pure crystals. − ^{1}H NMR: δ = 1.23 (m, 6 H, 2 CH_3), 2.68 (dd, $^2J_{P-H}$ = 22.59 Hz, 2 H, CH_2-α), 4.00 (m, 4 H, 2 OCH_2), 6.64 (dd, $^3J_{H-H}$ = 10.83 Hz, 1 H, CH-γ), 6.94 (m, 1 H, CH-β), 7.15−7.32 (m, 3 H, Ph-*m*,*m*′, *p*), 7.63 (d, 2 H, Ph-*o*,*o*′), 10.48 (s, 1 H, NH). − ^{13}C NMR: δ = 16.3 (CH_3), 29.5 and 30.9 ($^1J_{C-P}$ = 126.1 Hz, C-α), 62.6 (OCH_2), 124.1 (Ph, C-*o*,*o*′), 126.5 (Ph, C-*m*,*m*′), 128.7 (Ph, C-*p*), 132.7 and 132.8 ($^2J_{C-P}$ = 11.17 Hz, C-β), 136.1 and 136.3 ($^3J_{C-P}$ = 14.19 Hz, C-γ), 139.0 (Ph, C-*i*), 192.4 (C=S). − ^{31}P NMR: δ = 26.37. − $C_{14}H_{20}NO_3PS$ (313.4): calcd. C 53.66, H 6.43, N 4.57, S 10.23; found C 54.10, H 6.62, N 4.33, S 10.27. − MS; *m*/*z*: 313. − M.p. 105−106 °C. − IR [cm^{-1}]: ṽ = 1099 (C=S), 1387, 1541.

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