N-Phosphorylated lactams
2.* Reversible phosphorylation of silyllactams

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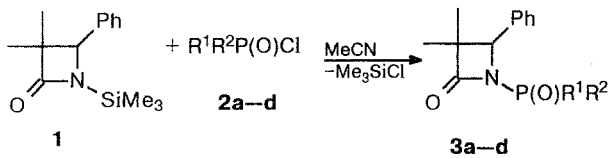
The phosphorylation of *N*-trimethylsilyllactams by phosphorus(III) acid chlorides results in corresponding *N*-phosphinolactams in high yields. The derivatives thus obtained have been used in the synthesis of *N*-phosphoryl- and *N*-thiophosphoryllactams. The reversibility of the reaction of phosphinolactams has been established.

Key words: *N*-trimethylsilyllactams; reversible phosphorylation; *N*-phosphoryllactams, synthesis.

Recently we have suggested an approach to the synthesis of *N*-phosphoryllactams based on treating corresponding γ-, δ-, and ε-silyllactams with phosphorus(V) acid chlorides.[1] It was also of interest to extend the synthetic capabilities of this reaction and to use it for obtaining phosphorylated β-lactams.[2,3]

We have studied the interaction of the *N*-silylated derivative of 3,3-dimethyl-4-phenylazetidin-2-one (**1**), the most available β-lactam,[4] with chlorides of phosphinic (**2a,b**) and dialkylphosphoric (**2c,d**) acids. Phosphoryl chlorides **2a,b** react with **1** at the nitrogen atom (as in the case of five-, six-, and seven-membered silyllactams) resulting in *N*-(diphenylphosphoryl)- and *N*-(dibutylphosphoryl)azetidin-2-ones (**3a,b**) in 62 and 74 % yields, respectively. However, in the reaction of phosphorylation, the reactivity of compound **1** is lower than those of silyllactams previously studied resulting in the increase of the reaction time from 3 (see Ref. 1) to 16 h (acetonitrile, 80—90°C).

Interaction between **1** and dialkyl chlorophosphates **2c,d** is still slower. The reaction proceeds with the satisfactory rate only at 110—115 °C, but these conditions resulted in formation of complex mixtures of compounds, and *N*-phosphoryllactams **3c,d** were isolated only in 27 and 9 % yields, respectively.



1 **2a–d** **3a–d**

$R^1 = R^2$ = Ph (**a**); Bu (**b**); EtO (**c**); Pr^iO (**d**)

Previously, we interpreted the low yields of *N*-phosphorylated derivatives of five-, six-, and seven-membered lactams from competitive phosphorylation at the oxygen atom resulting in the formation of dialkyl(trimethylsilyl)phosphates, but the generation of silylphosphates was not observed in the reaction of dialkyl chlorophosphates with lactam **1**. This can probably be explained by the rigid geometry of the four-membered ring, which hinders the formation of an *O*-phosphorylated intermediate with an endocyclic C=N bond.

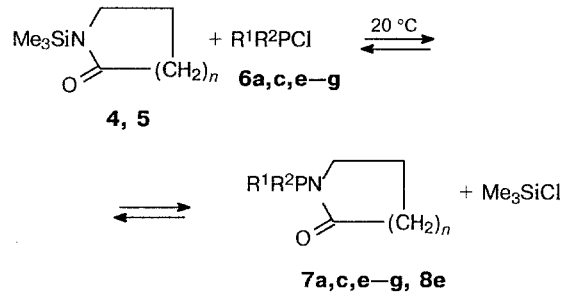
The possible cause of the low yields of compounds **3c,d** is their decomposition under the reaction conditions. The periodic ^{31}P NMR monitoring the composition of the reaction mixture showed that only *N*-phosphoryllactams **3c,d** were generated at the initial step of the process. The highest yields of these compounds (36 and 20 %, respectively) were reached when keeping the reaction mixture at 110—115 °C for 14—20 h. Further heating decreased the content of **3c,d** in the mixture and caused the formation of a large number of by-products. The attempts to phosphorylate **1** in the presence of nucleophilic catalysts, *N*-methylmorpholine and 4-dimethylaminopyridine, failed, as in this case the process of the decomposition of **3c,d** became predominant even at a lower temperature (65—70 °C).

As we failed to obtain *N*-phosphoryllactams from dialkyl chlorophosphates and silyllactams in high yields, we studied the possibility to synthesize them *via* the phosphorus(III) derivatives. Recently phosphorus trichloride was shown to interact with *N*-(trimethylsilyl)pyrrolidone (**4**) and *N*-(trimethylsilyl)caprolactam (**5**) with the substitution of all three halogen atoms for the nitrogen atom of the lactam ring.[5] We investigated the reaction of monochlorides of phosphorus(III) acids (**6**) with lactams **4** and **5**. The reaction proved to proceed as readily, as in the case of PCl_3. The analyses of reaction

* For communication 1 see Ref. 1.

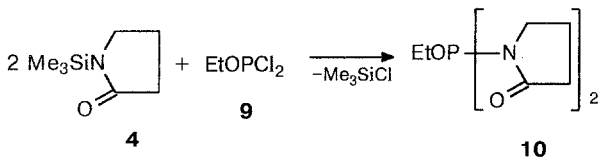
Translated from *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 11, pp. 2250—2255, November, 1995.

mixtures by ^{31}P NMR spectroscopy showed the phosphorylation to be regioselective and to result in the corresponding *N*-phosphinolactams **7** and **8** in 63—92 % yields.



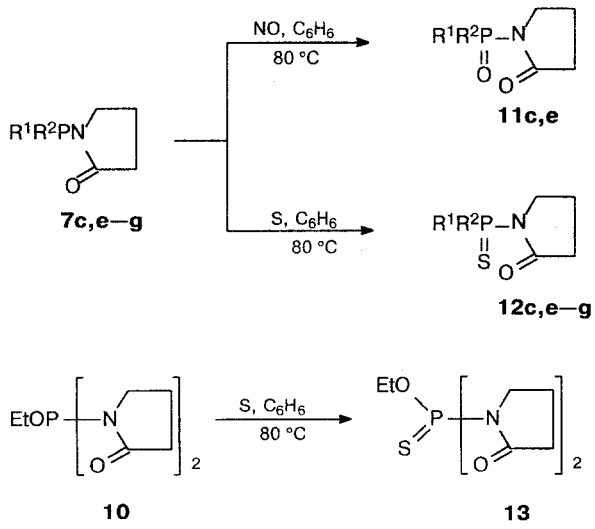
$R^1 = R^2 =$ Ph (**a**); EtO (**c**);
$R^1 + R^2 = O(CH_2)_3O$ (**e**); $O(CH_2)_2O$ (**f**); $OCHMeCH_2O$ (**g**);
$n = 1$ (**4, 7**); 3 (**5, 8**)

1,1′-Ethoxyphosphinylidenebis(2-pyrrolidone) (**10**) was obtained in the similar way from ethyl dichlorophosphite **9** and two equivalents of **4** in 94% yield.



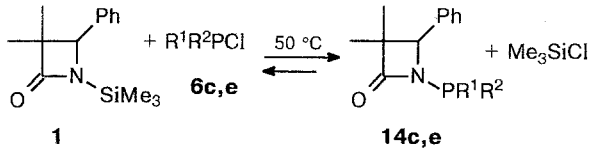
Compounds **7c,e—g** and **10** are viscous colorless liquids. Phosphinolactams **7a** and **8e** are solids. The structure of compounds **7**, **8**, and **10** was confirmed by IR and ^1H and ^{31}P NMR spectroscopy and elemental analysis data.

N-Phosphinolactams **7c,e—g**, and **10** are oxidized by nitrogen monoxide and sulfur at 80°C, resulting in the corresponding derivatives of tetracoordinated phosphorus (**11c,e**, **12c,e—g**, **13**) in high yields.



The approach to the synthesis of *N*-(dialkoxyphosphoryl)lactams **11c,e** *via* phosphorus(III) derivatives has some advantages over the method reported previously[1] because of the ease of the experiment and higher yields (50—60 %). Thiophosphorylated lactams **12c,e—g** and **13** were not described before.

We also used the interaction of *N*-trimethylsilyllactams with phosphorus(III) acid chlorides for obtaining phosphorylated β-lactams. Heating the mixture of **1** and chlorophosphites **6c,e** at 50°C for 7 h resulted in *N*-phosphinolactams **14c,e** in 81 and 71 % yields, respectively (^{31}P NMR data).



As compounds **14c,e** are viscous oily substances easily hydrolyzable by atmospheric moisture, they were oxidized to the corresponding derivatives of phosphoric acid **3c,e** without isolation and purification. The total yields of dialkoxyphosphoryl-β-lactams **3c,e** thus obtained were 40 and 42 % from **1**, exceeding the yields of phosphoryllactams obtained by treating **1** with chlorophosphates.

Study of the influence of the reaction conditions on the yields of *N*-phosphinolactams elucidated the reversibility of the reaction of phosphorus(III) acid chlorides with silyllactams. In most experiments the only partial conversion of an acid chloride to a phosphinolactam was observed at the equimolar ratio of the reagents even when keeping the reaction mixture for two months. ^{31}P NMR study of the mixtures of individual phosphinolactams **7a,c,e,g** and **8e** with trimethylchlorosilane showed that their composition is similar to those of the mixtures obtained in the reaction of silyllactams **4** and **5** with phosphorus(III) acid chlorides **6a,c,e,g**. These results allowed us to conclude that the process investigated is equilibrium one. At room temperature the equilibrium was established faster than in 1 h. At the equimolar ratio of reagents the equilibrium point could be inferred by the conversion of **6**. In most cases the latter ranges from 63 to 92% (Table 1) except for the reaction be-

Table 1. Equilibrium point in the reaction of silyllactams **4** and **5** with phosphorus(III) acid chlorides **6** at 20 °C

Silyllactam	Acid chloride	α (%)[a]
4	**6a**	87.2[b]
4	**6c**	91.6
4	**6e**	63.0
4	**6f**	89.3
4	**6g**	89.2
5	**6e**	67.3

Note: α is equilibrium conversion of the acid chloride. [a] Without solvent; [b] in benzene.

tween **4** and **9**, in which the equilibrium is completely shifted to phosphinolactam **10**.

Incomplete conversion of reagents was also observed in the reaction of chlorophosphites with silyl-β-lactam **1**. In this case the maximum conversion of a chlorophosphite at 50°C was reached in 7 h and comprised 81% for **6c** and 72% for **6e** at the equimolar ratio of starting compounds. The further heating of the reaction mixtures did not cause the change of the composition, so we can assume this reaction to be also an equilibrium. The possibility of the reverse process was not studied, as compounds **14c,e** were not isolated in analytically pure state.

The investigation of the interaction between **4** and **6c,d** at various temperatures showed that a temperature decrease for 25°C resulted in the 4—6 % increase of the yield of phosphinolactams **7c,d**. The yield of **7e** in the reaction of **4** with **6e** at the temperature in a range from −6 to +70°C varied from 65 to 56%, being in accord with variations of the equilibrium constant from 3.45 to 1.64 (Table 2). The value of ΔH of the reaction was estimated as -7.6 ± 1.6 kJ · mol^{-1} on the basis of the linear dependence of $\ln K_{eq}$ on $1/T$. So, the temperature decrease is favorable for the increase of the yield of **7**. The most convenient temperature for the synthesis of phosphinolactams **7** is 20°C, as in this case the ratio between the process rate and the conversion of the starting compounds is optimum. The increase of the phosphinolactam yield can also be achieved by applying the conventional methods for the shift of equilibrium point, *e.g.*, using the excess of an acid chloride, or removing Me_3SiCl *in vacuo*.

As can be seen from the results obtained, the reversibility is a common feature of the reactions of phosphorus(III) acid chlorides with silyllactams. Varying the structure both of the acid chloride and the silyllactam does not significantly influence the equilibrium point (Table 1). Going from five-membered acid chlorides **6f** and **6g** to six-membered cyclic chlorophosphite **6e** results in some decrease of conversion. At the same time, comparing the result of the reactions of **6e** with five- and seven-membered silyllactams **4** and **5** shows that the equilibrium point is slightly affected by the lactam cycle size.

Table 2. Temperature dependence of the equilibrium constant in the reaction of **4** with **6e**

T/K	α_{6e} (%)[a]	K_{eq}	$1/T \cdot 10^3$	ln K[b]
267	64.99	3.45	3.745	1.238
293	61.41	2.53	3.413	0.928
303	59.33	2.13	3.300	0.756
313	58.75	2.03	3.195	0.708
323	57.50	1.83	3.096	0.604
333	56.90	1.74	3.003	0.554
343	56.12	1.64	2.915	0.495

[a] Equilibrium conversion (α). [b] Calculated coefficients of the dependence $\ln K = a(1/T) + b$: $a = 908.7$, $b = -2.19$ ($r = 0.993$, $\sigma_0 = 0.0334$, $\sigma_a = 48.6$, $\sigma_b = 0.16$).

It is worthy of notice that the reversibility of phosphorylation by phosphorus(III) acid chlorides manifests itself in an explicit form only in their reactions with silyllactams. This distinguishes the latter compounds from other substances with N—Si bond. Thus, the position of the possible equilibrium is completely shifted to the formation of amidophosphites in the reaction of *N*-silylated amines with chlorophosphites, but there is only partial shift in the reaction of *N*-silylated amines with bromophosphites.[6,7] The reversibility of phosphorylation of *N*-silylated primary[8—9] and secondary[5] amides has not been revealed. Taking into account the data on the reaction of **4** and **6**, we can believe the equilibrium of the reaction of silylated lactams with PCl_3[5] to be completely shifted to the formation of the amidophosphite. The factors influencing the equilibrium point in the phosphorylation reactions of compounds with N—Si bond are the subject of further investigations.

So, we have discovered the reversibility of the reaction of phosphorus(III) acid chlorides with *N*-trimethylsilyllactams. We have also found that the equilibrium point can be easily shifted to the formation of *N*-phosphinolactams, which have been isolated in high yields and used for obtaining phosphorus(V) acid derivatives, phosphoryl- and thiophosphoryllactams.

Experimental

IR spectra were taken on a UR-20 spectrometer in Nujol or in KBr pellets. ^{1}H and ^{31}P NMR spectra were recorded on a Bruker WP-200-SY instrument at working frequencies of 200.13 and 81.01 MHz, respectively, relative to hexamethyldisiloxane as internal reference and 85% H_3PO_4 as external reference.

All synthetic procedures were performed in dry argon. Anhydrous solvents were used: acetonitrile was twice distilled from P_2O_5, and benzene was dried over sodium wire. Compounds **2b—d**, **4**, **5**, **6c,e—g**, and **9** were obtained by methods reported.[10—14] The purity of diethylchlorophospite **6c** was no less than 95%.

3,3-Dimethyl-1-trimethylsilyl-4-phenylazetidin-2-one (1). Hexamethyldisilazane (3.52 g, 21.8 mmol) and trimethylchlorosilane (0.24 g, 2.2 mmol) were added to 3,3-dimethyl-4-phenylazetidin-2-one[4] (1.27 g, 7.25 mmol). The mixture was refluxed for 3 h to complete dissolution of the crystals of the starting lactam. The mixture was evaporated at 8 Torr, and the residue was distilled *in vacuo* to give 1.62 g (90.3%) of **1**, bp 98—101 °C (0.1 Torr). Found (%): C, 67.56; H, 8.45. $C_{14}H_{21}NOSi$. Calculated (%): C, 67.96; H, 8.56. ^{1}H NMR ($CDCl_3$, δ, ppm): 0.19 (s, 9 H, Me_3Si); 0.7 (s, 3 H, CH_3); 1.38 (s, 3 H, CH_3); 4.28 (s, 1 H, $C\underline{H}C_6H_5$); 7.18—7.33 (m, 5 H, C_6H_5).

3,3-Dimethyl-1-(diphenylphosphoryl)-4-phenylazetidin-2-one (3a). A solution of 0.54 g (2.18 mmol) of **1** and 0.52 g (2.18 mmol) of chloride **2a** in 5 mL of MeCN was heated for 16 h at 80—85 °C. The mixture was evaporated *in vacuo* (15 Torr), and the solid residue was crystallized from MeCN to give 0.51 g (62.2%) of lactam **3a**, mp 185—187 °C. Found (%): C, 73.61; H, 6.07; P, 8.50. $C_{23}H_{22}NO_2P$. Calculated (%): C, 73.59; H, 5.91; P, 8.25. IR (KBr, ν/cm^{-1}): 1757 (C=O), 1205 (P=O). ^{1}H NMR (C_6D_6, δ, ppm, *J*/Hz): 0.54

(s, 3 H, CH_3); 1.04 (s, 3 H, CH_3), 4.67 (s, 1 H, CHC_6H_5); 6.90—7.09 (m, 11 H, Ph_2PO-(*m*- and *p*-), C_6H_5CH); 7.88—8.20 (dm, 4 H, Ph_2PO-*o*, $^3J_{PH}$ = 34). ^{31}P NMR (CH_2Cl_2, δ, ppm): +17.6.

1-(Dibutylphosphoryl)-3,3-dimethyl-4-phenylazetidin-2-one (3b) was obtained in a way similar to that used for **3a** by heating a solution of 0.71 g (2.87 mmol) of **1** and 0.56 g (2.87 mmol) of **2b** in 6 mL of MeCN for 16 h at 80—95 °C. Then the volatile compounds were removed *in vacuo* (15 Torr), and the residue was purified by flash-chromatography on silica gel L 100/160 μm (Et_2O as the eluent) to give 0.69 g (74.3%) of **3b** as a viscous colorless oil. Found (%): C, 67.31; H, 9.13; P, 8.79. $C_{19}H_{30}NO_2P$. Calculated (%): C, 66.85; H, 9.35; P, 9.58. ^1H NMR (C_6D_6, δ, ppm, *J*/Hz): 0.59 (s, 3 H, $CH_3C(CH_3)CO$); 0.71 (dt, 6 H, $(CH_3(CH_2)_3)_2P$, J_1 = 7.2 and J_2 = 15.2); 1.14 (s, 3 H, $CH_3C(CH_3)CO$); 1.11—2.05 (m, 12 H, $(CH_3(CH_2)_3)_2P$); 4.62 (s, 1 H, CHC_6H_5); 7.01—7.17 (m, 5 H, C_6H_5). ^{31}P NMR (CH_2Cl_2, δ, ppm): +41.8.

1-(Diethoxyphosphoryl)-3,3-dimethyl-4-phenylazetidin-2-one (3c). (a) Synthesis from 1 and 2c. A mixture of 1.69 g (6.83 mmol) of **1**, 1.18 g (6.83 mmol) of **2c**, and 14 mL of MeCN was heated in a sealed tube for 14 h at 110—115 °C. The mixture was then diluted with 40 mL of Et_2O and washed with water, with saturated aqueous solution of $NaHCO_3$, and again with water. The organic layer was dried over anhydrous Na_2SO_4, the solvent was removed *in vacuo* (15 Torr), and the residue was purified by flash-chromatography on silica gel L 40/100 μm (acetone—pentane, 1 : 3, as the eluent) to give 0.58 g (27.4%) of **3c** as a viscous oil. Found (%): C, 57.85; H, 7.33; P, 9.18. $C_{15}H_{22}NO_4P$. Calculated (%): C, 57.87; H, 7.12; P, 9.95. IR (film, ν/cm^{-1}): 1780 (C=O), 1275 (P=O), 1030, 980 (POC). ^1H NMR (C_6D_6, δ, ppm, *J*/Hz): 0.56 (s, 3 H, $CH_3C(CH_3)CO$); 0.97 (dt, 6 H, $(CH_3CH_2O)_2P$, J_1 = 3.3 and J_2 = 7.1); 1.11 (s, 3 H, $CH_3C(CH_3)CO$); 3.91—4.07 (m, 4 H, $(CH_3CH_2O)_2P$, *J* = 7.5); 4.58 (s, 1 H, CHC_6H_5); 7.00—7.17 (m, 5 H, C_6H_5). ^{31}P NMR (CH_2Cl_2, δ, ppm): −8.44.

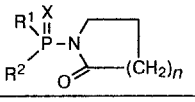
(b) Synthesis from 1 and 6c. A mixture of 0.63 g (2.55 mmol) of **1** and 0.4 g (2.55 mmol) of **6c** was kept for 7 h at 50°C. Then the volatile compounds were removed *in vacuo* (1 Torr). The residue was dissolved in 10 mL of benzene, and dry NO was passed through the solution for 1.5 h at 80°C. The reaction mixture was sequentially washed with water, with saturated aqueous solution of $NaHCO_3$, and again with water, dried over anhydrous Na_2SO_4, and evaporated. The residue was chromatographed on silica gel L 40/100 μm (acetone—pentane, 1 : 3, as the eluent) to give 0.33 g (42%) of **3c**. The spectral data for the compound obtained is similar to that of **3c** synthesized from **1** and **2c**.

1-(Diisopropoxyphosphoryl)-3,3-dimethyl-4-phenylazetidin-2-one (3d) was obtained in a way similar to that used for compound **3c** by heating a mixture of **1** (2.11 g, 8.77 mmol), **2d** (1.76 g, (8.77 mmol), and 18 mL of MeCN for 35 h at 90—110 °C. Flash-chromatography on silica gel L 110/160 μm (acetone—pentane, 1 : 4, as the eluent) resulted in 0.27 g (9.1%) of **3d** as a viscous oil. Found (%): C, 59.92; H, 8.21; P, 9.13. $C_{17}H_{26}NO_4P$. Calculated (%): C, 60.17; H, 7.72; P, 9.13. ^1H NMR (C_6D_6, δ, ppm, *J*/Hz): 0.55 (s, 3 H, $CH_3C(CH_3)CO$); 1.02—1.14 (m, 12 H, $((CH_3)_2CHO)_2P$); 1.09 (s, 3 H, $CH_3C(CH_3)CO$); 4.54 (s, 1 H, CHC_6H_5); 4.57—4.85 (m, 2 H, $(CH_3)_2CHO)_2P$); 6.97—7.19 (m, 5 H, C_6H_5). ^{31}P NMR (CH_2Cl_2, δ, ppm): −10.6.

***N*-Phosphinolactams 7 and 8 (general procedure).** Acid chloride **6** (26.6 mmol) was added to silyllactam **4** or **5** (26.6 mmol) during 15 min with stirring. The mixture was kept for 1—2 h at ~20°C, and the volatile compounds were removed *in vacuo* (8 Torr). Phosphinolactams **7** and **8** were isolated from the residue either by distillation *in vacuo* (0.5 Torr) in the case of **7c,e—g,** and **8e** or by crystallization in the case of **7a**. Yields, physical constants, and spectral data for the compounds obtained are given in Tables 3 and 4.

1,1′-Ethoxyphosphinylidenebis(2-pyrrolidone) (10) was obtained from **9** (1.70 g, 11.6 mmol) and **4** (3.62 g, 23.2 mmol) as described for **7** and **8**. Evaporating the reaction mixture *in vacuo* (0.1 Torr) gave 2.66 g (94%) of **10** as a viscous oil incapable to be distilled. ^1H NMR ($CDCl_3$, δ, ppm, *J*/Hz): 1.28 (t, 3 H, CH_3CH_2OP, *J* = 7.0); 2.10 (quint, 4 H, CH_2CH_2CO, *J* = 7.5); 2.42 (t, 4 H, CH_2CO, *J* = 8.0); 3.39 (t, 4 H, CH_2N, *J* = 7.0); 3.90—3.99 (m, 2 H, CH_3CH_2OP). ^{31}P NMR (THF, δ, ppm): +113.1. The compound obtained was used for the synthesis of thio derivative **13** without additional purification.

Table 3. *N*-Phosphinolactams



Compound	R^1	R^2	*n*	Yield (%)	B.p./°C (*p*/Torr) [M.p./°C] (solvent)	Empirical formula	Found / Calculated (%) C	H	P
7a	Ph	Ph	1	69.0	[129—132] (benzene)	$C_{16}H_{16}NOP$	71.58 / 71.37	6.12 / 5.99	11.22 / 11.50
7c	EtO	EtO	1	69.3	95—102 (0.5)	$C_8H_{16}NO_3P$	46.82 / 46.83	7.69 / 7.86	14.67 / 15.09
7e	$-O(CH_2)_3O-$		1	76.6	118—120 (0.5)	$C_7H_{12}NO_3P$	43.93 / 44.45	6.38 / 6.39	16.12 / 16.38
7f	$-O(CH_2)_2O-$		1	73.0	112—114 (1)	$C_6H_{10}NO_3P$	41.28 / 41.15	5.97 / 5.76	16.77 / 16.69
7g	$-OCH(CH_3)CH_2O-$		1	72.9*	117—119 (0.5)	$C_7H_{12}NO_3P$	43.90 / 44.45	6.13 / 6.39	16.30 / 16.38
8e	$-O(CH_2)_3O-$		3	62.7	155—156(1) [93—96]	$C_9H_{16}NO_3P$	49.71 / 49.77	7.48 / 7.43	14.02 / 14.26

* Mixture of diastereomers, 1 : 3.15.

Table 4. Spectral data for phosphorylated lactams

Compound	IR (ν/cm^{-1}) C=O	IR (ν/cm^{-1}) POC	δ^{31}P	^{1}H NMR δ
7a	1695	—	+31.0	1.11 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 8.0); 1.90 (t, 2 H, CH$_2$CO, J = 8.3); 2.64 (t, 2 H, CH$_2$N, J = 7.8); 6.96—7.11 (m, 6 H, Ar); 7.20—7.36 (m, 4 H, Ar)
7c	1670	1030	+133.3	1.18 (t, 6 H, (C$\underline{H}_3$CH$_2$O)$_2$P, J = 7); 1.94 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.6); 2.32 (t, 2 H, CH$_2$CO, J = 8.0); 3.45 (t, 2 H, CH$_2$N, J = 7.0); 3.80 (dq, 4 H, (CH$_3$C$\underline{H}_2$O)$_2$P, J_1 = 7.0, J_2 = 9.0)
7e	1680	1060	+122.5	0.91—1.05 (m, 1 H, H$_e$-5); 1.44 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 1.79—2.01 (m, 1 H, H$_a$-5); 2.09 (t, 2 H, CH$_2$CO, J = 8.0); 3.10 (t, 2 H, CH$_2$N, J = 6.9); 3.60—3.75 (m, 2 H, C$_e$-4,6); 3.92—4.07 (m, 2 H, C$_a$-4,6)
7f	1700	1025	+126.6	1.89 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 2.23 (t, 2 H, CH$_2$CO, J = 8.0); 3.30 (t, 2 H,CH$_2$N, J = 7.0); 3.87—4.12 (m, 4 H, (CH$_2$O)$_2$P)
7g	1700	995	+134.7 +129.1	1.25 (d, 3 H, CH$_3$, isomer **A**, J = 6.1); 1.38 (d, 3 H, CH$_3$, isomer **B**, J = 6.0); 1.93 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, isomer **A**, J = 7.5); 1.95 (quint, C$\underline{H}_2$CH$_2$CO, isomer **B**, J = 7.3); 2.28 (t, 2 H, CH$_2$CO, isomer **A**, J = 8.0); 2.31 (t, 2 H, CH$_2$CO, isomer **B**, J = 8.1); 3.24—4.45 (m, 1 H, C$_e$-5); 3.48 (t, 2 H, CH$_2$N, isomer **B**); 3.51 (t, 2 H, CH$_2$N, isomer **A**); 4.07— 4.26 (m, 1 H, C$_a$-5); 4.35—4.51 (m, 1 H, C-4)
8e	1640	1065	+123.7	1.16—1.23 (m, 1 H, C$_e$-5); 1.26—1.50 (m, 6 H, (C$\underline{H}_2$)$_3$CH$_2$CO); 1.50—1.70 (m, 1 H, C$_a$-5); 2.31—2.42 (m, 2 H, CH$_2$CO); 3.11—3.20 (m, CH$_2$N); 3.63—3.99 (m, 4 H, C-4, C-6)
11c	1735	1035	−1.6	1.15 (t, 6 H, (C$\underline{H}_3$CH$_2$O)$_2$P, J = 7.1); 1.92 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 2.27 (t, 2 H, CH$_2$CO, J = 8.0); 3.54 (t, 2 H, CH$_2$N, J = 7.0); 3.86—4.12 (m, 4 H, (CH$_3$C$\underline{H}_2$O)$_2$P)
11e	1715	1050	−9.5	1.94—2.36 (m, 2 H, C-5); 2.08 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 2.43 (t, 2 H, CH$_2$CO, J = 8.0); 3.74 (t, 2 H, CH$_2$N, J = 7.0), 4.36—4.53 (m, 2 H, C$_a$-4, C$_a$-6)
12c	1730	1030	+63.6	1.34 (t, 4 H, (C$\underline{H}_3$CH$_2$O)$_2$P, J = 7.0); 2.05 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 2.48 (t, 2 H, CH$_2$CO, J = 8.1); 3.74 (t, 2 H, CH$_2$N, J = 7.0); 4.19 (dq (CH$_3$C$\underline{H}_2$O)$_2$P, J_1 = 7.0, J_2 = 10.0)
12e	1725	1030	+57.6	2.05—2.17 (m, 4 H, C-5 and C$\underline{H}_2$CH$_2$CO); 2.51 (t, 2 H, CH$_2$CO, J = 8.1); 3.81 (t, 2 H, CH$_2$N, J = 7.0); 4.48—4.61 (m, 4 H, C-4 and C-6)
12f	1715	1040	+79.3	2.08 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 2.52 (t, 2 H, CH$_2$CO, J = 8.0); 3.85 (t, 2 H, CH$_2$N, J = 7.0); 4.39—4.52 (m, 2 H, C-4 and C-5); 4.58—4.77 (m, 2 H, C-4 and C-5)
12g[a]	1725	1020	+77.9 +77.3	1.46 (d, 3 H, CH$_3$, J = 6.3); 2.05 (quint, 2 H, C$\underline{H}_2$CH$_2$CO, J = 7.5); 2.51 (t, 2 H, CH$_2$CO, J = 8.0); 3.84 (t, 2 H, CH$_2$N, J = 7.0); 3.95—4.08 (m, 1 H, dioxaphosph. ring); 4.61—4.76 (m, 1 H, dioxaphosph. ring); 5.03—5.22 (m, 1 H, dioxaphosph. ring)

[a] ^{1}H NMR spectrum of the diastereomer with δ^{31}P +77.9 ppm is given. The ^{1}H NMR spectrum of another diastereomer is also consistent with the structure assumed.

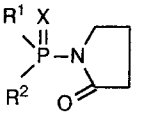
***N*-Phosphorylpyrrolidones 11.** Dry NO was passed through a solution of 10 mmol of **7c,e** in 20 mL of C_6H_6 for 2 h at 80°C. The solvent was removed *in vacuo* (15 Torr), and the residue was either distilled *in vacuo* (0.5 Torr, for **7c**), or crystallized from ethyl acetate—hexane (for **7e**). Yields, physical constants, and spectral data for the compounds obtained are given in Tables 4 and 5.

***N*-Thiophosphorylpyrrolidones 12 (general procedure).** A mixture of **7** (5.18 mmol), sulfur (0.17 g, 5.3 mmol), and 10 mL of C_6H_6 was refluxed for 3—5 h, and then the solvent was removed *in vacuo* (15 Torr). The residue was dissolved in 5 mL of $CHCl_3$, cooled to 5°C, and filtered off from the excess of sulfur. The filtrate was evaporated, and the residue was either chromatographed on silica gel L 40/100 μm (petroleum ether—ethyl acetate, 3 : 2, as the eluent) in the case of **12c** or crystallized in the case of **12e—g**. Yields, physical constants, and spectral data for the compounds obtained are given in Tables 4 and 5.

Ethoxythiophosphorylidenebis(2-pyrrolidone) (13) was obtained by heating **10** (1.4 g, 5.74 mmol) and sulfur (0.19 g, 6.0 mmol) as described for **12**. Yield: 1.4 g (88.4%) of **13**, mp 75.5—77.0 °C (Et_2O). Found (%): C, 43.37; H, 6.01; P, 11.16; S, 11.68. $C_{10}H_{17}N_2O_3PS$. Calculated (%): C, 43.47; H, 6.20; P, 11.21; S, 11.69. IR (KBr, ν/cm^{-1}): 1710 (C=O), 1040, 970 (POC). ^{1}H NMR ($CDCl_3$, δ, ppm, J/Hz): 1.32 (t, 3 H, C$\underline{H}_3$CH$_2$OP, J = 7.2); 2.05 (quint, 4 H, C$\underline{H}_2$CH$_2$CO, J = 7.4); 2.42 (t, 4 H, CH$_2$CO, J = 8.0), 3.84 (t, 4 H, CH$_2$N, J = 7.0), 4.17 (d.quart, 2 H, CH$_3$C$\underline{H}_2$OP, J_1 = 7.2, and J_2 = 11.4). ^{31}P NMR ($CHCl_3$, δ, ppm): +54.8.

2-(3,3-Dimethyl-2-oxo-4-phenylazetidin-1-yl)-1,3,2-dioxaphosphorinane (14e). A mixture of **1** (0.61 g, 2.46 mmol)

Table 5. *N*-Phosphorylpyrrolidones



Compound	R^1	R^2	X	Yield (%)	B.p./°C (*p*/Torr) [M.p./°C] (solvent)	Empirical formula	Found / Calculated (%) C	H	P	S
11c	EtO	EtO	O	82.5	108—110[a] (0.5)	—	—	—	—	—
11e	—O(CH$_2$)$_3$O—		O	62.6	[74.5—77.0] (MeCO$_2$Et—hexane)	$C_7H_{12}NO_4P$	41.13 / 40.98	5.97 / 5.96	15.05 / 15.10	—
12c	EtO	EtO	S	94.0	Oil	$C_8H_{16}NO_3PS$	40.80 / 40.50	6.80 / 6.80	12.85 / 13.05	13.72 / 13.51
12e	—O(CH$_2$)$_3$O—		S	86.1	[98—100.5] (MeCO$_2$Et—ether)	$C_7H_{12}NO_3PS$	38.01 / 38.01	5.56 / 5.47	14.14 / 14.00	14.38 / 14.49
12f	—O(CH$_2$)$_2$O—		S	69.0	[111—115] (MeCO$_2$Et—pentane)	$C_6H_{10}NO_3PS$	34.75 / 34.78	4.74 / 4.87	14.65 / 14.95	15.77 / 15.47
12g	-OC(CH$_3$)HCH$_2$O-		S	86.9[b]	[87—89] (MeCO$_2$Et—hexane)	$C_7H_{12}NO_3PS$	37.92 / 38.01	5.43 / 5.47	13.95 / 14.00	14.47 / 14.49

[a] B.p. 98—110 °C (0.5 Torr).[1] [b] Mixture of diastereomers, 1:1.23.

and **6e** (1.73 g, 12.33 mmol) was heated for 7 h at 50°C. Then the volatile compounds were removed *in vacuo* (0.5 Torr) to give **14e** as a viscous oil incapable of distillation. ^{1}H NMR (C_6D_6, δ, ppm, *J*/Hz): 0.84 (s, 3 H, $CH_3C(CH_3)CO$); 0.85—0.90 (m, 1 H, H_e-5); 1.14 (c, 3 H, $CH_3C(CH_3)CO$); 1.91—2.01 (m, 1 H, H_a-5); 3.58—3.79 (m, 2 H, H_e-4 and H_e-6); 4.27 (s, 1 H, CHC_6H_5); 4.51—4.71 (m, 2 H, H_a-4 and H_a-6); 6.95—7.08 (m, 5 H, C_6H_5). ^{31}P NMR ($CHCl_3$, δ, ppm): +112.2. The compound obtained was used for the synthesis of 2-oxo derivative **3e** without additional purification.

2-(3,3-Dimethyl-2-oxo-4-phenylazetidin-1-yl)-2-oxo-1,3,2-dioxaphosphorinane (3e). Dry NO was passed through a solution of **14e** (0.28 g, 1.00 mmol) in 5 mL of C_6H_6 at 80°C for 1.5 h. The reaction mixture was sequentially washed with water, saturated aqueous $NaHCO_3$ solution, and again with water and was dried over anhydrous Na_2SO_4. The solvent was removed *in vacuo* (15 Torr), and the residue was crystallized from ethyl acetate—pentane to give 0.12 g (42%) of **3e**, mp 145—146 °C. Found (%): C, 57.28; H, 6.63; P, 10.38. $C_{14}H_{18}NO_4P$. Calculated (%): C, 56.95; H, 6.14; P, 10.49. IR (KBr, ν/cm^{-1}): 1775 (C=O), 1220 (P=O), 1055 (POC). ^{1}H NMR (C_6D_6, δ, ppm, *J*/Hz): 0.53 (s, 3 H, $CH_3C(CH_3)CO$); 0.84—1.02 (m, 1 H, H_e-5); 1.04 (s, 3 H, $CH_3C(CH_3)CO$); 1.11—1.36 (m, 1 H, H_a-5); 3.53—3.83 (m, 2 H, H_e-4 and H_e-6); 4.12—4.28 (m, 1 H, H_a-4 and H_a-6); 4.30—4.54 (m, 1 H, H_a-4 and H_a-6); 4.64 (s, 1 H, CHC_6H_5); 6.94—7.15 (m, 5 H, C_6H_5). ^{31}P NMR (C_6H_6, δ, ppm): −15.5.

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Received April 25, 1995;
in revised form May 31, 1995