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Photochemical Transformation of Levoglucosan Imides to Anhydrosugar-Annelated Azepanediones and Azocanediones

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Summary. By reaction of O-protected 3-amino-1,6-anhydro-β-*D*-glucopyranose with succinic, glutaric, and tartaric anhydride, respectively, the corresponding 3-substituted succinimido, glutarimido, and tatarimido derivatives were obtained. Irradiation of the succinimido and glutarimido derivatives at 254 nm gave 1,4-diradical intermediates by γ-hydrogen abstraction (*Norrish* Type II reaction) which subsequently recombined (*Yang* cyclization) to form azetidinols. These in turn fragmented and led to azepanedione and azocanedione derivatives. In contrast, irradiation of the tartarimido derivative resulted in elimination and led to both isomeric enolethers.

Keywords. 1,6-Anhydroglucopyranose; Photochemistry; Intramolecular alkylation; Anhydrosugar-annelated azepanediones and azocanediones.

Introduction

For access to complex heterocycles, C–C-bond formation by radical reactions leading to highly regio- and stereospecific products is increasingly gaining importance. A well established radical method for this purpose is comprised by the *Norrish* Type II reaction. This photochemical induced intramolecular alkylation of N-alkylated imides by 1,6- or 1,7-hydrogen abstraction leads to compounds containing the annelated ε-lactame structure, an integer part of a large number of important pharmaceuticals with multiple applications [1, 2]. Previously, *Kanaoka et al.* have described the synthesis of ε-lactames such as **5** by irradiation of N-alkylsuccinimides **1** [3] (Scheme 1).

Irradiation of imido derivatives **1** with UV light (254 nm) generates an excited carbonyl group. For steric reasons, hydrogen abstraction from the γ-position (1,6-abstraction) is preferred leading to a six-membered transition state **2**. The approach of the photochemically excited carbonyl function induces the intramolecular γ-hydrogen abstraction, thus establishing the diradical intermediate **3**. Its subsequent

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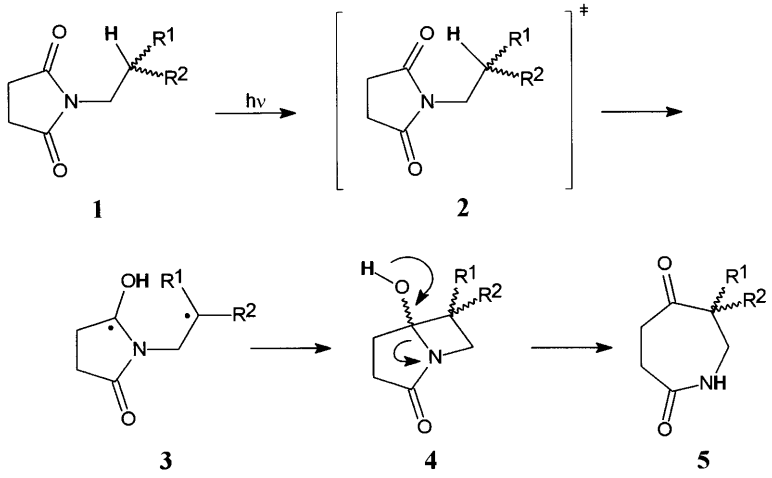
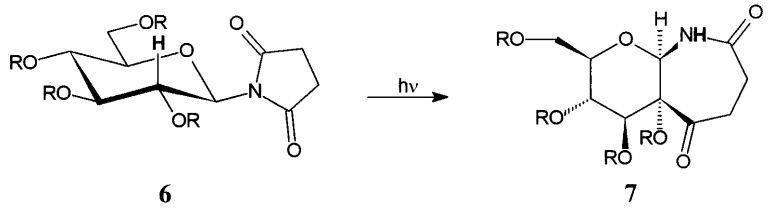


Scheme 1. Photocyclization of alkylimides



Scheme 2. Photocyclization of glycosylimides

Yang cyclization [4] results in formation of azetidinol **4** which in turn fragments in an irreversible retro-transannular ring opening and leads to the azepanedione **5**.

Previous studies of this photoreaction of 6-imidosaccharide derivatives [5] as well as N-glycosylimides [6–8] by *Thiem et al.* confirmed that corresponding carbohydrate compounds, *e.g.* **6**, can be transformed into sugar-derived azepanediones such as **7** (Scheme 2).

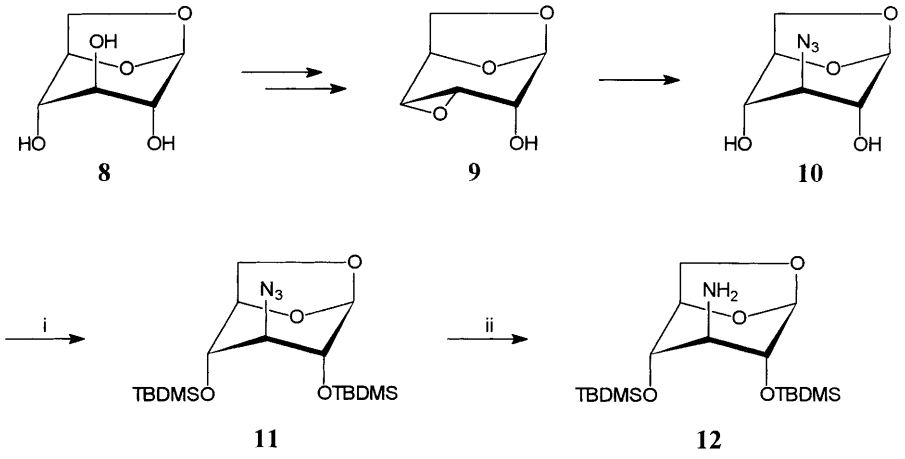
These investigations [5–8] have shown that the regiochemistry of the hydrogen abstraction is controlled by stereoelectronic and conformational factors. In order to elucidate the specific nature of these conformational effects, the bicyclic and thus conformationally fixed 1,6-anhydro-β-*D*-hexopyranoses were investigated.

Previous studies have focused on 2-imido-galactosan and 4-imido-mannosan derivatives [9]. In the following, we report about the synthesis of various 3-imido-glucosan derivatives and the results of their subsequent irradiation.

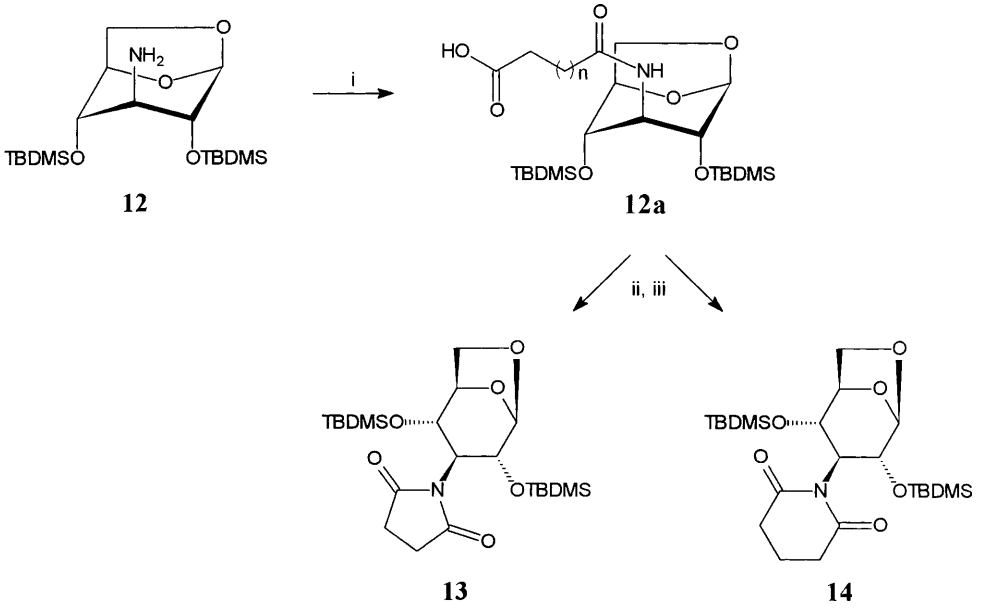
Results and Discussion

Preparation of saccharide imides

The synthesis of 3-imido-glucosan derivatives (Schemes 3 and 4) started from 1,6-anhydro-β-*D*-glucopyranose (levoglucosan, **8**) and followed the well-known pathway described by *Cerny et al.* [10, 11] leading to 1,6;3,4-dianhydro-β-*D*-allopyranose **9**. Regioselective opening of this epoxide by sodium azide gave the



Scheme 3. *i*: *tert*-Butyldimethylsilyl triflate, pyridine, 0°C – room temperature, 20 h, 77%; *ii*: H_2, Pd/C, ethyl acetate/MeOH, room temperature, 24 h, 95%



Scheme 4. *i*: Succinic anhydride ($n = 1$), glutaric anhydride ($n = 2$), *DIPEA*, room temperature, 24 h; *ii*: pyridine, Ac_2O, room temperature, 24 h, 65%; *iii*: pyridine, Ac_2O, 60°C, 48 h, 55%

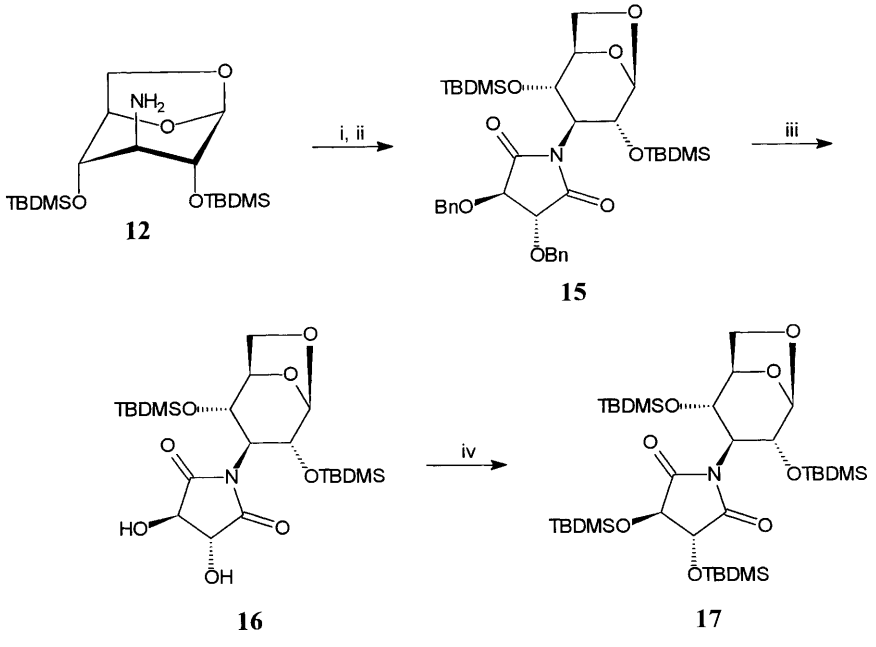
gluco-configurated 3-azido derivative **10** [12]. Then the hydroxyl functions were protected as photochemically inert *tert*-butyldimethylsilyl (*TBDMS*) ethers using *TBDMS*-triflate in pyridine at 0°C. Further, reduction of the protected azide **11** by hydrogenolysis using palladium on activated charcoal led to the corresponding amine **12** in quantitive yield.

In a very versatile approach, imido-substituted derivatives are available by condensation of primary amines with different dicarbonic acid anhydrides [8, 13, 14]. Starting with the amine derivative **12**, reaction with 10 equivalents

of succinic ($n = 1$) or glutaric ($n = 2$) anhydride in dichloromethane and N-ethyldiisopropylamine (*DIPEA*) as auxiliary base led to the corresponding succinamidic and glutaramidic acid derivatives **12a**. These were not isolated; acetylation with acetic anhydride in pyridine led to a cyclization affording the desired saccharide imides **13** and **14** in moderate to good yields.

Whereas the cyclization step of the succinamidic acid succeeded at room temperature within 24 hours, the corresponding reaction to obtain the glutarimide required both higher temperatures (60°C) and longer reaction time (48 h). Apparently, these different reaction conditions originate from the chain length of the dicarbonic acids. The ratio of formation of the imidosaccharide derivates could be monitored by NMR spectroscopy. In case of the succinimide derivative **13**, the four protons of the five-membered succinimide ring coincide in one singulet in the ^{1}H NMR spectrum due to the free rotation of the C3–N-bond and hence their chemical equivalence. In contrast, the six protons of the glutarimide ring in derivative **14** appear in two characteristic signals, one triplet for the four *meta*-positioned protons and one quintet for the two *para*-positionend protons.

In further attempts, another approach to functionalized imido derivatives was investigated (Scheme 5). Such compounds with additional chirality in the imide structure should be interesting starting materials for further transformations to derive branched-chain sugars. According to the synthesis of the succinimide and glutarimide derivatives, the reaction of the amine **12** with 3,4-di-O-benzyl-tartaric anhydride led to the corresponding tartaramidic acid, the subsequent cyclization step of which afforded the substituted imido derivative **15** in good yield. Since benzyl groups were not suitable for the following irradiation step due to their UV



Scheme 5. *i*: 3,4-Di-O-benzyl-tartaric anhydride, *DIPEA*, room temperature, 20 h; *ii*: Ac_2O, pyridine, room temperature, 24 h, 76%; *iii*: H_2, Pd/C, MeOH, room temperature, 48 h, 86%; *iv*: *tert*-butyldimethylsilyl triflate, 2,6-dimethylpyridine, −40°C – room temperature, 48 h, 55%

absorption, a change of the protecting groups had to take place. By hydrogenolysis using palladium on activated charcoal the deprotected tartarimido derivative **16** was obtained, the free hydroxyl groups of which were subsequently protected as *TBDMS* ethers with *tert*-butyldimethylsilyltrifluoromethanesulfonate in 2,6-dimethylpyridine at −40°C to give compound **17**.

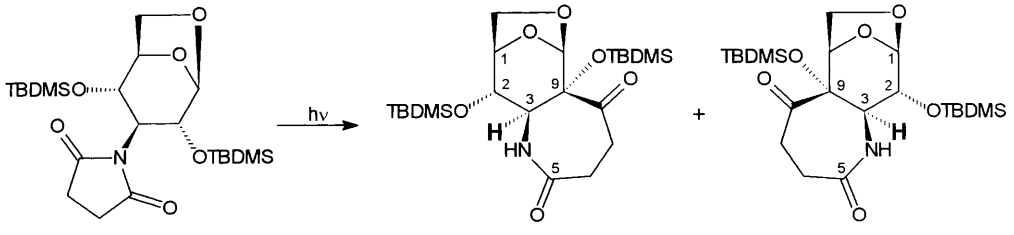
Irradiation of saccharide imides

All irradiations were performed with a low pressure mercury lamp at 254 nm under an argon atmosphere on solutions in anhydrous acetonitrile. To avoid heating of the reaction system by radiationless energy transfer, water cooling was required.

An abstraction in terms of a *Norrish* Type II reaction can be obtained only from a *cis*-positioned hydrogen [5–9]. Considering the geometry of the glucosan derivatives **13** and **14**, two suitable *cis*-hydrogen atoms (H-2 and H-4) are present for abstraction. Irradiation of **13** was completed after 6 hours as indicated by TLC. In accordance with its geometry, both isomers **18** and **19** were obtained in almost equal yields in addition to 11% of starting material (Scheme 6).

The ^{1}H NMR spectrum of the heterocyclic sugar derivatives showed characteristic signals suitable for the assignment of the above structures. The new NH protons were located as doublets at 6.31 ppm in **18** and 5.69 ppm in **19**, respectively. The coupling constants of these protons with H-3 of the sugar system (highlighted in Scheme 6) were determined to 6.0 (**18**) and 6.5 (**19**) Hz. The original singulet of the succinimide CH_2-groups was split into two multiplets due to formation of the novel seven-membered ring. The formation of a new quarternary center C-9 was evident from the disappearance of proton H-9 and verified by the corresponding signals in the ^{13}C NMR spectrum at 77.65 (**18**) and 80.17 (**19**) ppm. Furthermore, the ^{13}C NMR spectrum displayed two typical signals of the amide groups at 175.67 (**18**) and 175.82 (**19**) ppm; the keto functions led to resonances at 205.68 (**18**) and 209.13 (**19**) ppm in addition to two new signals of secondary carbons instead of the former identical secondary carbon atoms of the succinimide ring. The coupling constants of the sugar systems in these novel tricyclic structures did not show significant changes compared to the starting material, thus indicating a chair conformation of the pyranose ring.

Both photoproducts crystallized and allowed X-ray structural studies; the corresponding data are summarized in Table 1. Figure 1 shows an ORTEP drawing of compound **19** to support the structure as deduced from the NMR data.



13 **18** **19**

Scheme 6. *i*: 254 nm, CH_3CN, 18°C, 6 h; **18**: 26%, **19**: 28%

Table 1. Crystal data, data collection parameters, and refinement results for **19** (Enraf-Nonius CAD4 diffractometer)

Formula	$C_{22}H_{41}NO_6Si_2$
Formula weight	471.74
Crystal dimension (mm)	$0.6 \times 0.5 \times 0.1$
Crystal system	orthorhombic
Space group	$P2_12_12_1$ (No. 19)
a (pm)	835.4 (1)
b (pm)	1229.2 (1)
c (pm)	2664.7 (2)
V (10^6 pm^3)	2736.3 (4)
Z	4
ρ_{calcd} (g · cm^{-1})	1.145
$F(000)$	1024
Radiation	CuK_α
λ (pm)	154.178
μ (mm^{-1})	1.45
T (°C)	−100
$2\theta_{max}$ (°)	152.74
Unique reflexions	3268
Observed reflexions	3014
R_{all}	0.0558
Flack parameter	−0.06 (5)
$S = GooF$	0.857

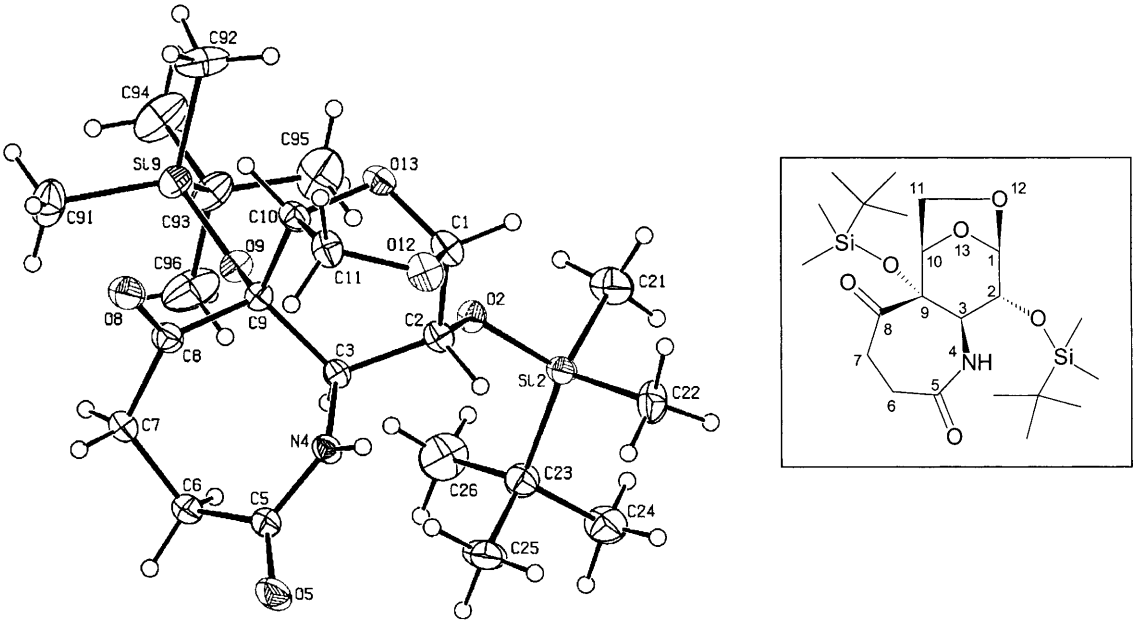


Fig. 1. ORTEP drawing of **19**

Even though the R value in case of compound **18** turned out to be less convincing compared to the corresponding value of derivative **19**, its structure is also shown here (Fig. 2). Apparently, the single crystal of **18** was of lower quality;

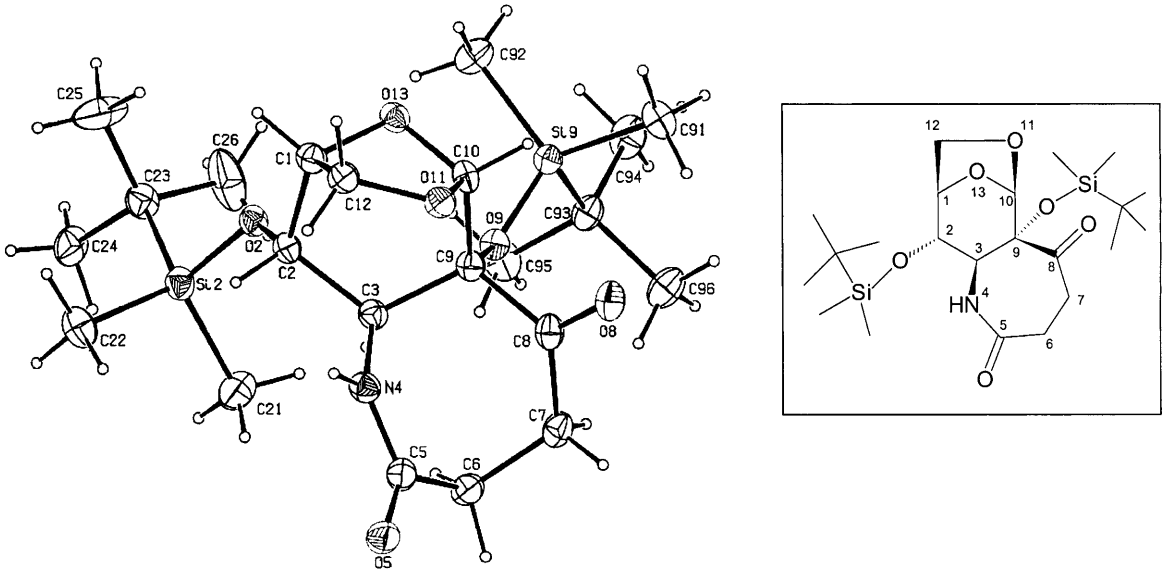
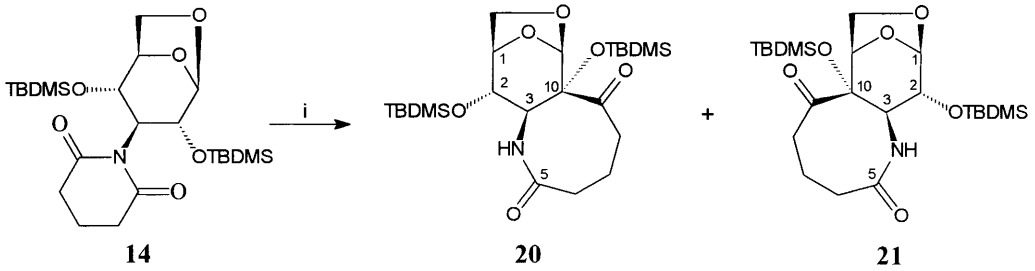


Fig. 2. ORTEP drawing of **18**

however, the data set obtained from NMR spectroscopy was rather similar to the corresponding data set of compound **19**.

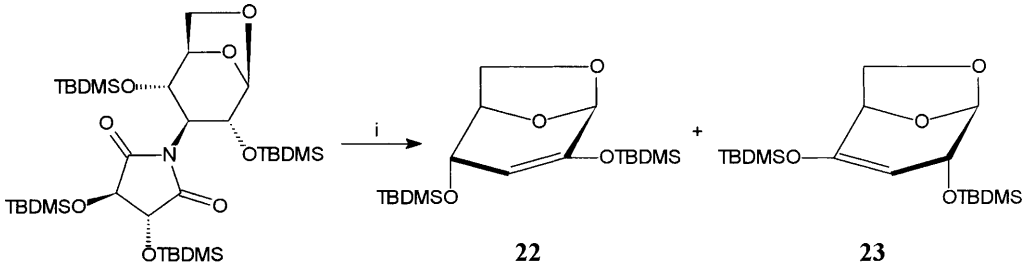
The reaction of the glutarimido derivative **14** was complete after 4 hours of irradiation (Scheme 7). According to geometric reasons, hydrogen abstraction from position 2 and position 4 proceeded as expected and gave the heterocyclic sugars **20** and **21**.

Both structures were elucidated by NMR spectroscopy showing the characteristic signals of the amide group (NH proton as a doublet at 5.65 (**20**) and 5.97 (**21**) ppm; lactame carbon at 172.52 (**20**) and 177.23 (**21**) ppm) and the keto function at 207.89 ppm for derivative **20** and 210.70 ppm for compound **21**. The new quarternary centres at C-10 (78.20 (**20**) and 81.69 (**21**) ppm) were in accordance with the absence of the signals of H-10 in the ^{1}H NMR spectra. The former glutarimide system appeared in case of isomer **20** at 23.40 (C-7), 33.83 (C-6), and 38.44 (C-8) ppm, now fixed in the annelated eight membered ring. Similar data were found for compound **21**: 24.53 (C-7), 34.33 (C-6), and 38.20 (C-8) ppm. Again, no changes concerning the coupling constants of the sugar system were noted which proves that the conformation of the pyranose ring did not change.



14 **20** **21**

Scheme 7. *i*: 254 nm, CH_3CN, 18°C, 4 h; **20**: 23%, **21**: 25%



Scheme 8. *i*: 254 nm, CH_3CN, 18°C, 20 h; **22**: 12%, **23**: 18%

In case of the tartarimido derivative **17**, the irradiation was stopped after 20 hours (Scheme 8) due to increasing degradation of the starting material as monitored by TLC. Two main products were isolated and characterized; they prooved to be the unsaturated derivatives **22** and **23**.

Obviously, the excited state did not react to give the expected lactames but led after elimination of the protected imide to the enolethers **22** and **23**. It may be tentatively assumed that the *TBDMS* protecting groups could stabilize the five-membered ring and assist an elimination in contrast to the photoreactions of the succinimide and glutarimide derivatives **13** and **14**.

Experimental

All reactions were monitored by TLC analysis with silica gel 60-coated sheets (Merck). Compounds were visualized by spraying with 20% H_2SO_4 in EtOH followed by heating and/or UV irradiation. Column chromatography was performed on silica gel 60 (230–240 mesh, grain size 0.040–0.063 mm, Merck). All irradiations were performed in dry acetonitrile (Fluka) deoxygenated by degassing (30 min) with Ar in an ultrasonic bath employing a 60 W low-pressure Hg vapour lamp ($\lambda = 254$ nm) from Heraeus. The photoreactor was made of quartz glass and measured 35 cm in length and 4.5 cm in diameter. To maintain the temperature at 18°C, H_2O cooling was used. Melting points were measured on a ST-apotec apparatus and are reported uncorrected. Optical rotations were determined at room temperature with a Perkin Elmer Polarimeter 243. Elemental analyses were performed by the microanalytical laboratory of the Institute of Organic Chemistry of the University of Hamburg; their results agreed favourably with the calculated values. IR spectra were recorded on an ATI Mattson FTIR instrument (Genesis Series). NMR spectra were recorded on a Bruker AMX-400 spectrometer (^1H: 400 MHz, ^{13}C: 100 MHz); chemical shifts are referred to the solvent used, *J*-values are given in Hz.

Imide formation (A)

A suspension of the amine (10.0 mmol), the quoted dicarbonic acid anhydride (100.0 mmol), and N-ethyldiisopropylamine (10.0 mmol) in 75 cm^3 dry CH_2Cl_2 was stirred overnight at room temperature. After addition of 10 cm^3 MeOH the solvent was evaporated under reduced pressure. The residue was dissolved in 30 cm^3 dry pyridine and 30 cm^3 acetic anhydride and stirred for the quoted time at the given temperature. The reaction mixture was concentrated under reduced pressure and codestillated twice with toluene. The residue was taken up in CH_2Cl_2, neutralized with satured aqueous $NaHCO_3$ solution, and washed with brine. Drying and evaporation of the solvent afforded the crude product which was purified by column chromatography using the quoted eluent.

Irradiation (B)

The imido-substituted sugar (0.5–2.0 mmol) was dissolved in 200 cm^3 dry, deoxygenated acetonitrile and irradiated at 18°C under an Ar atmosphere for the quoted time. Evaporation of the solvent and purification by column chromatography using the quoted eluent led to the product.

1,6-Anhydro-3-azido-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-β-D-glucopyranose (**11**: $C_{18}H_{37}N_3O_4Si_2$)

A solution of **10** (700 mg, 3.74 mmol) in 20 cm^3 pyridine was cooled to 0°C and treated with *tert*-butyldimethylsilyltrifluoromethanesulfonate (8.23 mmol, 2.2 equiv.). After stirring at room temperature for 20 h the solvent was evaporated under reduced pressure. The residue was codestilled with toluene, taken up in CH_2Cl_2, and washed with saturated aqueous $NaHCO_3$ and brine. Drying and evaporation of the solvent left the crude product. Purification by column chromatography using toluene:petroleum ether = 15:1 as eluent afforded the product **11** (1.2 g, 2.89 mmol, 77%) as light yellow crystals.

M.p.: 54°C; $[\alpha]_D^{20} = -24.7$ ($c = 1.0$, $CHCl_3$); IR (KBr): $\nu = 2112$ (N_3) cm^{-1}; ^1H NMR ($CDCl_3$): $\delta = 0.07$, 0.09, 0.13, 0.14 (4s, 12H, 2 Me–Si), 0.93 (s, 18H, 2 *tert*-Bu–Si), 3.31–3.32 (m, 2H, $J_{2,3} = 4.0$ Hz, $J_{2,4} = 7.5$ Hz, H-3, H-4), 3.37 (dd, 1H, H-2), 3.60–3.67 (m, 2H, $J_{5,6a} = 5.0$ Hz, $J_{6a,6b} = 7.0$ Hz, H-6a, H-6b), 4.33 (d, 1H, H-5), 5.20 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.80$, −3.54, −2.72, −2.62 (4C, 2 Me–Si), 16.89, 16.94 (2C, q, 2 *tert*-Bu–Si), 24.66, 24.68 (6C, 2 *tert*-Bu–Si), 66.63 (1C, $-CH_2$, C-6), 67.36 (1C, C-4), 73.87 (1C, C-2), 74.07 (1C, C-3), 77.99 (1C, C-5), 103.39 (1C, C-1) ppm.

3-Amino-1,6-anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-β-D-glucopyranose (**12**; $C_{18}H_{39}NO_4Si_2$)

Compound **11** (2.23 g, 5.36 mmol) was dissolved in a mixture of 25 cm^3 dry ethyl acetate and 25 cm^3 dry MeOH and hydrogenated using 0.22 g (10% of weight) Pd/C (10%) by stirring at room temperature under an atmosphere of H_2 for 24 h. Removal of the catalyst by filtration and evaporation of the solvents yielded the amine which was used in the next step without further purification. **12** (1.98 g, 5.08 mmol, 95%) was obtained as a colourless oil.

$[\alpha]_D^{20} = -26.2°$ ($c = 0.5$, $CHCl_3$); ^1H NMR ($CDCl_3$): $\delta = 0.08$, 0.10, 0.11, 0.12 (4s, 12H, 2 Me–Si), 0.91, 0.92 (2s, 18H, 2 *tert*-Bu–Si), 2.81 (t, 1H, $J_{2,4} = 7.0$ Hz, H-4), 3.25 (d, 1H, $J_{2,3} = 1.0$ Hz, H-2), 3.33 (dd, 1H, $J_{3,4} = 7.0$ Hz, H-3), 3.61 (dd, 1H, $J_{5,6a} = 4.5$ Hz, $J_{6a,6b} = 7.0$ Hz, H-6a), 3.69 (m, 1H, H-6b), 4.29 (d, 1H, H-5), 5.18 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.63$, −4.54, −4.51, −4.43 (4C, 2 Me–Si), 17.92, 17.98 (2C, q, 2 *tert*-Bu–Si), 25.75, 25.77, 25.83, 25.86 (6C, 2 *tert*-Bu–Si), 56.17 (1C, C-3), 66.42 (1C, $-CH_2$, C-6), 72.00, 73.08 (2C, C-2, C-4), 78.00 (1C, C-5), 103.37 (1C, C-1) ppm.

1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-3-N-succinimido-β-D-gluco-pyranose (**13**; $C_{22}H_{41}NO_6Si_2$)

The protected 3-amino derivative **12** (150 mg, 0.38 mmol) was reacted with succinic anhydride (0.38 g, 3.8 mmol) and N-ethyldiisopropylamine (0.1 cm^3, 0.38 mmol) according to procedure A. The cyclization was performed by stirring overnight at room temperature. The crude product was purified by column chromatography using toluene:acetone = 50:1 as eluent to give **13** (117 mg, 0.25 mmol, 65%) as white needles.

M.p.: 112°C; $[\alpha]_D^{20} = -27.2°$ ($c = 1.0$, $CHCl_3$); IR (KBr): $\nu = 1779$, 1698 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$): $\delta = -0.12$, −0.11, 0.04, 0.07 (4s, 12H, 2 Me–Si), 0.84 (s, 18H, 2 *tert*-Bu–Si), 2.65 (s, 4H,

–CH_2–CH_2–, imide), 3.72 (dd, 1H, $J_{5,6a} = 5.0$ Hz, $J_{6a,6b} = 7.5$ Hz, H-6a), 3.80 (dd, 1H, $J_{5,6b} = 1.0$ Hz, H-6b), 4.01 (d, 1H, $J_{2,4} = 8.5$ Hz, H-2), 4.10–4.19 (m, 2H, $J_{3,4} = 8.5$ Hz, H-3, H-4), 4.35 (d, 1H, H-5), 5.22 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.61$, -3.77, -2.87, -2.68 (4C, 2 Me–Si), 16.58, 16.64 (2C, q, 2 *tert*-Bu–Si), 24.44 (6C, 2 *tert*-Bu–Si), 26.88 (2C, –CH_2–CH_2–, imide), 56.27 (1C, C-4), 66.51 (1C, –CH_2, C-6), 67.81, 70.16 (2C, C-2, C-3), 78.32 (1C, C-5), 104.21 (1C, C-1) ppm.

1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-3-N-glutarimido-β-D-glucopyranose (**14**; $C_{23}H_{43}NO_6Si_2$)

The 3-amino-derivative **12** (1.14 g, 2.93 mmol) was reacted with glutaric anhydride (3.34 g, 29.28 mmol) and N-ethyldiisopropylamine (0.5 cm^3, 2.93 mmol) according to procedure A. The cyclization was performed by stirring for 48 h at 60°C. The crude product was purified by column chromatography using petroleum ether:ethyl acetate = 7:1 as eluent to give **14** (250 mg, 0.25 mmol, 65%) as yellow oil.

$[\alpha]_D^{20} = -57.6°$ ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$): $\delta = -0.1$, -0.09, -0.03, 0.02 (4s, 12H, 2 Me–Si), 0.82, 0.83 (2s, 18H, 2 *tert*-Bu–Si), 1.89–1.96 (m, 2H, –CH_2–CH_2–CH_2–, imide), 2.63 (t, 4H, –CH_2–CH_2–CH_2–, imide), 3.71 (dd, 1H, $J_{5,6a} = 6.0$ Hz, $J_{6a,6b} = 7.5$ Hz, H-6a), 3.80 (dd, 1H, $J_{5,6b} = 1.5$ Hz, H-6b), 3.99 (d, 1H, $J_{2,3} = 8.0$ Hz, H-2), 4.08 (d, 1H, $J_{3,4} = 8.0$ Hz, H-4), 4.33 (dd, 1H, H-5), 4.84 (t, 1H, H-3), 5.20 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -5.09$, -4.95, -4.59, -4.47 (4C, 2 Me–Si); 18.06 (2C, q, 2 *tert*-Bu–Si); 25.46 (6C, 2 *tert*-Bu–Si), 33.0, 33.66 (2C, –CH_2–CH_2–CH_2–, imide), 57.56 (1C, C-3), 67.01 (1C, –CH_2, C-6), 71.70 (2C, C-2, C-4), 79.33 (1C, C-5), 105.31 (1C, C-1) ppm.

1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-3-N-((3′R,4′R)-3′,4′-bis-O-benzyl)-tatarimido-β-D-glucopyranose (**15**; $C_{36}H_{53}NO_8Si_2$)

Compound **12** (700 mg, 1.8 mmol) was reacted with 3,4-di-O-benzyltataric anhydride (1.12 g, 3.59 mmol) and N-ethyldiisopropylamine (0.31 cm^3, 1.8 mmol) according to procedure A. The cyclization step was carried out by stirring overnight at room temperature. The crude product was purified by column chromatography using petroleum ether:acetone = 30:1 as eluent to give compound **15** (939 mg, 76%) as colourless oil.

$[\alpha]_D^{20} = -100.5°$ ($c = 0.008$, $CHCl_3$); IR (KBr): $\nu = 1721$, 1679 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$): $\delta = -0.12$, -0.11, 0.00, 0.03 (4s, 12H, 2 Me–Si), 0.82 (s, 18H, 2 *tert*-Bu–Si), 3.73 (dd, 1H, $J_{5,6a} = 5.0$ Hz, $J_{6a,6b} = 7.0$ Hz, H-6a), 3.79 (dd, 1H, $J_{5,6b} = 4.5$ Hz, H-6b), 3.94 (dd, 1H, $J_{2,4} = 7.0$ Hz, $J_{3,4} = 2.0$ Hz, H-4), 4.09–4.16 (m, 2H, H-2, H-3), 4.26 (s, 2H, –CH–CH–, imide), 4.35 (d, 1H, H-5), 4.74 (d, 2H, –CH_2, –OBn), 4.99 (d, 2H, –CH_2, –O*Bn*), 5.23 (s, 1H, H-1), 7.31–7.36 (m, 10H, –CH, –O*Bn*) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.67$, -4.53, -4.24, -3.98 (4C, 2 Me–Si), 17.96, 18.04 (2C, q, 2 *tert*-Bu–Si), 25.87, 25.93 (6C, 2 *tert*-Bu–Si), 57.76 (1C, C-4), 68.04 (1C, –CH_2, C-6), 71.41, 79.64 (3C, C-2, C-3, C-5), 73.66 (2C, 2 -CH_2, –O*Bn*), 78.76 (2C, –CH–CH–, imide), 105.50 (1C, C-1), 127.35 (10C, –CH, –O*Bn*), 135.67 (2C, q, –O*Bn*), 172.00 (2C, 2 C=O) ppm.

1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-3-N-((3′R,4′R)-3′,4′-bis-O-hydroxy)-tatarimido-β-D-glucopyranose (**16**; $C_{22}H_{41}NO_8Si_2$)

A solution of **15** (900 mg, 1.32 mmol) in 30 cm^3 dry MeOH was hydrogenated using 90 mg (10% of weight) Pd/C (10%) by stirring at room temperature under an atmosphere of H_2 for 24 h. Removal of the catalyst by filtration and evaporation of the solvents yielded compound **16** (574 mg, 86%), which was used in the next step without further purification.

M.p.: 85°C; $[\alpha]_D^{20} = -83.3°$ ($c = 1.0$, $CHCl_3$); IR (KBr): $\nu = 1754$ (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$): $\delta = -0.09$, -0.01, 0.05 (3s, 12H, 2 Me–Si), 0.84 (s, 18H, 2 *tert*-Bu–Si), 3.10 (s, 2H, 2 OH), 3.71 (dd, 1H, $J_{5,6a} = 5.0$ Hz, $J_{6a,6b} = 7.5$ Hz, H-6a), 3.80 (dd, 1H, $J_{5,6b} = 4.5$ Hz, H-6b), 3.87–3.93

(m, 1H, $J_{2,4} = 6.5$ Hz, $J_{3,4} = 2.0$ Hz, H-4), 4.11–4.14 (m, 2H, H-2, H-3), 4.35 (d, 1H, H-5), 4.49 (s, 2H, –CH–CH–, imide), 5.23 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.50$, -4.53, -4.17, -3.97 (4C, 2 Me–Si), 17.94, 18.04 (2C, q, 2 *tert*-Bu–Si), 25.83, 25.88 (6C, 2 *tert*-Bu–Si), 58.30 (1C, C-4), 68.21 (1C, $-CH_2$, C-6), 71.31, 71.55 (2C, C-2, C-3), 74.95 (2C, –CH–CH–, imide), 79.65 (1C, C-5), 105.37 (1C, C-1), 175.00 (1C, 2 C=O) ppm.

1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-3-N-((3′R,4′R)-3′,4′-bis-O-(tert-butyldimethylsilyl))-tatarimido-β-D-glucopyranose (**17**; $C_{34}H_{69}NO_8Si_4$)

Compound **16** (574 mg, 1.14 mmol) was dissolved in 10 cm^3 dry CH_2Cl_2 cooled to -40°C and treated with *tert*-butyldimethylsilyltrifluoromethanesulfonate (0.65 cm^3, 2.85 mmol) and 2,6-dimethylpyridine (0.33 cm^3, 2.85 mmol). After stirring under warming to room temperature for 48 h the mixture was washed with saturated aqueous NH_4Cl, saturated aqueous $NaHCO_3$, and brine. Drying and evaporation of the solvent afforded the crude product which was purified by column chromatography with petroleum ether:ethyl acetae = 100:1 to give **17** (460 mg, 55%) as a white solid.

M.p.: 101°C; $[\alpha]_D^{20} = -103.3°$ ($c = 1.0$, $CHCl_3$); IR (KBr): $\nu = 1725$ (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$): $\delta = -0.10$, -0.09, 0.00, 0.03, 0.14, 0.20 (6s, 24H, 4 Me–Si), 0.83, 0.83, 0.93 (3s, 36H, 4 *tert*-Bu–Si), 3.68 (dd, 1H, $J_{5,6a} = 5.0$ Hz, $J_{6a,6b} = 7.0$ Hz, H-6a), 3.80 (dd, 1H, H-6b), 3.91 (d, 1H, $J_{2,4} = 8.5$ Hz, H-2), 4.08–4.14 (m, 2H, H-3, H-4), 4.32 (d, 1H, H-5), 4.34 (s, 2H, –CH–CH–, imide), 5.20 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -5.53$, -4.11 (8C, 2 Me–Si), 16.56–17.84 (4C, q, 2 *tert*-Bu–Si), 25.83, 25.93, 26.03 (12C, 4 *tert*-Bu–Si), 57.37 (1C, C-4), 68.14 (1C, $-CH_2$, C-6), 71.27, 71.49 (2C, C-2, C-3), 77.17 (2C, –CH–CH–, imide), 79.71 (1C, C-5), 105.54 (1C, C-1), 176.20 (2C, 2 C=O) ppm.

(1R,2R,8S,9S,10R)-4-Aza-2,9-bis-tert-butyldimethylsiloxy-11,13-dioxa-tricyclo[8.2.1.0^{3,9}]tridecane-5,8-dione (**18**; $C_{22}H_{41}NO_6Si_2$)
and *(1R,2S,8R,9R,10R)-4-Aza-2,9-bis-tert-butyldimethylsiloxy-12,13-dioxa-tricyclo[8.2.1.0^{3,9}]tridecane-5,8-dione* (**19**; $C_{22}H_{41}NO_6Si_2$)

A solution of succinimide **13** (500 mg, 1.06 mmol) was irradiated for 6 h according to procedure B. Purification by column chromatography with toluene:acetone = 50:1 afforded **19** (146 mg, 0.31 mmol, 28%) and **18** (134 mg, 0.28 mmol, 26%), both as white crystals.

18: M.p.: 153°C; $[\alpha]_D^{20} = +16.0°$ ($c = 0.5$, $CHCl_3$); IR (KBr): $\nu = 3241$ (NH), 1711, 1679 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$): $\delta = -0.07$, 0.00, 0.11 (3s, 12H, 2 Me–Si), 0.79, 0.81 (2s, 18H, 2 *tert*-Bu–Si), 2.30 (dd, 1H, H-4a), 2.45–2.55 (m, 1H, H-5a), 2.88–2.98 (m, 2H, H-4b, H-5b), 3.57 (s, 1H, H-9), 3.61 (dd, 1H, $J_{10,11a} = 5.0$ Hz, $J_{11a,11b} = 8.5$ Hz, H-11a), 3.72–3.76 (m, 2H, $J_{3,NH} = 6.0$ Hz, H-3, H-11b), 4.34 (dd, 1H, H-10), 5.62 (s, 1H, H-1), 6.31 (d, 1H, NH) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -2.18$, -1.03, -0.85 (4C, 2 Me–Si), 22.69 (2C, q, 2 *tert*-Bu–Si), 28.33, 28.49 (6C, 2 *tert*-Bu–Si), 31.73, 38.05 (2C, 2-CH_2, C-4, C-5), 65.87 (1C, C-8), 68.08 (1C, $-CH_2$, C-11), 74.45 (1C, C-9), 77.65 (1C, q, C-2), 80.80 (1C, C-10), 102.87 (1C, C-1), 175.67 (1C, q, NHC=O), 205.68 (1C, q, C=O) ppm.

19: M.p.: 148°C; $[\alpha]_D^{20} = -44.4°$ ($c = 0.5$, $CHCl_3$); IR (KBr): $\nu = 3369$ (NH), 1704, 1684 (C=O) ppm; ^{1}H NMR ($CDCl_3$): $\delta = 0.04$, 0.11, 0.12, 0.24 (4s, 12H, 2 Me–Si), 0.92 (s, 18H, 2 *tert*-Bu–Si), 2.47–2.61 (m, 2H, H-6a, H-7a), 3.02–3.12 (m, 1H, H-7b), 3.19–3.27 (m, 1H, H-6b), 3.52 (s, 1H, H-2), 3.79 (dd, 1H, $J_{10,11a} = 5.5$ Hz, $J_{11a,11b} = 8.5$ Hz, H-11a), 3.83 (d, 1H, $J_{3,NH} = 6.5$ Hz, H-3), 3.90 (dd, 1H, $J_{10,11b} = 1.0$ Hz, H-11b), 4.73 (dd, 1H, H-10), 5.31 (s, 1H, H-1), 5.69 (d, 1H, NH) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -2.00$, -1.93, -0.89, 3.85 (4C, 2 Me–Si), 21.24 (2C, q, 2 *tert*-Bu–Si), 28.58, 28.78 (6C, 2 *tert*-Bu–Si), 32.05, 36.69 (2C, $-CH_2-$, C-6, C-7), 63.52 (1C, C-3), 68.20 (1C, $-CH_2-$, C-11), 74.04 (1C, C-10), 77.70 (1C, C-2), 80.17 (1C, q, C-9), 104.98 (1C, C-1), 175 (1C, q, CO, NHC=O), 209.13 (1C, q, C=O) ppm.

(1R,2R,9S,10S,11R)-4-Aza-2,10-bis-tert-butyldimethylsiloxy-12,14-dioxa-tricyclo [9.2.1.0^{3,10}]tetradecane-5,7-dione (**20**; $C_{23}H_{43}NO_6Si_2$)
and *(1R,2S,9R,10R,11R)-4-Aza-2,10-bis-tert-butyldimethylsiloxy-13,14-dioxa-tricyclo [9.2.1.0^{3,10}]tetradecane-5,9-dione* (**21**; $C_{23}H_{43}NO_6Si_2$)

A solution of the 3-glutarimide **14** (250 mg, 0.51 mmol) was irradiated for 4 h according to procedure B. Purification by column chromatography with toluene:acetone = 30:1 afforded **20** (58.29 mg, 0.12 mmol, 23%) and **21** (61.93 mg, 0.13 mmol, 25%), both as colourless oils.

20: $[\alpha]_D^{20} = -123.5°$ ($c = 0.5$, $CHCl_3$); ^{1}H NMR ($CDCl_3$): $\delta = 0.02$, 0.11, 0.13, 0.23 (4s, 12H, 2 Me–Si), 0.92, 0.95 (2s, 18H, 2 *tert*-Bu–Si), 1.95–1.98 (m, 1H, H-7a), 2.08–2.13 (m, 1H, H-7b), 2.22–2.26 (m, 1H, H-8a), 2.43–2.54 (m, 2H, H-6a, H-6b), 3.31–3.36 (dt, 1H, H-8b), 3.62 (s, 1H, H-2), 3.79–3.83 (m, 2H, $J_{3,NH} = 10.0$ Hz, $J_{11,12a} = 5.0$ Hz, $J_{12a,12b} = 8.5$ Hz, H-3, H-12a), 4.26 (d, 1H, H-12b), 4.55 (d, 1H, H-11), 5.34 (s, 1H, H-1), 5.98 (d, 1H, NH) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.96$, −4.71, −3.37, −2.68 (4C, 2 Me–Si), 18.53 (2C, q, 2 *tert*-Bu–Si), 24.53 (1C, –CH_2, C-7), 25.96, 26.00 (6C, 2 *tert*-Bu–Si), 34.33 (1C, –CH_2, C-6), 38.20 (1C, –CH_2, C-8), 58.30 (1C, C-3), 65.32 (1C, C-12), 72.20 (1C, C-2), 75.37 (1C, C-11), 79.01 (1C, C-10), 102.42 (1C, C-1), 174.55 (1C, q, NH–C=O), 210.70 (1C, q, C=O) ppm.

21: $[\alpha]_D^{20} = +34.7°$ ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$): $\delta = 0.02$, 0.12, 0.13, 0.20 (4s, 12H, 2 Me–Si), 0.93 (2s, 18H, 2 *tert*-Bu–Si), 2.00 (m, 1H, –CH_2, H-7a), 2.25 (m, 2H, –CH_2, H-8a, H-7b), 2.45 (m, 1H, –CH_2, H-6a), 2.58 (m, 1H, –CH_2, H-6b), 3.20 (m, 1H, –CH_2, H-8b), 3.70 (s, 1H, H-2), 3.76 (dd, 1H, $J_{1,13a} = 5.0$ Hz, $J_{13a,13b} = 9.0$ Hz, H-13a), 3.90 (d, 1H, $J_{3,NH} = 11.50$ Hz), 3.95 (d, 1H, H-13b), 4.42 (d, 1H, H-1), 5.62 (s, 1H, H-11), 5.64 (d, 1H, NH) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.87$, −4.73, −3.26, −2.37 (4C, 2 Me–Si), 17.85 (2C, q, 2 *tert*-Bu–Si), 23.40 (1C, –CH_2, C-7), 25.88, 25.90 (6C, 2 *tert*-Bu–Si), 33.83 (1C, –CH_2, C-6), 38.44 1C, –CH_2, C-8), 60.08 (1C, C-3), 65.88 (1C, –CH_2, C-13), 73.04 (1C, C-2), 78.20 (2C, C-1, C-10), 100.30 (1C, C-11), 172.52 (1C, q, NH–C=O), 207.89 (1C, q, C=O) ppm.

1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-β-D-erythro-hex-2-enopyranose (**22**; $C_{18}H_{36}O_4Si_2$) and *1,6-Anhydro-2,4-bis-O-(tert-butyldimethylsilyl)-3-deoxy-β-D-erythro-hex-3-enopyranose* (**23**; $C_{18}H_{36}O_4Si_2$)

Compound **17** (410 mg, 0.56 mmol) was irradiated for 20 h according to procedure B. Subsequent column chromatography with petroleum ether:ethyl acetate = 100:1 yielded compounds **22** (38 mg, 18%) and **23** (25 mg, 12%).

22: ^{1}H NMR ($CDCl_3$): $\delta = 0.1$, 0.17, 0.22, (3s, 12H, 2 Me–Si), 0.90, 0.92 (2s, 18H, 2 *tert*-Bu–Si), 3.60–3.72 (m, 2H, $J_{5,6a} = 4.0$ Hz, $J_{6a,6b} = 6.0$ Hz, H-6a, H-6b), 3.90 (dd, 1H, $J_{3,4} = 4.0$ Hz, $J_{4,5} = 1.0$ Hz, H-4), 4.41 (d, 1H, H-5), 4.59 (d, 1H, H-3), 5.34 (s, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.83$, −3.64, −2.35, −1.98 (4C, 2 Me–Si), 16.97, 17.30 (2C, q, 2 *tert*-Bu–Si), 24.51, 24.90 (6C, 2 *tert*-Bu–Si), 67.22 (1C, C-4), 67.94 (1C, –CH_2, C-6), 72.74 (1C, C-5), 98.20 (1C, C-3), 101.94 (1C, C-1), 152.51 (1C, q, C-2) ppm.

23: ^{1}H NMR ($CDCl_3$): $\delta = 0.11$, 0.17, 0.18 (3s, 12H, 2 Me–Si), 0.91, 0.92 (2s, 18H, 2 *tert*-Bu–Si), 3.37 (dd, 1H, $J_{5,6a} = 1.5$ Hz, $J_{6a,6b} = 7.5$ Hz, H-6a), 3.84 (dd, $J_{5,6b} = 6.5$ Hz, H-6b), 3.87 (dd, 1H, $J_{1,2} = 1.5$ Hz, $J_{2,3} = 5.0$ Hz, H-2), 4.49–4.52 (m, 1H, H-5), 4.61–4.64 (m, 1H, H-3), 5.20 (d, 1H, H-1) ppm; ^{13}C NMR ($CDCl_3$): $\delta = -4.64$, −3.37, −2.81, −1.99 (4C, 2 Me–Si), 17.03, 17.29 (2C, q, 2 *tert*-Bu–Si), 24.51, 24.69 (6C, 2 *tert*-Bu–Si), 62.43 (1C, –CH_2, C-6), 67.59 (1C, C-2), 76.31 (1C, C-5), 97.95 (1C, C-1), 98.09 (1C, C-3), 152.70 (1C, q, C-4) ppm.

Complete crystallographic data have been deposited with the Cambridge Crystallographic Data Centre, CCDC no. 167716 (**19**). Copies may be obtained free of charge from The Director, CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44-1223-336033, e-mail: deposit@ccdc.cam.ac.uk or http://www.ccdc.cam.ac.uk).

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