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Tribute

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Professor Horst Kunz

A Tribute

This special issue of Arkivoc is dedicated to Professor Dr. Horst Kunz on the occasion of his 80th birthday, to acknowledge his contributions to synthetic organic and bioorganic chemistry

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Horst Kunz was born in Frankenhausen, district Zwickau/Saxony in 1940. After the war this area belonged to the Eastern German sector. Hence, the way of life of Horst Kunz was distinctly influenced by the conditions prevailing in a divided Germany. He attended school in Frankenhausen and in the neighboring city of Crimmitschau but after completion of the Matura examination in 1959, it was only possible for him to study after undergoing military service. He was able to do this as a member of the army ice-hockey team (at that time in the Eastern German premier league). He was then approved to study chemistry at the Humboldt University in East Berlin in 1961, the year the Berlin wall was erected. He found a way to surmount this perilous border in autumn 1961. Arriving in Western Germany, he was obliged to repeat the Matura examination (in Offenbach/Main), before restarting the study of chemistry at the University of Mainz in 1962. He completed his Ph.D. (on organo-phosphorous macrocycles) under the supervision of Leopold Horner in 1969.

At the invitation of Professor Horner he stayed at the university for his Habilitation which he completed on alkaline hydrolysis of esters of choline-analogous alcohols and their application in protective group chemistry in January 1977. He then started his research group and in 1979 was appointed Associate Professor after declining the offer of an equivalent position at the University of Wuppertal. In 1988 he became Full Professor of Organic and Bioorganic Chemistry at Mainz again after declining the offer of an equivalent chair at the Free University of Berlin.

His and his group's research was recognized by the award of the Max Bergmann Medal in 1992, the Emil Fischer Medal of the Gesellschaft Deutscher Chemiker (GDCh) in 2000 and the Adolf Windaus Medal of the University of Goettingen in 2001. In 1998 he was elected Corresponding Member of the Saxony Academy of Sciences at Leipzig. He gave the Sandoz Foundation Lecture at Regensburg in 1995 and held the Novartis Lectureship in 1999. In 1995, he was Guest Professor at the University of Paris-Sud at Orsay.

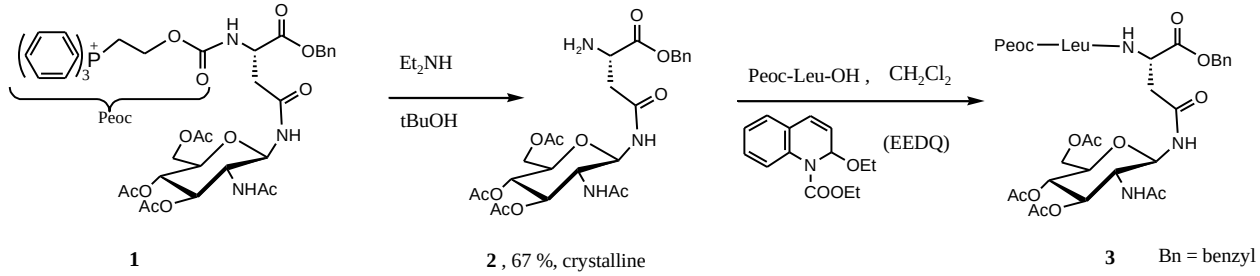
His research has resulted in about 400 publications. He has been involved in interdisciplinary research initiatives and projects, in particular, in cooperation with medicinal disciplines, and he served the Deutsche Forschungsgemeinschaft (DFG) as an elected reviewer for many years. He supervised 130 doctoral students and numerous post-docs and diploma students. His research interests include preparative chemistry, biological and medicinal chemistry and mechanistic aspects of stereochemistry.

Research fields

The research activity of Horst Kunz began with an investigation of acetylcholine analogs during the habilitation period and led him and his group from protecting group chemistry to peptide syntheses and glycopeptide chemistry, at that time (1980) a field of unsolved problems. The group also ventured into carbohydrate chemistry and the following selected examples of his research achievements illustrate the development of his science.

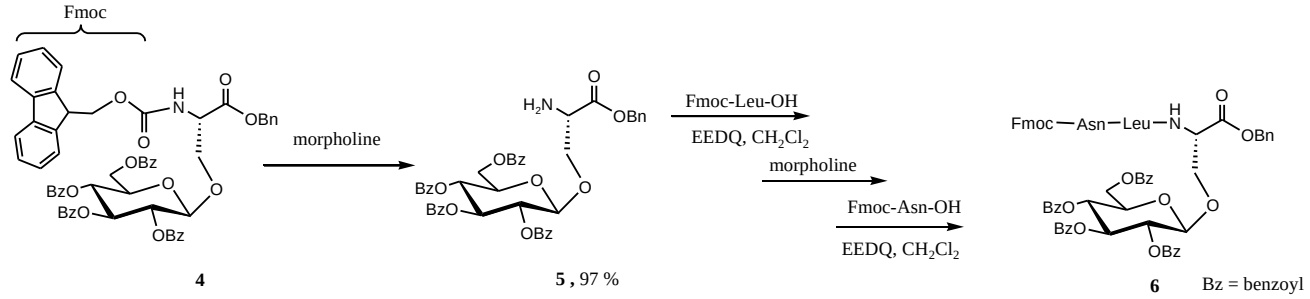
Protecting groups, peptides and glycopeptide chemistry

The triphenylphosphonio-ethoxycarbonyl-(Peoc)-group,[1-3] an analog of acetylcholine, was introduced to protect the amino function. It is stable to acids, removable with weak bases and promotes solubility in water. Thus, it rendered peptide synthesis possible in water.[2] Using the Peoc and analogous protecting groups, selective removal of protection, e. g. from **1**, Scheme 1, and



Scheme 1. Glycopeptide synthesis.[3]

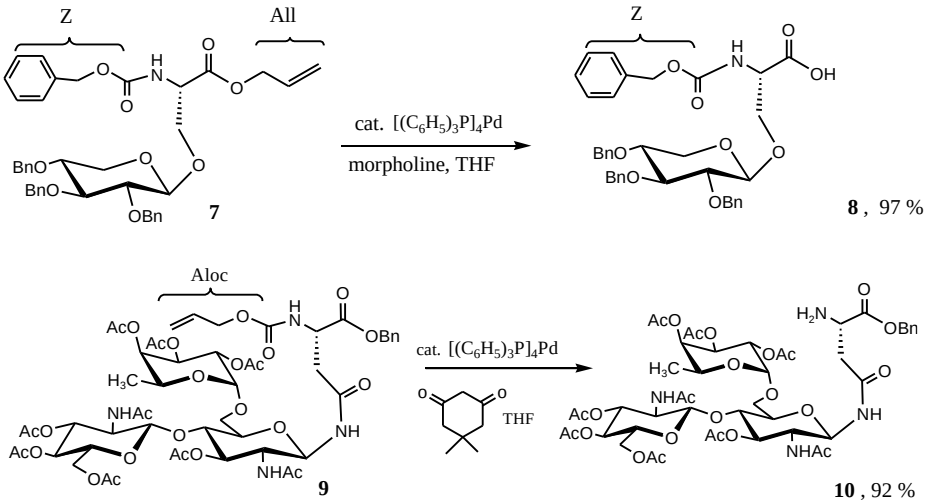
glycopeptide formation was successful without affecting glycoside bonds. Subsequently, the group introduced the well-known Fmoc-group into glycopeptide chemistry (Scheme 2),[5] which nowadays is applied in solid-phase syntheses of complex glycopeptide partial structure of biologically interesting glycoproteins using resins with Wang- or trityl-linkers.[6-7]



Scheme 2. Fmoc group in early glycopeptide synthesis.[5]

In addition, the principle of two-step-protective groups, e. g. the 2-(2-pyridyl)ethoxycarbonyl-(Pyoc)-group,[8] were introduced to glycopeptide synthesis. The original form of protection is stable, but after conversion (in the given case by N-methylation) it is very sensitive and removable by mild bases.[9]

The introduction of allylic protecting groups and their Pd(0)-catalyzed removal from amino- and carboxy groups proved to be particularly useful in glycopeptide syntheses (Scheme 3).[10-17] In the case of allyl ester cleavage, the intermediate π-allyl palladium complex is favorably trapped using a mild base as the nucleophile.

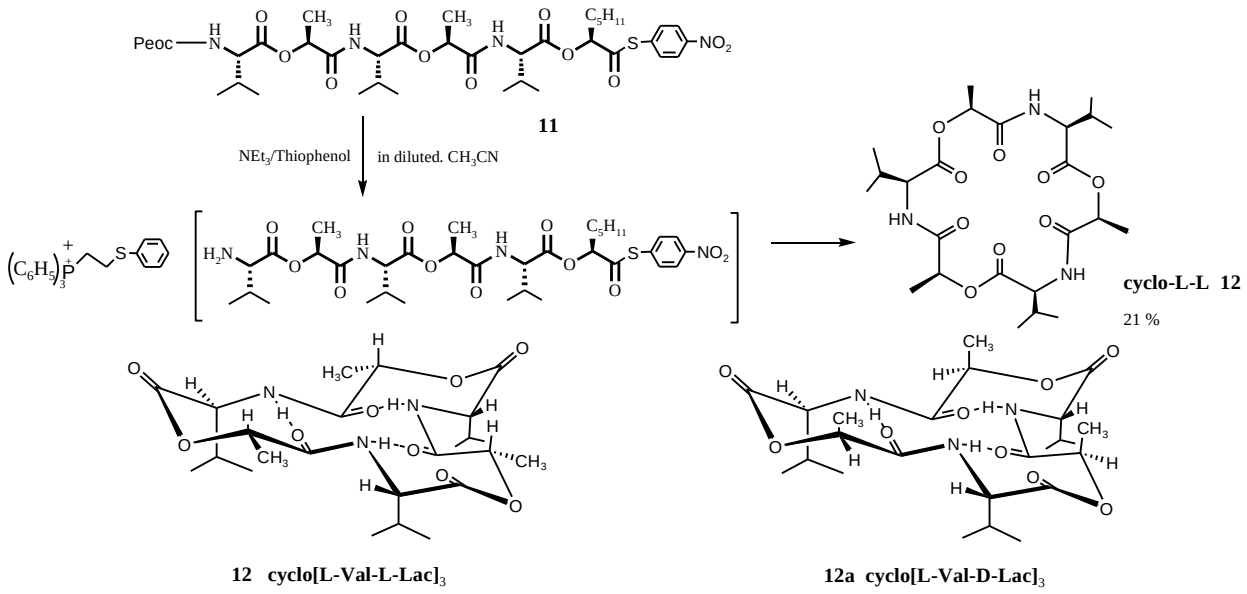


Scheme 3. Allylic protecting groups in peptide and glycopeptide chemistry.[10-12]

For removal of the allyloxycarbonyl-(Aloc)-group, the anion of a mild acid, e. g. N.N'-dimethyl-barbituric acid,[13] is recommended as the trapping nucleophile. The allylic protecting groups are orthogonally stable to the Fmoc- and Boc protecting groups. Thus, the allylic esters were developed as an alternative orthogonal anchoring principle in solid-phase syntheses, for example, in tumor-associated mucin MUC1-glycopeptde antigens and vaccines.[14-16] Allyl ethers can also be cleaved by a modified Pd(0)-catalyzed methodology, for example, from solid-phase linked carbohydrate scaffolds.[17]

Cyclodepsipeptides – strained macroheterocycles

The marked acid-stability of the acetylcholine-like N-Peoc protection rendered the preparation of N-protected amino-acid chlorides possible which turned out to be useful for the synthesis of depsipeptide natural products.[18] On the basis of this strong activation, N-Peoc-oligodepsipeptide active esters, for example, the hexadepsipeptide thioester **11**, were formed which, after mild N-deprotection, underwent cyclization to afford the strained eighteen-membered oligodepsipeptides **12** (Enniatin analogs, Scheme 4).[19] The groups of Shemyakin and Ovchinnikov had shown that compounds of this type with identical configuration of all building blocks (**cyclo-LL-12)** are almost inaccessible.

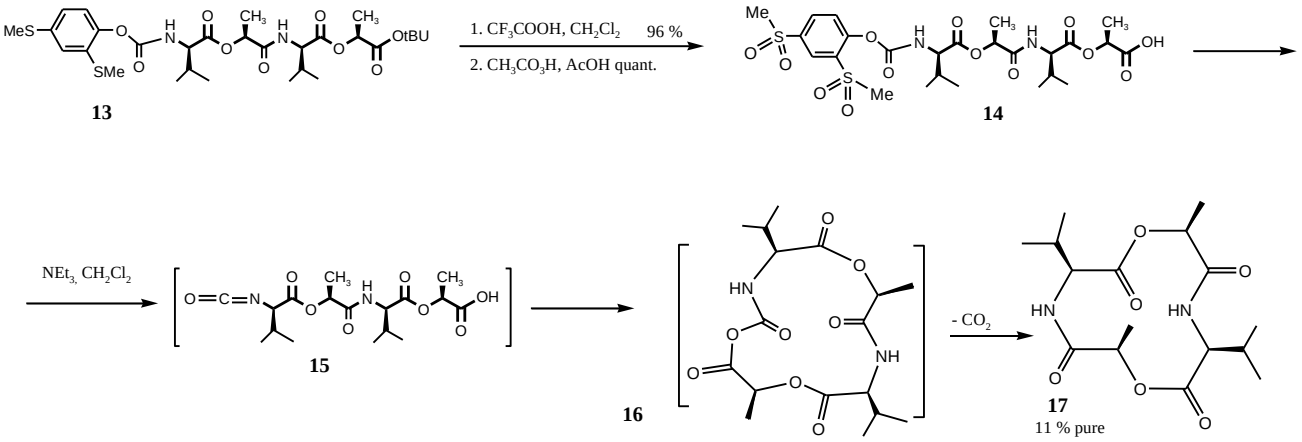


Scheme 4. Synthesis of cyclo-oligodepsipeptides based on the acid-stable N-Peoc protection.

The analogous cyclization of oligodepsipeptides with alternating configuration proceeded much more readily and furnished the diastereomer cyclo-hexadepsipeptide **12a** (cyclo-L-D).[19] It is particularly interesting that these two diastereomers differ completely in their complexing ability towards simple radially-symmetric alkali ions in water. While cyclo-LD **12a** forms 2:1-complexes with sodium (optimum), cyclo-LL **12** does not coordinate to the cation.[19] This is presumed that such differentiation may have contributed originally to the separation of enantiomers.

The concept of two-step protecting groups[8-9,20-21] also proved to be useful for the synthesis of highly strained cyclodepsipeptides according to the *principle of peptide bond formation after N-terminal activation*. The *t*-Bu-ester of *N*-(bismethylthio)phenoxycarbonyl-(Bmpc)-tetradepsipeptide **13** was first acidolyzed. Subsequent oxidation of the stable Bmpc group to the base-sensitive bis-sulfonyl form (Bspc) **14** and

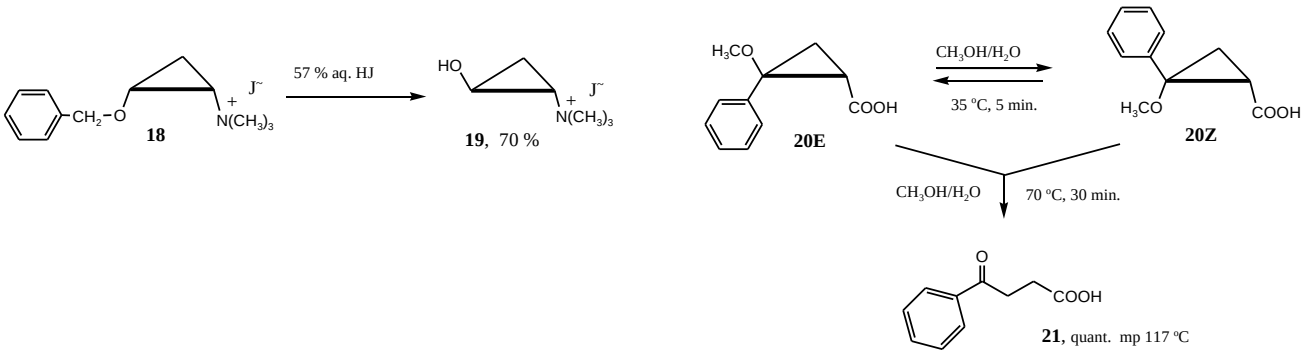
treatment with an appropriate base, furnished the intermediate isocyanate **15**. The reactive N-terminal isocyanate cyclized to afford the (more relaxed) fourteen-membered carboxy-carbaminyl anhydride **16**, which lost carbon dioxide to result in the highly strained twelve-membered cyclodepsipeptide **17** with an all-L-configuration.[21]



Scheme 5. Synthesis of cyclodepsipeptides through peptide formation *via* N-terminal activation.[21]

Chemistry of cyclopropanes

The synthesis of sterically fixed choline-like compounds gave some unexpected results, which shone light on the particular properties of the cyclopropane frontier orbitals. Aiming at a syn-clinal choline analogue, the *cis*-2-benzyloxy-cyclopropyl-ammonium salt **18** was treated with aqueous hydrogen iodide (Scheme 6, left).[22]



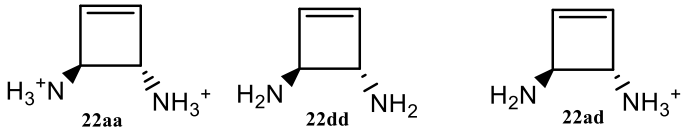
Scheme 6. Surprising chemistry of cyclopropanes.[22]

Surprisingly, the ether cleavage was accompanied by complete inversion of configuration. Cyclopropanols undergoing S_N2-type reactions should lead to the iodide. On the other hand, cyclopropyl cations should open dis-rotatorily to give allyl cations, blocked in this case by the positively charged substituent.

This result focused attention on the influence of electron-withdrawing and electron-donating substituents on electrocyclic reactions, particularly in small rings. The investigations showed, that donor-acceptor substituted cyclopropanes, for example the trans-configured compound **20E**, readily undergo inversion of configuration in polar media at room temperature.[23] Obviously, the trigonal basic Walsh-orbital formed by the three Csp2-orbitals stabilizes the ring during the rotation from *trans* to *cis* and vice versa. At

elevated temperature, cleavage of the polar cyclopropane bond occurred in the polar solvent to furnish the -keto-carboxylic acid **21** quantitatively.

In fact, donor-acceptor substituted (polar) bonds are also opened more readily in electrocyclic processes as was shown in an MNDO/2 study on 3,4-disubstituted cyclobutenes (Scheme 7).[24]



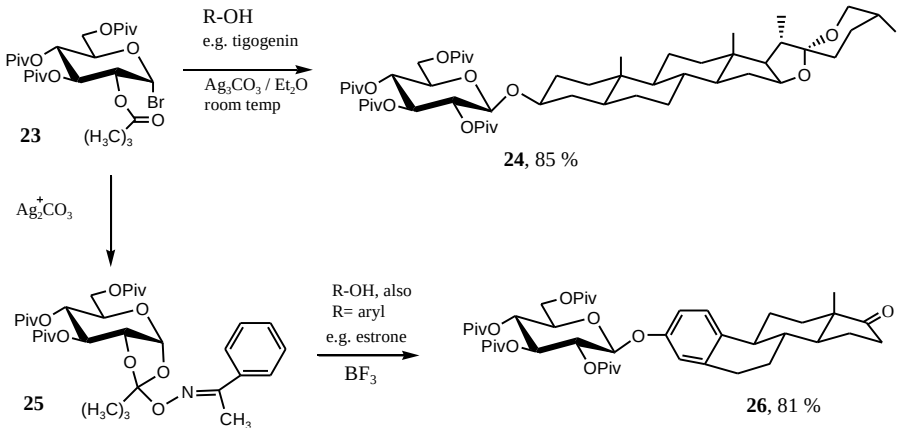
Conrotatory ring opening: calc. activating energy **22aa** > **22dd** > **22ad**

Scheme 7. Electronic substituent influence on conrotatory thermal ring opening – a MNDO study.[24]

The results suggest that the energetic differentiation between thermally allowed and forbidden processes according to the principle of conservation of orbital symmetry, is reduced for more polar bonds (lower covalent amount of binding energy) involved in the process under consideration.

Methodology of glycoside synthesis

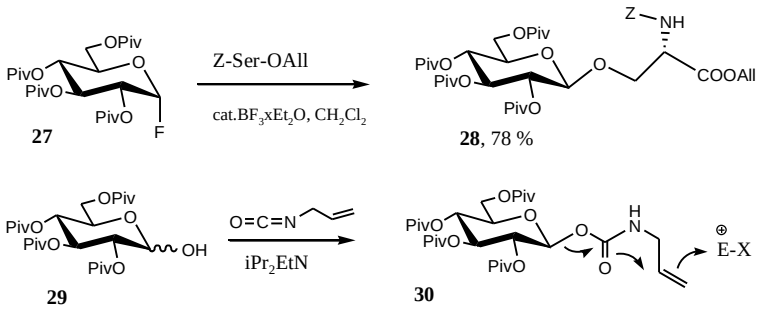
Early investigations into carbohydrate chemistry concerned syntheses of 3-keto-glycals and their stereoselective conversion to C-glycosides using silyl enol ethers.[25] In addition, carbohydrate alcohols, e. g. diacetone glucose, were used for mechanistic studies of the Mitsunobu reaction, which revealed that the initial adduct of triphenylphosphine to azodicarboxylate, after further addition of the alcohol, underwent a 1,3-N to O shift to form an alkoxy-iminoxy-phosphorane which after attack of the nucleophile-delivering electrophile (E-Y or H-X) at the imine nitrogen gives the alkoxy-phosphonium salt[26] (isolated in the case of diacetone glucose). This finally undergoes a Michaelis-Arbusov rearrangement to yield the substitution product with inversion of configuration.[25-27] However, major focus concerned the efficient and stereoselective glycosylation reactions. Here, the introduction of the 2-O-pivaloyl protection enabled 1,2-trans glycosylation with high efficiency e. g. of tigogenin, even under classical Koenigs-Knorr conditions through suppression of orthoester formation (Scheme 8).[28-29]



Scheme 8. 2-O-Pivaloyl protected glycosyl donors suppress orthoester formation.

When the pivaloyl-protected glucosyl bromide **23** was reacted with acetophenone oxime under these conditions then, due to the minimal steric demand, the storable orthoester **25** was obtained, which can be used as an alternative glycosyl donor.[30]

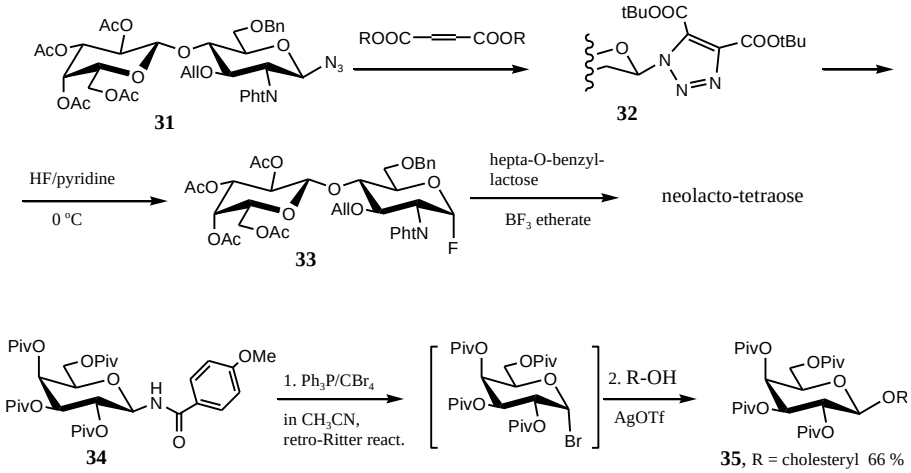
Glycosyl fluorides are stable towards hydrolysis. Mukayama et al. activated them for glycosylation with $SnCl_2$ and silver salts, Noyori et al. used $SiCl_4$. However, BF_3 etherate is a convenient promoter whereby O-acyl- (example **27**), O-benzyl- and O-isopropylidene protected glycosyl fluorides gave the corresponding glycosides in high yields (Scheme 9, top).[31]



Scheme 9. Improved and novel glycosylation methods.

Saccharides unprotected at the anomeric position (**29**) were converted with allyl isocyanate to the corresponding glycosyl-N-allyl urethanes (**30**) which can be activated with soft electrophiles (e.g. I^+) for glycosylation forming an oxazolidinone as the leaving group.[32] In an analogous fashion 1-O-pentenoyl[33] and 1-S-pentenyl glycosides[34] were transformed to efficient glycosl donors.

In addition to an improved synthesis of β-mannosides based on an intramolecular S_N2-reaction at 2-position of β-glycosides,[35] new concepts were introduced for transforming stable protecting groups at the anomeric position into potent leaving groups of glycosyl donors. In this sense, glycosyl azides (**31**) proved to be stable during multi-step syntheses of N-glycans of N-glycoproteins.[6,12,36] These were converted with acetylene derivatives in a 1,3-dipolar cycloaddition to glycosyl triazoles which with HF/pyridine afforded glycosyl flourides (**33**),-potent glycosyl donors, e. g. in the construction of oligo-lactosamines Scheme 10).[37]



Scheme 10. Conversion of anomerically protected saccharides in glycosyl donors.

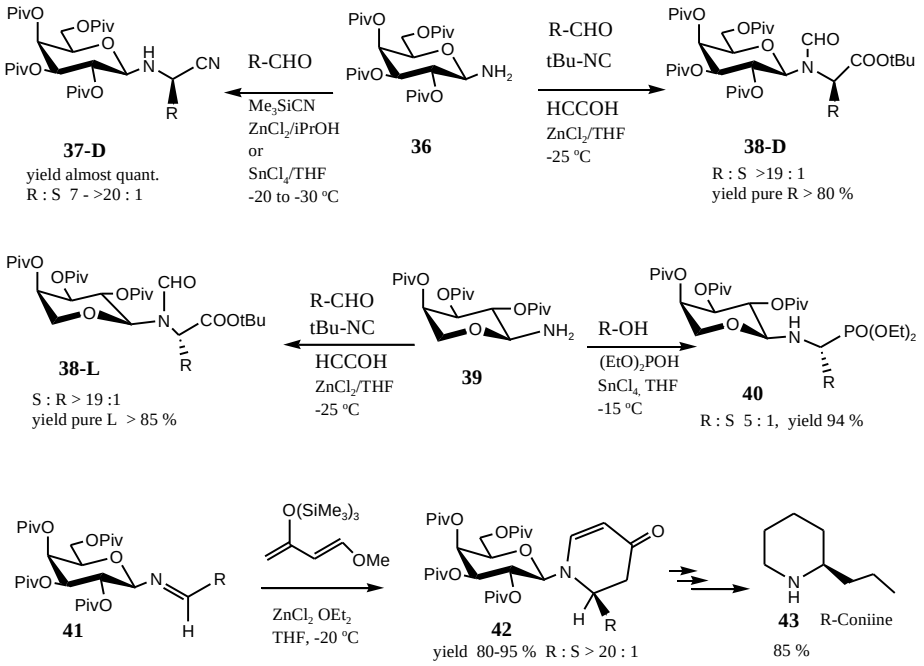
N-Glycosyl amides (**34**) also constitute stable N-protected saccharides. Their activation for glycosylation was achieved through treatment with Appel's reagent (triphenylphosphine-carbon-tetrabromide) forming the imido-bromide and subsequently in a retro-Ritter reaction the glycosyl bromide which acts as the glycosyl donor.[38]

Carbohydrates as stereo-differentiating auxiliaries in asymmetric synthesis

The idea of applying carbohydrates in diastereoselective reactions derived from experiences in O-glycopeptide synthesis. The high base-sensitivity of O-glycosyl serine was rationalized by the pronounced complexing abilities of carbohydrates towards cations, making the carbohydrate a good leaving group. Actually, carbohydrate esters of N-protected amino acids are turned into active esters for peptide synthesis by simple coordination to lithium ions.[39] This interpretation also encouraged the use of carbohydrates as stereodifferentiating tools in stereoselectice alkylation of ester enolates[40] and in Diels-Alder reactions.[41]

Glycosylamines, readily accessible from glycosyl azides, (*vide supra*) proved to be versatile auxiliaries in stereoselective syntheses of O-pivaloyled galactosylamine **36** (Scheme 11). In one-pot-Strecker reactions it reacts with aldehydes and trimethylsilyl cyanide in the presence of a suitable Lewis acid to give D-amino nitriles **37-D** almost quantitatively and with high diastereoselectivity.[42] Even higher stereoselectivity was achieved in corresponding Ugi four-component reactions. Simple recrystallization from n-heptane yielded pure D- amino acid amides **38-D** in excellent yields.[43]

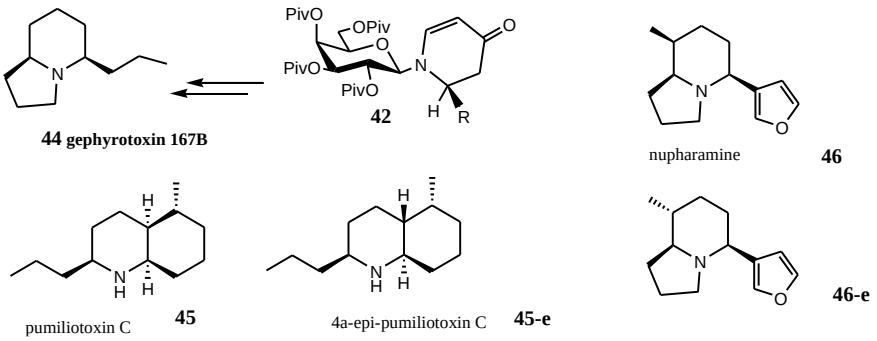
Using D-arabinopyranosylamine **39** as a pseudo-enantiomer, **36** provided an efficient synthesis of L-amino acid amides **38-L**.[44] When diethylphosphite was applied in this one-pot process, interesting D-amino phosphonic esters **40** were obtained in high yield and diastereoselectivity.[45]



Scheme 11. Diastereoselective syntheses using glycosylamines as the auxiliaries.

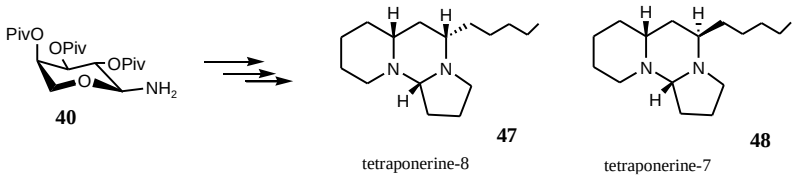
In all these conversions, Schiff bases like **41**, are formed primarily. Aldimes **41,** treated with Danishefsky diene in the presence of an appropriate Lewis acid react in a domino-Mannich-Michael-condensation sequence to yield 2-substituted piperidinones **42** with excellent diastereoselectivity.[46] Besides (R)-coniine **43**,

(S)-anabasin, (+)-pinidine, gephyrotoxin 167B **44** and other alkaloids were stereoselectively synthesized in this way.[47] In the course of pumiliotoxin synthesis, the natural *cis*-fused structure **45** and the *trans*-fused epimer (**45-e**) can be obtained selectively depending



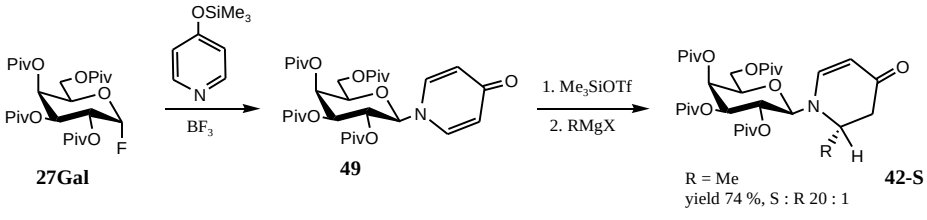
Scheme 12. Alkaloids synthesized via the N-galactosyl route.

on protonation of the intermediary enolate. When the N-galactosyl substituent was exchanged for a (flat) phenoxycarbonyl group, the *cis*-fused pumiliotoxin framework was formed, but in the presence of the N-galactosyl group, protonation of the enolate was directed under contra thermodynamic control to result in the trans-fused (4-epi, histrionicotoxin series) structure.[48] Control of the CH-acidity of an intermediary piperidinone through the N-galactosyl group is also responsible for the preferred formation of the all-cis nupharamine **46**, which can be converted to the trans-substituted epimer **46-e** by treatment with base.[49] The scope of this stereoselective methodology becomes obvious if one keeps in mind that the series of opposite alkaloid enantiomers is accessible by use of D-arabinosylamine **40**, demonstrated in the stereoselective syntheses of tertraponorine-8 **47** and -7 **48** (Scheme 13), toxins of a New Guinea ant.[50]



Scheme 13. Stereoselective synthesis of ant toxins from arabinosylamine.

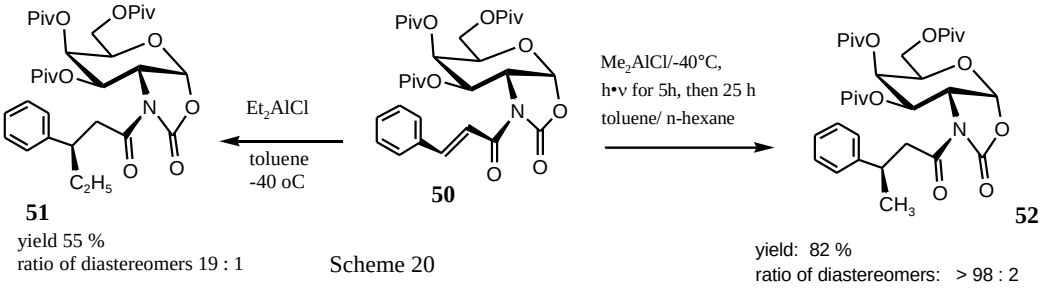
Stereoselective steering through carbohydrate auxiliaries was expanded further by using glycosylation as a tool for desymmetrization. Symmetric ɣ-pyridone was N-glycosylated to give **49**. After O-silylation, Grignard reagents were added to the pyridinium intermediate and the 2-substituted piperidinone **42-S** was formed with excellent stereoselectivity (Scheme 14).[51]



Scheme 14. Desymmetrization through glycosylation, a new concept of stereoselective conversion.

The product has the opposite configuration of the heterocycle compared to **42** although D-galactosyl served as the differentiating substituent in both processes. Combined with subsequent conjugate additions and domino-palladium-catalyzed Heck and Suzuki couplings, benzomorphan derivatives were synthesized using this strategy with high diastereoselectivity.[52] The adaption of this concept to α-pyridone was also successful.[53] N-Glycosylation combined with activation of symmetric imines resulted in the successful variation of these stereo-differentiating syntheses, for example of 1-substituted tetrahydroisoquinolines.[54]

A different diastereoselective differentiation was introduced by a new reaction consisting of the conjugate addition of organo-aluminum reagents to α,β-unsaturated N-acyl oxazolidinones derived from glycosamines **50** (Scheme 15).[55]



51
yield 55 %
ratio of diastereomers 19 : 1

50

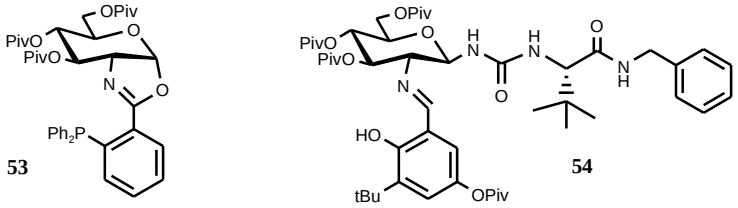
52
yield: 82 %
ratio of diastereomers: > 98 : 2

Scheme 20

Scheme 15. Conjugate addition of organoaluminum compounds to α,β-unsaturated N-acyl-oxazolidinones.

An interesting feature of these reactions is that higher alkyl- and arylaluminum chlorides add to the acceptors at low temperature to yield the β-branched products **51** with high diastereoselectivity, while dimethylaluminum chloride does not. It needs irradiation (radical formation) for initiation of the 1,4-addition to yield methyl-branched compounds of type **52**.[56] In fact under thermal conditions dimethylaluminum chloride promoted the 1,4-addition of sterically hindered alkylaluminum reagents (tBu), but did not add itself.[57] The 1,4-additions can also be combined with stereoselective α-functionalization, for example, to afford β-branched α-chloro carboxylic acid derivatives.[58]

More recently, carbohydrates were introduced as enantioselective catalysts in stereoselective synthesis. At first, the glucosamine-derivative, oxazoline **53** was shown to be a potent stereo-differentiating ligand in Pd(0)-catalyzed enantioselective allyl substitution reactions (Scheme 16).[60]



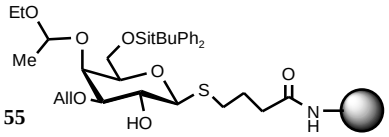
53 **54**

Scheme 16. Carbohydrates in enantioselective catalysis.

The glycosamine-derived urea-tert.-leucin amide **54** was shown to be an efficient enantioselective organocatalyst of Strecker and Mannich reactions.[61] For a recent comprehensive survey on carbohydrates in stereoselective syntheses, see reference 54

Carbohydrates as multi-valent scaffolds in combinatorial syntheses

Combinatorial synthesis appeared attractive in the search for biologically active lead structures. In this sense, carbohydrates were developed as multi-functional scaffolds, to which diverse functional side chains can be coupled in a combinatorial versatility.[62] An example **55** for the galactopyranose stereochemistry is given in Scheme 17.[63]



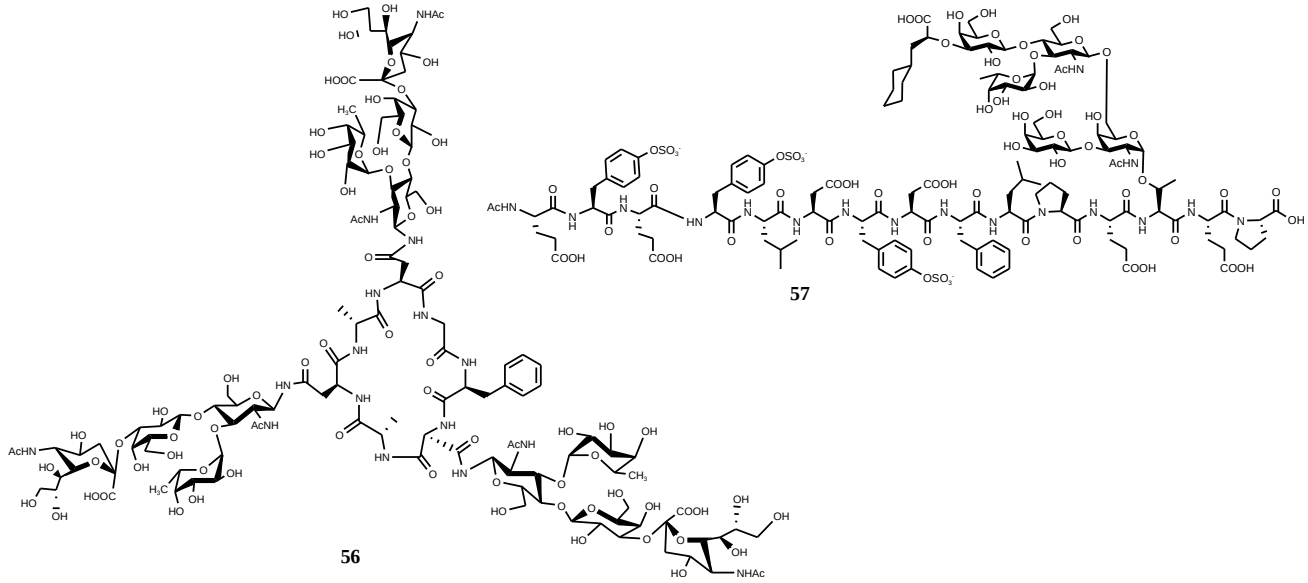
Scheme 17. Carbohydrate scaffolds in combinatorial syntheses.

Subsequent selective removal of protecting groups from these scaffolds, followed by introduction of specific side chains, in particular, amino acids and peptides,[64] open up access to a broad spectrum of potential drug structures, especially as the activation of the thio glycoside linkage provides the option of introducing a fifth substituent.

The combinatorial solid-phase synthesis was also applied to Ugi four-component reactions[65] and to the versatile stereoselective synthesis of piperidine derivatives (see, Scheme 11).[66]

Glycopeptides – selective inhibitors of cell adhesion processes

Cell adhesion plays a crucial role in a great number of biological processes, for example in the recruitment of leukocytes in inflammatory diseases. The selective inhibition of participating selectins, decisive receptors on leukocytes and endothelial cells, is of high interest. For inhibition of E- and P-selectin, N- and O-glycopeptides were synthesized on resins equipped with acid-sensitive linkers.



Scheme 18. Glycopeptide ligands with selective affinity to selectins.

For example, the cyclic triple sialyl-LewisX glycopeptide **56** was constructed *via* solid-phase peptide synthesis followed by cyclization, deprotection of the aspartic acid side chains and simultaneous coupling of three pre-formed sialyl-LewisX saccharides. It proved to be a selective ligand of endothelial (E-) selectin.[36]

However, in most cases the glycopeptide ligands were obtained by first carrying out the multi-step synthesis of the N-protected glycosyl amino acid building blocks and their subsequent introduction in the course of the solid-phase glycopeptide synthesis[6-8,14-16,67-69]

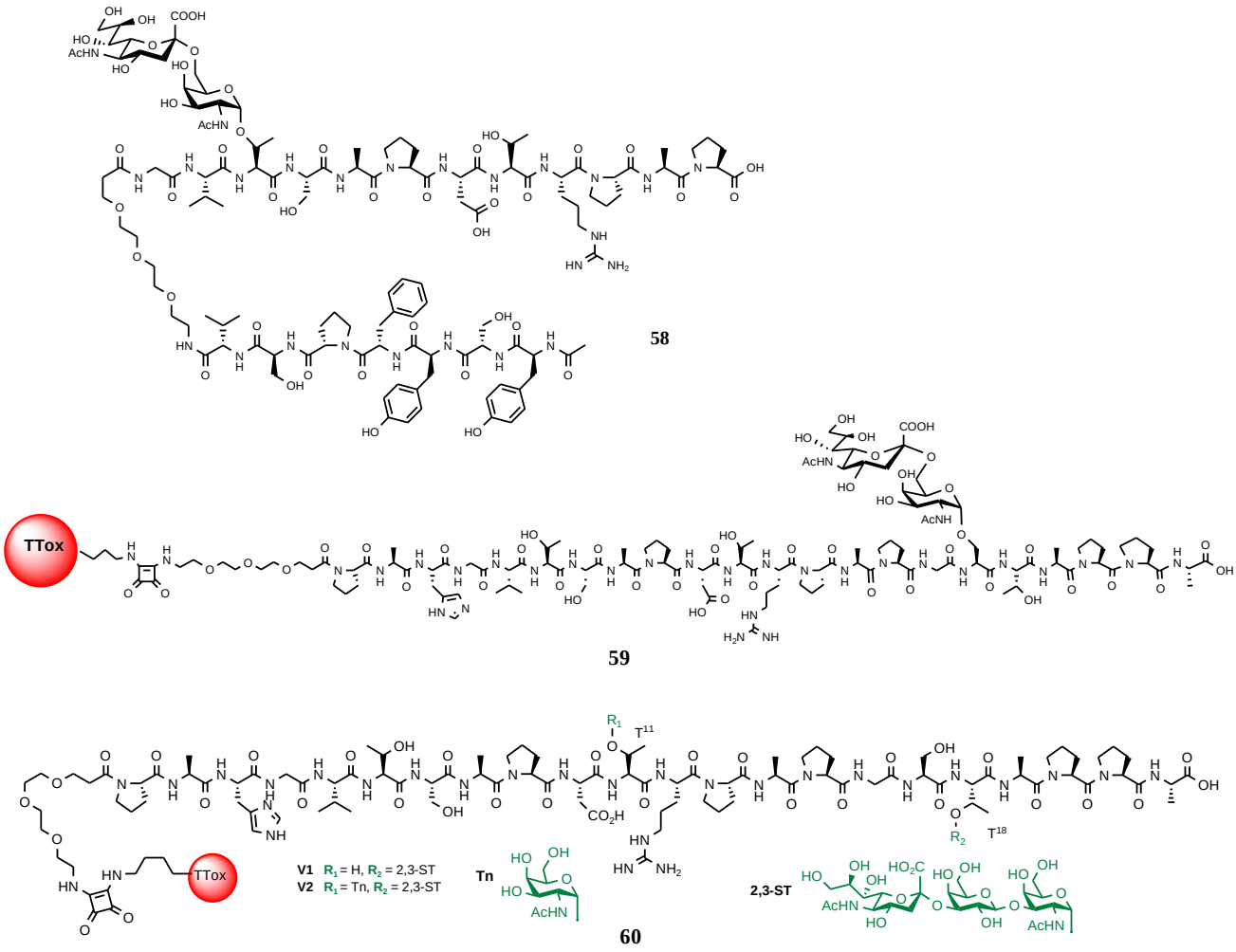
The multi-step syntheses of the saccharide structures certainly constitute the major challenge in these syntheses. For example, the hexasaccharide part of the glycopeptide recognition region of P-selectin glycoprotein ligand (PSGL-1) of P-selectin (analogous to **57**) was built up *via* a crucial regio- and stereoselective block glycosylation of a sialyl -LewisX tetrasaccharide donor to the T-antigen disaccharide-threonine acceptor before the solid-phase glycopeptide synthesis was performed.[70] The synthesis of the potently selective P-selectin binding glycopeptide **57** was achieved by an analogous strategy. It involved a chemical O-sulfation of hetyrosines not affecting the acid- and base-sensitive structure.[71] These investigations took advantage from a fruitful interdisciplinary cooperation with the groups of Professor D. Vestweber, University of Muenster, and Dr. G. Kretzschmar, former Hauptlaboratorium of the Hoechst AG.

Glycopeptide anti-tumor vaccines – partial structures of tumor-associated glycoproteins

Stimulated by reports on typical differences of the glycosylation pattern of endothelial membrane glycoproteins, in particular of the mucin MUC1, between normal human endothelial tissues and tumor tissues, syntheses of tumor-associated glycopeptide antigen structures were developed aiming at active immunization of patients against tumor cells. For this objective, the tumor-selective structures must be prepared with strict precision, otherwise an autoimmune reaction may be induced. Synthetic glycopeptide antigens of tumor-associated MUC1 meet these demands. They were constructed through solid-phase synthesis on allylic anchors (**58**) or on resins equipped with acid-sensitive linkers (**59**, **60**). Because these glycopeptide antigens are endogenous structures, they exhibit only low immunogenicity. In order to elicit a sufficiently strong immune response, for example in mice, they need to be combined with T-cell activating components. In the early case of **58** the MUC1 glycopeptide (upper part) was conjugated to a T-cell epitope from ovalbumin. Thus, the fully synthetic vaccine **58** induced a very strong and specific IgG immune reaction. The induced antibodies neither recognized the peptide part alone nor the isolated sialyl-Tn glycosyl threonine.[72] In the second example, the anti-tumor vaccine **59** was obtained by coupling the MUC1 glycopeptide antigen to Tetanus Toxoid (TTox).[72-73] Very strong, specific immune responses were induced using **59**. The induced serum specifically bonds to tumor cells, not to normal cells In mammalian tumor tissues.[74] A monoclonal antibody GGSK-1/30 obtained from this immunization specifically recognized tumor cells in pancreatic tumors.[75]

The vaccine **59** induced strong immune responses in trans-genic mice expressing the human MUC1.[76] Prophylactic immunization of tumor- transfected mice with **59** resulted in a markedly reduced tumor growth and prolonged life time.[77] The MUC1 glycopeptide TTox vaccine **60** containing two tumor-associated saccharide side chains, represents a further promising candidate in this series.[78]

The work in this area was augmented by cooperation with the group of Professor E. Schmitt, Immunology, University of Mainz, and by international collaboration with the groups of Prof. Yan-Mei Li, Tsinghua University, Beijing, China,[79] and Prof. Ulrika Westerlind, now at the University of Umea, Sweden.[80] Of course, the scientific spirit of the chemistry and biomedical chemistry students at the University of Mainz is the major source of the results presented in this tribute.



Scheme 19. Synthetic glycopeptide anti-tumor vaccines.

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