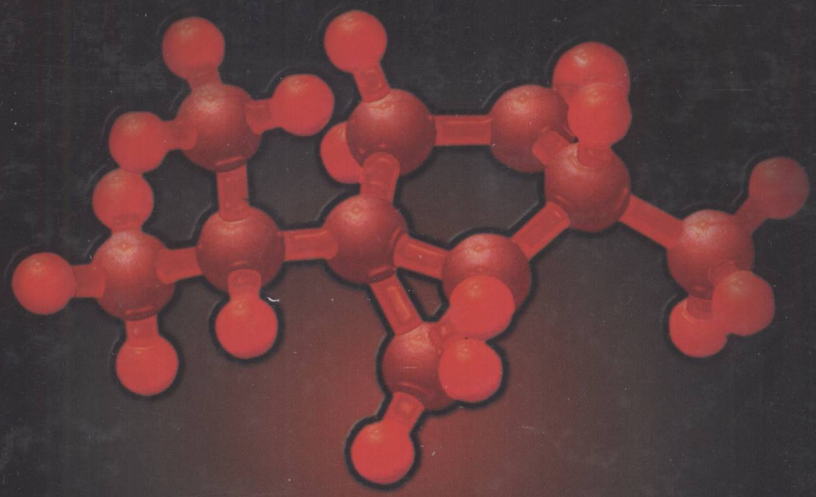
WILEY



Handbook of Reagents for Organic Synthesis

Reagents for Glycoside, Nucleotide, and Peptide Synthesis

Edited by
David Crich

To see the complete collection of organic reagents online visit:
www.mrw.interscience.wiley.com/eros/

Handbook of Reagents for Organic Synthesis

Reagents for Glycoside, Nucleotide, and Peptide Synthesis

Edited by

David Crich

University of Illinois at Chicago, Chicago, IL, USA

WILEY

The Atrium, Southern Gate,
Chichester, West Sussex
PO19 8SQ, England

Telephone (+44) 1243 779777

E-mail (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wileyeurope.com or www.wiley.com

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street,
Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street,
San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12,
D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street,
Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01,
Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 5353 Dundas Street West, Suite 400
Etobicoke, Ontario, Canada M9B 6HB

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Handbook of reagents for organic synthesis.
p. cm.
Includes bibliographical references.
Contents: [1] Reagents, auxiliaries, and catalysts for C–C bond formation/edited by Robert M. Coates and Scott E. Denmark [2] Oxidising and reducing agents/edited by Steven D. Burke and Riek L. Danheiser [3] Acidic and basic reagents/edited by Hans J. Reich and James H. Rigby [4] Activating agents and protecting groups/edited by Anthony J. Pearson and William R. Roush [5] Chiral Reagents for Asymmetric Synthesis/edited by Leo A. Paquette
ISBN 0-471-97924-4 (v. 1) ISBN 0-471-97926-0 (v. 2)
ISBN 0-471-97925-2 (v. 3) ISBN 0-471-97927-9 (v. 4)
ISBN 0-470-85625-4 (v. 5) ISBN 0-470-86298-X (v. 6)
ISBN 0-470-02304-X (v. 7)
1. Chemical tests and reagents. 2. Organic compounds–Synthesis.
QD77.H37 1999
547′.2 dc 21 98-53088
CIP

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN 10: 0-470-02304-X (Hb)
ISBN 13: 978-0470-02304-4
Typeset in 9½/11½ pt Times Roman by Thomson Press (India) Ltd., New Delhi.
Printed and bound in Great Britain by Antony Rowe, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

General Abbreviations

Ac	acetyl
acac	acetylacetonate
AIBN	2,2′-azobisisobutyronitrile
Ar	aryl
BBN	borabicyclo[3.3.1]nonane
BCME	dis(chloromethyl)ether
BHT	butylated hydroxytoluene (2,6-di-*t*-butyl-*p*-cresol)
BINAL-H	2,2′-dihydroxy-1,1′-binaphthyl-lithium aluminum hydride
BINAP	2,2′-bis(diphenylphosphino)-1,1′-binaphthyl
BINOL	1,1′-bi-2,2′-naphthol
bipy	2,2′-bipyridyl
BMS	borane–dimethyl sulfide
Bn	benzyl
Boc	*t*-butoxycarbonyl
BOM	benzyloxymethyl
bp	boiling point
Bs	brosyl (4-bromobenzenesulfonyl)
BSA	*N,O*-bis(trimethylsilyl)acetamide
Bu	*n*-butyl
Bz	benzoyl
CAN	cerium(IV) ammonium nitrate
Cbz	benzyloxycarbonyl
CDI	*N,N′*-carbonyldiimidazole
CHIRAPHOS	2,3-bis(diphenylphosphino)butane
Chx	= Cy
cod	cyclooctadiene
cot	cyclooctatetraene
Cp	cyclopentadienyl
CRA	complex reducing agent
CSA	10-camphorsulfonic acid
CSI	chlorosulfonyl isocyanate
Cy	cyclohexyl
d	density
DABCO	1,4-diazabicyclo[2.2.2]octane
DAST	*N,N′*-diethylaminosulfur trifluoride
dba	dibenzylideneacetone
DBAD	di-*t*-butyl azodicarboxylate
DBN	1,5-diazabicyclo[4.3.0]non-5-ene
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DCC	*N,N′*-dicyclohexylcarbodiimide
DCME	dichloromethyl methyl ether
DDO	dimethyldioxirane
DDQ	2,3-dichloro-5,6-dicyano-1,4-benzoquinone
de	diastereomeric excess
DEAD	diethyl azodicarboxylate
DET	diethyl tartrate
DIBAL	diisobutylaluminum hydride
DIEA	= DIPEA
DIOP	2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis-(diphenylphosphino)butane
DIPEA	diisopropylethylamine
diphos	=dppe
DIPT	diisopropyl tartrate
DMA	dimethylacetamide
DMAD	dimethyl acetylenedicarboxylate
DMAP	4-(dimethylamino)pyridine
DME	1,2-dimethoxyethane
DMF	dimethylformamide
dmg	dimethylglyoximato
DMPU	*N,N′*-dimethylpropyleneurea
DMS	dimethyl sulfide
DMSO	dimethyl sulfoxide
DMTSF	dimethyl(methylthio) sulfonium tetrafluoroborate
dppb	1,4-bis(diphenylphosphino)butane
dppe	1,2-bis(diphenylphosphino)ethane
dppf	1,1′-bis(diphenylphosphino)ferrocene
dppp	1,3-bis(diphenylphosphino)propane
DTBP	di-*t*-butyl peroxide
EDA	ethyl diazoacetate
EDC	1-ethyl-3-(3-dimethylaminopropyl)-carbodiimide
EDCI	= EDC
ee	enantiomeric excess
EE	1-ethoxyethyl
Et	ethyl
ETSA	ethyl trimethylsilylacetate
EWG	electron withdrawing group
Fc	ferrocenyl
Fmoc	9-fluorenylmethoxycarbonyl
fp	flash point
Hex	*n*-hexyl
HMDS	hexamethyldisilazane
HMPA	hexamethylphosphoric triamide
HOBt	l-hydroxybenzotriazole
HOBT	=HOBt
HOSu	*N*-hydroxysuccinimide
Im	imidazole (imidazolyl)
Ipc	isopinocampheyl
IR	infrared
KHDMS	potassium hexamethyldisilazide
LAH	lithium aluminum hydride
LD_{50}	dose that is lethal to 50% of test subjects

LDA	lithium diisopropylamide
LDMAN	lithium 1-(dimethylamino)naphthalenide
LHMDS	= LiHMDS
LICA	lithium isopropylcyclohexylamide
LiHMDS	lithium hexamethyldisilazide
LiTMP	lithium 2,2,6,6-tetramethylpiperidide
LTMP	= LiTMP
LTA	lead tetraacetate
lut	lutidine
m-CPBA	*m*-chloroperbenzoic acid
MA	maleic anhydride
MAD	methylaluminum bis(2,6-di-*t*-butyl-4-methylphenoxide)
MAT	methylaluminum bis(2,4,6-tri-*t*-butylphenoxide)
Me	methyl
MEK	methyl ethyl ketone
MEM	(2-methoxyethoxy)methyl
MIC	methyl isocyanate
MMPP	magnesium monoperoxyphthalate
MOM	methoxymethyl
MoOPH	oxodiperoxomolybdenum(pyridine)-(hexamethylphosphoric triamide)
mp	melting point
MPM	= PMB
Ms	mesyl (methanesulfonyl)
MS	mass spectrometry; molecular sieves
MTBE	methyl *t*-butyl ether
MTM	methylthiomethyl
MVK	methyl vinyl ketone
n	refractive index
NaHDMS	sodium hexamethyldisilazide
Naph	naphthyl
NBA	*N*-bromoacetamide
nbd	norbornadiene (bicyclo[2.2.1]hepta-2,5-diene)
NBS	*N*-bromosuccinimide
NCS	*N*-chlorosuccinimide
NIS	*N*-iodosuccinimide
NMO	*N*-methylmorpholine *N*-oxide
NMP	*N*-methyl-2-pyrrolidinone
NMR	nuclear magnetic resonance
NORPHOS	bis(diphenylphosphino)bicyclo[2.2.1]-hept-5-ene
Np	= Naph
PCC	pyridinium chlorochromate
PDC	pyridinium dichromate
Pent	*n*-pentyl
Ph	phenyl
phen	1,10-phenanthroline
Phth	phthaloyl
Piv	pivaloyl
PMB	*p*-methoxybenzyl
PMDTA	*N,N,N′,N″,N″*-pentamethyldiethylene-triamine
PPA	polyphosphoric acid
PPE	polyphosphate ester
PPTS	pyridinium *p*-toluenesulfonate
Pr	*n*-propyl
PTC	phase transfer catalyst/catalysis
PTSA	*p*-toluenesulfonic acid
py	pyridine
RAMP	(R)-1-amino-2-(methoxymethyl)pyrrolidine
rt	room temperature
salen	bis(salicylidene)ethylenediamine
SAMP	(*S*)-1-amino-2-(methoxymethyl)pyrrolidine
SET	single electron transfer
Sia	siamyl (3-methyl-2-butyl)
TASF	tris(diethylamino)sulfonium difluorotrimethylsilicate
TBAB	tetrabutylammonium bromide
TBAF	tetrabutylammonium fluoride
TBAD	= DBAD
TBAI	tetrabutylammonium iodide
TBAP	tetrabutylammonium perruthenate
TBDMS	*t*-butyldimethylsilyl
TBDPS	*t*-butyldiphenylsilyl
TBHP	*t*-butyl hydroperoxide
TBS	= TBDMS
TCNE	tetracyanoethylene
TCNQ	7,7,8,8-tetracyanoquinodimethane
TEA	triethylamine
TEBA	triethylbenzylammonium chloride
TEBAC	= TEBA
TEMPO	2,2,6,6-tetramethylpiperidinoxyl
TES	triethylsilyl
Tf	triflyl (trifluoromethanesulfonyl)
TFA	trifluoroacetic acid
TFAA	trifluoroacetic anhydride
THF	tetrahydrofuran
THP	tetrahydropyran; tetrahydropyranyl
Thx	thexyl (2,3-dimethyl-2-butyl)
TIPS	triisopropylsilyl
TMANO	trimethylamine *N*-oxide
TMEDA	*N,N,N′,N′*-tetramethylethylenediamine
TMG	1,1,3,3-tetramethylguanidine
TMS	trimethylsilyl
Tol	*p*-tolyl
TPAP	tetrapropylammonium perruthenate
TBHP	*t*-butyl hydroperoxide
TPP	tetraphenylporphyrin
Tr	trityl (triphenylmethyl)
Ts	tosyl (*p*-toluenesulfonyl)
TTN	thallium(III) nitrate
UHP	urea–hydrogen peroxide complex
Z	= Cbz

Handbook of Reagents
for Organic Synthesis

Reagents for Glycoside, Nucleotide, and Peptide Synthesis

OTHER TITLES IN THIS COLLECTION

Reagents for High-Throughput Solid-Phase and Solution-Phase Organic Synthesis
Edited by Peter Wipf
ISBN 0 470 86298 X

Chiral Reagents for Asymmetric Synthesis
Edited by Leo A. Paquette
ISBN 0 470 85625 4

Oxidizing and Reducing Agents
Edited by Steven D. Burke and Rick L. Danheiser
ISBN 0 471 97926 0

Acidic and Basic Reagents
Edited by Hans J. Reich and James H. Rigby
ISBN 0 471 97925 2

Activating Agents and Protecting Groups
Edited by Anthony J. Pearson and William R. Roush
ISBN 0 471 97927 9

Reagents, Auxiliaries, and Catalysts for C-C Bond Formation
Edited by Robert M. Coates and Scott E. Denmark
ISBN 0 471 97924 4

e-EROS Editorial Board

Preface

As stated in its Preface, the major motivation for our undertaking publication of the *Encyclopedia of Reagents for Organic Synthesis* was "to incorporate into a single work a genuinely authoritative and systematic description of the utility of all reagents used in organic chemistry." By all accounts, this reference compendium succeeded admirably in approaching this objective. Experts from around the globe contributed many relevant facts that define the various uses characteristic of each reagent. The choice of a masthead format for providing relevant information about each entry, the highlighting of key transformations with illustrative equations, and the incorporation of detailed indexes serve in tandem to facilitate the retrieval of desired information.

Notwithstanding these accomplishments, the editors came to recognize that the large size of this eight-volume work and its cost of purchase often deterred the placement of copies of the *Encyclopedia* in or near laboratories where the need for this type of information is most critical. In an effort to meet this demand in a cost-effective manner, the decision was made to cull from the major work that information having the highest probability for repeated consultation and to incorporate the same into a set of handbooks. The latter would also be purchasable on a single unit basis.

The ultimate result of these deliberations was the publication of the *Handbook of Reagents for Organic Synthesis*, the first four volumes of which appeared in 1999:

Oxidizing and Reducing Agents
Edited by Steven D. Burke and Rick L. Danheiser

Acidic and Basic Reagents
Edited by Hans J. Reich and James H. Rigby

Activating Agents and Protecting Groups
Edited by Anthony J. Pearson and William R. Roush

Reagents, Auxiliaries, and Catalysts for C-C Bond Formation
Edited by Robert M. Coates and Scott E. Denmark

Since then, the fifth and sixth members of this series have made their appearance in 2003 and 2005, respectively:

Chiral Reagents for Asymmetric Synthesis
Edited by Leo A. Paquette

Reagents for High-Throughput Solid-Phase and Solution-Phase Organic Synthesis
Edited by Peter Wipf

Each of the volumes contains a selected compilation of those entries from the original *Encyclopedia* that bear on the specific topic. The coverage of the last two handbooks also extends to the electronic sequel *e-EROS*. Ample listings can be found to functionally related reagents contained in the original work. For the sake of current awareness, references to recent reviews and monographs have been included, as have relevant new procedures from *Organic Syntheses*.

The present volume, entitled *Reagents for Glycoside, Nucleotide, and Peptide Synthesis*, constitutes the seventh entry in this continuing series of utilitarian reference works. As with its predecessors, this handbook is intended to be an affordable, enlightening compilation that will hopefully find its way into the laboratories of all practicing synthetic chemists. Every attempt has been made to be of the broadest possible relevance and the expectation is that our colleagues will share in this opinion.

Leo A. Paquette
Department of Chemistry
The Ohio State University
Columbus, OH, USA

Introduction

With the advent of Chemical Biology, mainstream organic and medicinal chemists are increasingly aware of the need for, and are turning their attention to, the synthesis of bioconjugates. These might take the form of more classical peptides, nucleotides, or oligosaccharides, or some hybrid thereof, and may be required in straightforward soluble forms or appended to soluble or insoluble polymeric supports, nanoparticles, dendrimers, gold or silicon surfaces, or microtiter plates. Whatever the system or eventual use, the need for the efficient synthesis of glycoside, nucleotide, or peptide bonds has never been greater. The synthesis of each of these three main classes of biopolymers has evolved into a fine and sophisticated art in recent years with many reagents available to the experienced practitioner. The aim of this handbook is to collect the more important of these reagents together into a convenient, single volume and so aid the non-specialist in locating information and in making an informed choice when the need for the synthesis of a glycoside, nucleotide, or peptide bond arises. This handbook focuses on the chemical reagents required for glycoside, nucleotide, and peptide bond: information on polymeric supports and a broader selection of supported reagents, obviously very important considerations in this area, can be found in the recent *Handbook of Reagents for High-Throughput Solid-Phase and Solution-Phase Organic Synthesis* edited by Professor Peter Wipf.

Of the reagents featured in this volume, approximately one third are taken from the *Encyclopedia of Reagents for Organic Synthesis* (*EROS*), published in 1995. Many of these are classical reagents in the field whose principal use has not changed in the intervening period. The remainder, and indeed the bulk, of the entries are comprised either of completely new articles, or of updated versions of original *EROS* articles taking into account recent developments, written by experts in the field for the continually-expanding online encyclopedia (*e-EROS*). The volume opens with a selection of recent monographs and review articles intended to help the reader in searching the literature. This list is divided into three sections: Glycoside, Nucleotide, and Peptide Bond Formation. The main sequence of reagents in this volume is alphabetical in keeping with the *EROS* and *e-EROS* format.

Finally, it is hoped that this volume will be a useful and convenient handbook for any researcher involved in the synthesis of bioconjugates, perhaps even helping to identify present shortcomings in the field and, so, spur the design and development of even more and better reagents for the same.

David Crich
Department of Chemistry
University of Illinois at Chicago
Chicago, IL, USA

Contents

Recent Review Articles and Monographs

Glycoside Bond Formation

Lockhoff, O. Acetals at the Anomeric Cemter of Carbohydrates, In *Houben-Weyl. Methods of Organic Chemistry*, 4th ed.; Hagemann, H.; Klamann, D., Eds.; Georg Thieme Verlag: Stuttgart, 1992; Vol. E14a/3, pp 621–1077.

Ogura, H.; Hasegawa, A.; Suami, T., Eds., *Carbohydrates*; Kondansha: Tokyo, 1992

van Boeckel, C. A. A. Protective Group Strategies in the Synthesis of Functionalized Carbohydrates, In *Modern Synthetic Methods*; Scheffold, R., Ed.; Verlag Helvetica Chimica Acta: Basel, 1992; Vol. 6, pp 439–481.

Toshima, K.; Tatsuta, K. Recent Progress in O-Glycosylation Methods and Its Application to Natural Products Synthesis, *Chem. Rev.* **1993**, *93*, 1503–1531.

Barresi, F.; Hindsgaul, O. Chemically Synthesized Oligosaccharides, 1994. A Searchable Table of Glycosidic Linkages, *J. Carbohydr. Chem.* **1995**, *14*, 1043–1087.

Bols, M. *Carbohydrate Building Blocks*; Wiley: New York, 1995.

Collins, P. M.; Ferrier, R. J. *Monosaccharides: Their Chemistry and Their Roles in Natural Products*; Wiley: Chichester, 1995.

Levy, D. E.; Tang, C. *The Chemistry of C-Glycosides*; Pergamon: Oxford, 1995.

Montreuil, J.; Vliegenthart, J. F. G.; Schachter, H., Eds., *Glycoproteins*; Elsevier: Amsterdam, 1995

Paulsen, H. Progress in Oligosaccharide Synthesis through a New Orthogonal Glycosylation Strategy, *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1432–1434.

Postema, M. H. D., Ed. *C-Glycoside Synthesis*; CRC: Boca Raton, 1995

Wilson, L. J.; Hager, M. W.; Elkattan, Y. A.; Liotta, D. C. Nitrogen Glycosylation Reactions Involving Pyrimidine and Purine Nucleoside Bases with Furanoside Sugars, *Synthesis* **1995**, 1465–1479.

Boons, G. J. Strategies in Oligosaccharide Synthesis, *Tetrahedron* **1996**, *52*, 1095–1121.

Danishefsky, S. J.; Bilodeau, M. T. Glycals in Organic Synthesis: The Evolution of Comprehensive Strategies for the Assembly of Oligosaccharides and Glycoconjugates of Biological Consequence, *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1380–1419.

Gijsen, H. J. M.; Qiao, L.; Fitz, W.; Wong, C. H. Recent Advances in the Chemoenzymatic Synthesis of Carbohydrates and Carbohydrate Mimetics, *Chem. Rev.* **1996**, *96*, 443–473.

Khan, S. H.; O'Neill, R. A., Eds., *Modern Methods in Carbohydrate Synthesis*; Harwood: Amsterdam, 1996

Schelhaas, M.; Waldmann, H. Protecting Group Strategies in Organic Synthesis, *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2056–2083.

Arya, P.; Ben, R. N. Combinatorial Chemistry for the Synthesis of Carbohydrate Libraries, *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1280–1282.

Beau, J.-M.; Gallagher, T. Nucleophilic C-Glycosyl Donors for C-Glycoside Synthesis, *Top. Curr. Chem.* **1997**, *187*, 1–54.

David, S. *Molecular and Supramolecular Chemistry of Carbohydrates: Chemical Introduction to the Glyco-Sciences*; Oxford University Press: Oxford, 1997.

Fernandez Mayoralas, A. Synthesis and Modification of Carbohydrates Using Glycosidases and Lipases, *Top. Curr. Chem.* **1997**, *186*, 1–20.

Gambert, U.; Thiem, J. Chemical Transformations Employing Glycosyl Transferases, *Top. Curr. Chem.* **1997**, *186*, 21–43.

Garegg, P. J. Thioglycosides as Glycosyl Donors in Oligosaccharide Synthesis, *Adv. Carbohydr. Chem. Biochem.* **1997**, *52*, 179–205.

Guibé, F. Allylic Protecting Groups and Their Use in a Complex Environment.1. Allylic Protection of Alcohols, *Tetrahedron* **1997**, *53*, 13509–13556.

Hanessian, S., Ed. *Preparative Carbohydrate Chemistry*; Dekker: New York, 1997

Imperiali, B. Protein Glycosylation: The Clash of the Titans, *Acc. Chem. Res.* **1997**, *30*, 452–459.

Kirschning, A.; Bechthold, A. F. W.; Rohr, J. Chemical and Biochemical Aspects of Deoxysugars and Deoxysugar Oligosaccharides, *Top. Curr. Chem.* **1997**, *188*, 1–84.

Kren, V. Enzymatic and Chemical Glycosylations of Ergot Alkaloids and Biological Aspects of New Compounds, *Top. Curr. Chem.* **1997**, *186*, 45–64.

Kren, V.; Thiem, J. Glycosylation Employing Bio-Systems: From Enzymes to Whole Cells, *Chem. Soc. Rev.* **1997**, *26*, 463–473.

McGarvey, G. J.; Wong, C. H. Chemical, Enzymatic and Structural Studies in Molecular Glycobiology, *Liebigs Ann. Chem.* **1997**, 1059–1074.

Montreuil, J.; Vliegenthart, J. F. G.; Schachter, H., Eds., *Glycoproteins II*; Elsevier: Amsterdam, 1997

Nicotra, F. Synthesis of C-Glycosides of Biological Interest, *Top. Curr. Chem.* **1997**, *1987*, 55–83.

Ziegler, T. Pyruvated Saccharides - Novel Strategies for Oligosaccharide Synthesis, *Top. Curr. Chem.* **1997**, *186*, 203–229.

Boons, G. J., Ed. *Carbohydrate Chemistry*; Blackie Academic & Professional: Glasgow, 1998

Chapleur, Y., Ed. *Carbohydrate Mimics*; Wiley-VCH: Weinheim, 1998

Grindley, T. B. Applications of Tin-Containing Intermediates to Carbohydrate Chemistry, *Adv. Carbohydr. Chem. Biochem.* **1998**, *53*, 17–142.

Guibé, F. Allylic Protecting Groups and Their Use in a Complex Environment. Part 2: Allylic Protecting Groups and Their Removal through Catalytic π-Allyl Methodology, *Tetrahedron* **1998**, *54*, 2967–3042.

Kirschning, A. Hypervalent Iodine and Carbohydrates - a New Liaison, *Eur. J. Org. Chem.* **1998**, 2267–2274.

Lehmann, J. *Carbohydrates: Structure and Biology*; Thieme: Stuttgart, 1998.

Seeberger, P. H.; Danishefsky, S. J. Solid-Phase Synthesis of Oligosaccharides and Glycoconjugates by the Glycal Assembly Method: A Five Year Retrospective, *Acc. Chem. Res.* **1998**, *31*, 685–695.

Seitz, O. New Protecting Group Strategies for the Solid-Phase Synthesis and Modification of Peptides, Oligonucleotides, and Oligosaccharides, *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 3109–3111.

Taylor, C. M. Glycopeptides and Glycoproteins: Focus on the Glycosidic Linkage, *Tetrahedron* **1998**, *54*, 11317–11362.

Arsequell, G.; Valencia, G. Recent Advances in the Synthesis of Complex N-Glycopeptides, *Tetrahedron: Asymmetry* **1999**, *10*, 3045–3094.

Davis, B. G. Recent Developments in Glycoconjugates, *J. Chem. Soc., Perkin Trans. 1* **1999**, 3215–3237.

Finch, P., Ed. *Carbohydrates, Structures, Syntheses and Dynamics*; Kluwer: Dordrecht, Netherlands, 1999

Hecht, S. M., Ed. *Bioorganic Chemistry: Carbohydrates*; Oxford University Press: New York, 1999

Imperiali, B.; O'Connor, S. E.; Hendrickson, T.; Kellenberger, C. Chemistry and Biology of Asparagine-Linked Glycosylation, *Pure Appl. Chem.* **1999**, *71*, 777–787.

Ohrlein, R. Glycosyl Transferase-Catalyzed Synthesis of Non-Natural Oligosaccharides, *Top. Curr. Chem.* **1999**, *200*, 227–254.

Boons, G.-J.; Demchenko, A. V. Recent Advances in O-Sialylation, *Chem. Rev.* **2000**, *100*, 4539–4565.

Danishefsky, S. J.; Allen, J. R. From the Laboratory to the Clinic: A Retrospective on Fully Synthetic Carbohydrate-Based Anticancer Vaccines, *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 837–863.

Davis, B. G. Recent Developments in Oligosaccharide Synthesis, *J. Chem. Soc., Perkin Trans. 1* **2000**, 2137–2160.

Dondoni, A.; Marra, A. Methods for Anomeric Carbon-Linked and Fused Sugar Amino Acid Synthesis: The Gateway to Artificial Glycopeptides, *Chem. Rev.* **2000**, *100*, 4395–4422.

Ernst, B.; Hart, G. W.; Sinaÿ, P., Eds., *Carbohydrates in Chemistry and Biology*; Wiley-VCH: Weinheim, 2000

Fernandez, J. M. G.; Mellet, C. O. Chemistry and Developments of N-Thiocarbonyl Carbohydrate Derivatives: Sugar Isothiocyanates, Thioamides, Thioureas, Thiocarbamates, and Their Conjugates, *Adv. Carbohydr. Chem. Biochem.* **2000**, *55*, 35–135.

Gridley, J. J.; Osborn, H. M. I. Recent Advances in the Construction of β-D-Mannose and β-D-Mannosamine Linkages, *J. Chem. Soc., Perkin Trans. 1* **2000**, 1471–1491.

Haase, W. C.; Seeberger, P. H. Recent Progress in Polymer-Supported Synthesis of Oligosaccharides and Carbohydrate Libraries, *Curr. Org. Chem.* **2000**, *4*, 481–511.

Herzner, H.; Reipen, T.; Schultz, M.; Kunz, H. Synthesis of Glycopeptides Containing Carbohydrate and Peptide Recognition Motifs, *Chem. Rev.* **2000**, *100*, 4495–4537.

Jung, K.-H.; Müller, M.; Schmidt, R. R. Intramolecular O-Glycoside Bond Formation, *Chem. Rev.* **2000**, *100*, 4423–4442.

Kartha, K. P. R.; Aloui, M.; Cura, P.; Marsh, S. J.; Field, R. A. Iodine, A Versatile Reagent in Carbohydrate Chemistry: Activation of Thioglycosides and Glycosyl Sulfoxides, In *Advances in Sulfur Chemistry*; Rayner, C. M., Ed.; Jai Press: Stamford, 2000; Vol. 2, pp 37–56.

Kochetkov, N. K. Solid-Phase Synthesis of Oligosaccharides and Glycoconjugates, *Russ. Chem. Rev. (Engl. Transl.)* **2000**, *69*, 795–820.

Koeller, K. M.; Wong, C. H. Synthesis of Complex Carbohydrates and Glycoconjugates: Enzyme-Based and Programmable One-Pot Strategies, *Chem. Rev.* **2000**, *100*, 4465–4493.

Kuberan, B.; Lindhardt, R. J. Carbohydrate Based Vaccines, *Curr. Org. Chem.* **2000**, *4*, 653–677.

Marzabadi, C. H.; Franck, R. W. The Synthesis of 2-Deoxyglycosides: 1988–1999, *Tetrahedron* **2000**, *56*, 8385–8417.

Seeberger, P. H.; Haase, W. C. Solid-Phase Oligosaccharide Synthesis and Combinatorial Carbohydrate Libraries, *Chem. Rev.* **2000**, *100*, 4349–4393.

St Hilaire, P. M.; Meldal, M. Glycopeptide and Oligosaccharide Libraries, *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 1163–1179.

Toshima, K. Glycosyl Fluorides in Glycosidations, *Carbohydr. Res.* **2000**, *327*, 15–26.

Vankar, Y. D.; Schmidt, R. R. Chemistry of Glycosphingolipids-Carbohydrate Molecules of Biological Significance, *Chem. Soc. Rev.* **2000**, *29*, 201–216.

Williams, S. J.; Withers, S. G. Glycosyl Fluorides in Enzymatic Reactions, *Carbohydr. Res.* **2000**, *327*, 27–46.

Barkley, A.; Arya, P. Combinatorial Chemistry toward Understanding the Function(s) of Carbohydrates and Carbohydrate Conjugates, *Chem. Eur. J.* **2001**, *7*, 555–563.

Bertozzi, C. R.; Kiessling, L. L. Chemical Glycobiology, *Science* **2001**, *291*, 2357–2364.

Fraser-Reid, F.; Kuniaki, T.; Thiem, J., Eds., *Glycoscience: Chemistry and Chemical Biology*; Springer-Verlag: Berlin, 2001

Hang, H. C.; Bertozzi, C. R. Chemoselective Approaches to Glycoprotein Assembly, *Acc. Chem. Res.* **2001**, *34*, 727–736.

Nicolaou, K. C.; Mitchell, H. J. Adventures in Carbohydrate Chemistry: New Synthetic Technologies, Chemical Synthesis, Molecular Design, and Chemical Biology, *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 1576–1624.

Ritter, T. K.; Wong, C. H. Carbohydrate-Based Antibiotics: A New Approach to Tackling the Problem of Resistance, *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 3509–3533.

Seeberger, P. H., Ed. *Solid Support Oligosaccharide Synthesis and Combinatorial Carbohydrate Libraries*; Wiley: New York, 2001

Stick, R. V. *Carbohydrates: The Sweet Molecules of Life*; Academic Press: San Diego, 2001.

Thorson, J. S.; Hosted, T. J.; Jiang, J. Q.; Biggins, J. B.; Ahlert, J. Nature's Carbohydrate Chemists: The Enzymatic Glycosylation of Bioactive Bacterial Metabolites, *Curr. Org. Chem.* **2001**, *5*, 139–167.

Vaino, A. R.; Szarek, W. A. Iodine in Carbohydrate Chemistry, *Adv. Carbohydr. Chem. Biochem.* **2001**, *56*, 9–63.

Wang, P.; Bertozzi, C. R., Eds., *Glycochemistry: Principles, Synthesis, and Applications*; Dekker: New York, 2001

Zhang, J. B.; Wu, B. Y.; Liu, Z. Y.; Kowal, P.; Chen, X.; Shao, J.; Wang, P. G. Large-Scale Synthesis of Carbohydrates for Pharmaceutical Development, *Curr. Org. Chem.* **2001**, *5*, 1169–1176.

Angata, T.; Varki, A. Chemical Diversity in the Sialic Acids and Related α-Keto Acids: An Evolutionary Perspective, *Chem. Rev.* **2002**, *102*, 439–469.

Bogusiak, J. Synthesis of Glycofuranosides, *Pol. J. Chem.* **2002**, *76*, 1–12.

Crich, D. Chemistry of Glycosyl Triflates: Synthesis of β-Mannopyranosides, *J. Carbohydr. Chem.* **2002**, *21*, 667–690.

Davis, B. G. Synthesis of Glycoproteins, *Chem. Rev.* **2002**, *102*, 579–601.

Gin, D. Dehydrative Glycosylation with 1-Hydroxy Donors, *J. Carbohydr. Chem.* **2002**, *21*, 645–665.

Halcomb, R. L.; Chappell, M. D. Recent Developments in Technology for Glycosylation with Sialic Acid, *J. Carbohydr. Chem.* **2002**, *21*, 723–768.

Jensen, K. J. O-Glycosylations under Neutral or Basic Conditions, *J. Chem. Soc., Perkin Trans. 1* **2002**, 2219–2233.

Klefel, M. J.; von Itzstein, M. Recent Advances in the Synthesis of Sialic Acid Derivatives and Sialyl Mimetics as Biological Probes, *Chem. Rev.* **2002**, *102*, 471–490.

Lowary, T. L. D-Arabinofuranosides from Mycobacteria: Synthesis and Conformation, *J. Carbohydrate Chem.* **2002**, *21*, 691–722.

Palmacci, E. R.; Plante, O. J.; Seeberger, P. H. Oligosaccharide Synthesis in Solution and on Solid Support with Glycosyl Phosphates, *Eur. J. Org. Chem.* **2002**, 595–606.

Ritchie, G. E.; Moffatt, B. E.; Sim, R. B.; Morgan, B. P.; Dwek, R. A.; Rudd, P. M. Glycosylation and the Complement System, *Chem. Rev.* **2002**, *102*, 305–319.

Vankayalapati, H.; Jiang, S. D.; Singh, G. Glycosylation Based on Glycosyl Phosphates as Glycosyl Donors, *Synlett* **2002**, 16–25.

Wong, C.-H., Ed. *Carbohydrate-Based Drug Discovery*; Wiley-VCH: Weinheim, 2002

Demchenko, A. V. 1,2-Cis-O-Glycosylation: Methods, Strategies, Principles, *Curr. Org. Chem.* **2003**, *7*, 35–79.

Demchenko, A. V. Stereoselective Chemical 1,2-Cis-O-Glycosylation: From "Sugar Ray" to Modern Techniques of the 21st Century, *Synlett* **2003**, 1225–1240.

Ferrier, R. J.; Hoberg, J. O. Synthesis and Reactions of Unsaturated Sugars, *Adv. Carbohydr. Chem. Biochem.* **2003**, *58*, 55–119.

Ferrier, R. J.; Zubkov, O. A. Transformation of Glycals into 2,3-Unsaturated Glycosyl Derivatives, *Org. React.* **2003**, *62*, 569–736.

Lindhorst, T. K. *Essentials of Carbohydrate Chemistry and Biochemistry*; Wiley-VCH: Weinheim, 2003.

Osborn, H. M. I.; Harwood, L. M. *Best Synthetic Methods: Carbohydrates*; Academic Press: San Diego, CA, 2003.

Plante, O. J.; Palmacci, E. R.; Seeberger, P. H. Development of an Automated Oligosaccharide Synthesizer, *Adv. Carbohydr. Chem. Biochem.* **2003**, *58*, 35–54.

Seeberger, P. H. Automated Carbohydrate Synthesis to Drive Chemical Glycomics, *J. Chem. Soc., Chem. Commun.* **2003**, 1115–1121.

Shoda, S.-I.; Izumi, R.; Fujita, M. Green Process in Glycotechnology, *Bull. Chem. Soc. Jpn.* **2003**, *76*, 1–13.

Virta, P.; Katajisto, J.; Niittymaki, T.; Lonnberg, H. Solid-Supported Synthesis of Oligomeric Bioconjugates, *Tetrahedron* **2003**, *59*, 5137–5174.

Corsaro, A.; Chiacchio, U.; Pistara, V.; Romeo, G. Microwave-Assisted Chemistry of Carbohydrates, *Curr. Org. Chem.* **2004**, *8*, 511–538.

Crich, D.; Lim, L. B. L. Glycosylation with Sulfoxides and Sulfinates as Donors or Promoters, *Org. React.* **2004**, *64*, 115–251.

Das, S. K. Application of Microwave Irradition in the Synthesis of Carbohydrates, *Synlett* **2004**, 915–932.

Fraser-Reid, B.; López, J. C.; Gómez, A. M.; Uriel, C. Reciprocal Donor Acceptor Selectivity (RDAS) and Paulsen's Concept of "Match" in Saccharide Coupling, *Eur. J. Org. Chem.* **2004**, 1387–1395.

Pellissier, H. The Glycosylation of Steroids, *Tetrahedron* **2004**, *60*, 5123–5162.

Peri, F.; Nicotra, F. Chemoselective Ligation in Glycochemistry, *Chem Comm* **2004**, 623–627.

Petitou, M.; van Boeckel, C. A. A. A Synthetic Antithrombin III Binding Pentasaccharide Is Now a Drug! What Comes Next?, *Angew. Chem. Int. Ed. Engl.* **2004**, *43*, 3118–3133.

Taillefumier, C.; Chapleur, Y. Synthesis and Uses of Exo-Glycals, *Chem. Rev.* **2004**, *104*, 263–292.

Yu, B.; Yang, Z.; Cao, H. One-Pot Glycosylation (OPG) for the Chemical Synthesis of Oligosaccharides, *Curr. Org. Chem.* **2005**, *9*, 179–194.

Nucleotide Bond Formation

Beaucage, S. L.; Iyer, R. P. Advances in the Synthesis of Oligonucleotides by the Phosphoramidite Approach, *Tetrahedron* **1992**, *48*, 2223–2311.

Dueholm, K. L.; Pedersen, E. B. 2,3-Dideoxyfuranoses in Convergent Syntheses of 2',3'-Dideoxy Nucleosides, *Synthesis* **1992**, 1–22.

Engel, R., Ed. *Handbook of Organophosphorus Chemistry*; Dekker: New York, 1992

Huryn, D. M.; Okabe, M. Aids-Driven Nucleoside Chemistry, *Chem. Rev.* **1992**, *92*, 1745–1768.

Westheimer, F. H. Phosphorus Chemistry, In *Phosphorus Chemistry Developments in American Sciences*; Walsh, E. N.; Griffith, E. J.; Parry, R. W.; Quin, L. D., Eds.; American Chemical Society: Washington, 1992; Vol. 486, pp 1–18.

Baraniak, J.; Stec, W. J. Stereocontrolled Syntheses of P-Chiral Analogues of Nucleoside Cyclic 3',5'-Phosphates, *Rev. Heteroat. Chem.* **1993**, *8*, 143–164.

Beaucage, S. L.; Iyer, R. P. The Functionalization of Oligonucleotides via Phosphoramidite Derivatives, *Tetrahedron* **1993**, *49*, 1925–1963.

Beaucage, S. L.; Iyer, R. P. The Synthesis of Modified Oligonucleotides by the Phosphoramidite Approach and Their Applications, *Tetrahedron* **1993**, *49*, 6123–6194.

Beaucage, S. L.; Iyer, R. P. The Synthesis of Specific Ribonucleotides and Unrelated Phosphorylated Biomolecules by the Phosphoramidite Method, *Tetrahedron* **1993**, *49*, 10441–10488.

Billington, D. C. *The Inositol Phosphates: Chemical Synthesis and Biological Significance*; VCH: Weinheim, 1993.

Dorfman, Y. A.; Aleshkova, M. M.; Polimbetova, G. S.; Levina, L. V.; Petrova, T. V.; Abdreimova, R. R.; Doroshkevich, D. M.

New Reactions Involving the Oxidative O-, N-, and C-Phosphorylation of Organic Compounds by Phosphorus and Phosphides in the Presence of Metal Complexes, *Russ. Chem. Rev. (Engl. Transl.)* **1993**, *62*, 877–896.

Frauendorf, A.; Engels, J. W. Automated Synthesis, Structure and Biological Activity of Backbone-Modified Oligonucleotides - the Antisense Approach, In *Studies in Natural Products Chemistry*; Atta-ur-Rahman; Basha, F. Z., Eds.; Elsevier: Amsterdam, 1993; Vol. 13, pp 257–294.

Givens, R. S.; Kueper, L. W., III Photochemistry of Phosphate Esters, *Chem. Rev.* **1993**, *93*, 55–66.

Suska, A.; Grajkowski, A.; Wilk, A.; Uznanski, B.; Blaszczyk, J.; Wieczorek, M.; Stec, W. J. Antisense Oligonucleotides: Stereocontrolled Synthesis of Phosphorothioate Oligonucleotides, *Pure Appl. Chem.* **1993**, *65*, 707–714.

Troev, K. Dialkyl Hydrogen Phosphonates. 1. Structures of Dialkyl Hydrogen Phosphonates, *Rev. Heteroat. Chem.* **1993**, *8*, 165–181.

Varma, R. S. Synthesis of Oligonucleotide Analogs with Modified Backbones, *Synlett* **1993**, 621–637.

Wnuk, S. F. Sulfur- and Seleno-Sugar Modified Nucleosides. Synthesis, Chemical Transformations and Biological Properties, *Tetrahedron* **1993**, *49*, 9877–9936.

Stec, W. J.; Wilk, A. Stereocontrolled Synthesis of Oligo(Nucleoside Phosphorothioate)s, *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 709–722.

Timoshchuk, V. A. The Synthesis and Transformations of Uronic Acid Nucleosides, *Russ. Chem. Rev. (Engl. Transl.)* **1994**, *63*, 695–710.

Townsend, L. B., Ed. *Chemistry of Nucleosides and Nucleotides*; Plenum: New York, 1994; Vol. 3.

Troev, K. Dialkyl Hydrogen Phosphonates. 2. Substitution Reactions at Phosphorus Atom, *Rev. Heteroat. Chem.* **1994**, *10*, 89–119.

Knapp, S. Synthesis of Complex Nucleoside Antibiotics, *Chem. Rev.* **1995**, *95*, 1859–1876.

Vorbrüggen, H. Adventures in Silicon - Organic Chemistry, *Acc. Chem. Res.* **1995**, *28*, 509–520.

Wilson, L. J.; Hager, M. W.; El-Kattan, Y. A.; Liotta, D. C. Nitrogen Glycosylation Reactions Involving Pyrimidine and Purine Nucleoside Bases with Furanoside Sugars, *Synthesis* **1995**, 1465–1479.

De Clercq, E., Ed. *Advances in Antiviral Drug Design*; Jai Press Inc: Greenwich, CT, 1996; Vol. 2

Egli, M. Structural Aspects of Nucleic Acid Analogs and Antisense Nucleotides, *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1894–1909.

Hecht, S. M., Ed. *Bioorganic Chemistry: Nucleic Acids*; Oxford University Press: New York, 1996

Watanabe, Y. Selective Reactions and Total Synthesis of Inositol Phosphates, In *Studies in Natural Products Chemistry*; Atta-Ur-Rahman, Ed.; Elsevier: Amsterdam, 1996; Vol. 18, pp 391–456.

Nielsen, P. E.; Haaima, G. Peptide Nucleic Acid (PNA). A DNA Mimic with a Pseudopeptide Backbone, *Chem. Soc. Rev.* **1997**, *26*, 73–78.

Osborne, S. E.; Ellington, A. D. Nucleic Acid Selection and the Challenge of Combinatorial Chemistry, *Chem. Rev.* **1997**, *97*, 349–370.

Perreault, D. M.; Anslyn, E. V. Unifying the Current Data on the Mechanism of Cleavage - Transesterification of RNA, *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 432–450.

Sugimura, H. Methodology for the Stereoselective Synthesis of Nucleosides Utilizing 1-Thioglycoside as Glycosyl Donor, In *Recent Research Developments in Organic Chemistry*; Pandalai, S. G., Ed.; Transworld Research Network: Trivandrum, 1997; Vol. 1, pp 25–34.

Frauendorf, C.; Jaschke, A. Catalysis of Organic Reactions by RNA, *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 1378–1381.

Givens, R. S.; Weber, J. F. W.; Jung, A. H.; Park, C.-H. New Photoprotecting Groups: Desyl and *p*-Hydroxyphenacyl Phosphate and Carboxylate Esters, *Meth. Enzym.* **1998**, *291*, 1–29.

Izawa, K.; Shiragami, H. Practical Syntheses of Antiviral Nucleosides, *Pure Appl. Chem.* **1998**, *70*, 313–318.

Meier, C. Pro-Nucleotides - Recent Advances in the Design of Efficient Tools for the Delivery of Biologically Active Nucleoside Monophosphates, *Synlett* **1998**, 233–242.

Seitz, O. New Protecting Group Strategies for the Solid-Phase Synthesis and Modification of Peptides, Oligonucleotides, and Oligosaccharides, *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 3109–3111.

Uhlmann, E.; Peyman, A.; Breipohl, G.; Will, D. W. PNA: Synthetic Polyamide Nucleic Acids with Unusual Binding Properties, *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 2797–2823.

Yu, H. W.; Zhang, H. Y.; Yang, Z. J.; Min, J. M.; Ma, L. T.; Zhang, L. H. Studies on the Syntheses and Biological Activities of Isonucleosides, *Pure Appl. Chem.* **1998**, *70*, 435–438.

Butenandt, J.; Burgdorf, L. T.; Carell, T. Synthesis of DNA Lesions and DNA-Lesion-Containing Oligonucleotides for DNA-Repair Studies, *Synthesis* **1999**, 1085–1105.

Elhalabi, J. M.; Rice, K. G. Synthesis and Applications for Unnatural Sugar Nucleotides, *Curr. Med. Chem.* **1999**, *6*, 93–116.

Lamberth, C. The Chemistry of 4',5'-Unsaturated Nucleosides. A Review, *Org. Prep. Proced. Int.* **1999**, *31*, 379–397.

Vorbrüggen, H.; Ruh-Pohlenz, C. Synthesis of Nucleosides, *Org. React.* **1999**, *55*, 1–630.

Wengel, J. Synthesis of 3 'C- and 4 'C-Branched Oligodeoxynucleotides and the Development of Locked Nucleic Acid (LNA), *Acc. Chem. Res.* **1999**, *32*, 301–310.

Wozniak, L. A. Stereodefined Methanephosphonate Analogues of Nucleic Acids, *Rev. Heteroat. Chem.* **1999**, *19*, 173–202.

Yang, Z. J.; Zhang, H. Y.; Min, J. M.; Ma, L. T.; Zhang, L. H. Synthesis and Enzymatic Stability of Oligonucleotides Consisting of Isonucleosides, *Pure Appl. Chem.* **1999**, *71*, 1143–1146.

Yokoyama, M.; Momotake, A. Synthesis and Biological Activity of Azanucleosides, *Synthesis* **1999**, 1541–1554.

Burgess, K.; Cook, D. Syntheses of Nucleoside Triphosphates, *Chem. Rev.* **2000**, *100*, 2047–2059.

Couvreur, P.; Malvy, C., Eds., *Pharmaceutical Aspects of Oligonucleotides*; Taylor & Francis: London, 2000

Davies, M. J.; Shah, A.; Bruce, I. J. Synthesis of Fluorescently Labelled Oligonucleotides and Nucleic Acids, *Chem. Soc. Rev.* **2000**, *29*, 97–107.

Ferrero, M.; Gotor, V. Biocatalytic Selective Modifications of Conventional Nucleosides, Carbocyclic Nucleosides, and C-Nucleosides, *Chem. Rev.* **2000**, *100*, 4319–4347.

Ganesh, K. N.; Nielsen, P. E. Peptide Nucleic Acids: Analogs and Derivatives, *Curr. Org. Chem.* **2000**, *4*, 931–943.

A list of General Abbreviations appears on the front Endpapers