Experimental Section

Compound **13**: A mixture of **12** (1.00 g, 1.51 mmol), palladium(II) acetate (203 mg, 910 μmol), triphenylphosphane (475 mg, 1.81 mmol), and sodium pivalate (375 mg, 3.02 mmol) were dried in vacuo (10^{-2} mbar) for 1.5 h at 60 °C, and then dry *N*,*N*-dimethylacetamide (40 mL) was added. The orange-colored suspension was degassed three times and heated under argon for 4.5 h at 130 °C. After cooling to room temperature, the dark brown suspension was diluted with ethyl acetate, washed sequentially with 2N HCl and saturated aqueous NaCl solution, dried (Mg_2SO_4), and concentrated in vacuo. After flash chromatography on silica gel (dichloromethane/ethyl acetate 100:2), **13** (597 mg, 1.03 mmol, 68 %) was obtained as a red solid, which was crystallized from dichloromethane/petroleum ether. M.p. 138 °C; IR (KBr): $\tilde{\nu}$ = 2950, 1710, 1660, 1190, 1100 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$): δ = 1.40 – 1.56 (m, 12H; $CH(CH_3)_2$), 3.67 (s, 3H; OCH_3), 3.87 (s, 3H; OCH_3), 4.64 (sept, J = 6.1 Hz, 1H; $CH(CH_3)_2$), 4.77 (sept, J = 6.1 Hz, 1H; $CH(CH_3)_2$), 6.35 (d, J = 2.3 Hz, 1H; H-3′ or H-5′), 6.53 (d, J = 2.3 Hz, 1H; H-3′ or H-5′), 7.12 (d, J = 9.2 Hz, 1H; H-7), 7.80 (d, J = 8.9 Hz, 1H; H-6), 7.94 (s, 1H; H-2); ^{13}C NMR (63 MHz, $CDCl_3$): δ = 19.23 ($CH(CH_3)_2$), 21.88 ($CH(CH_3)_2$), 22.36 ($CH(CH_3)_2$), 55.75 (OCH_3), 57.69 (OCH_3), 73.11 ($CH(CH_3)_2$), 73.30 ($CH(CH_3)_2$), 93.79, 96,37, 102.53, 110.18, 116.67, 121.30, 123.62, 125.60, 128.02, 128.73, 133.02, 137.89, 139.21, 152.44, 155.61, 155.86, 156.85, 160.41, 161.75, 180.07 (C=O), 184.03 (C=O); MS (70 eV): *m*/*z* (%): 582/580 (5/5) [M^+], 509/507 (9/6) [$M^+ - C_4H_9O^+$], 467/465 (15/11) [$M^+ - C_8H_{19}^+$], 183 (100); elemental analysis (%): calcd for $C_{29}H_{25}O_8Br$ (581.42): C 59.91, H 4.33; found: C 59.66, H 4.25.

Compound (*P*)-**15**: The solvent was removed in vacuo from a solution of (*S*)-**14** (1.0 M in toluene, 360 μL, 360 μmol) and the residue was dissolved under argon in dry THF (1 mL). This solution was treated with a solution of the BH_3 – THF complex (1.0 M in THF, 480 mL) and stirred for 30 min at room temperature. After dropwise addition of a solution of the lactone **13** (69.8 mg, 120 μmol) in dry tetrahydrofuran (1 mL) at 0 °C the solution was stirred for 1 h at this temperature, then water (1 mL) and 2N HCl (1 mL) were added and the aqueous phase was thoroughly extracted with ethyl acetate. The combined organic phases were dried ($MgSO_4$) and the solvents were removed in vacuo. After flash chromatography of the residue on silica gel (dichloromethane/ethyl acetate 7:3), (*P*)-**15** (56.9 mg, 97.2 μmol, 81 %) was obtained as a yellow solid (96 % *ee*). Crystallization from dichloromethane/diethyl ether/*n*-hexane yielded yellow crystals (45.6 mg, 77.9 mmol, 65 %; > 99 % *ee*). M.p. 122 – 124 °C; $[\alpha]_D^{20} = -28$ (c = 0.01 in methanol); IR (KBr): $\tilde{\nu}$ = 3120 (br., OH), 2950, 1660, 1570, 1190, 1090 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.37 – 1.44 (m, 12H; $CH(CH_3)_2$), 3.59 (s, 3H; OCH_3), 3.76 (s, 3H; OCH_3), 4.33 (d, J = 13.7, 1H; CHHOH), 4.42 (d, J = 13.7, 1H; CHHOH), 4.55 (sept, J = 5.8 Hz, 1H; $CH(CH_3)_2$), 4.67 (sept, J = 5.8 Hz, 1H; $CH(CH_3)_2$), 6.12 (d, J = 1.8 Hz, 1H; H-3′ or H-5′), 6.20 (d, J = 1.8 Hz, 1H; H-3′ or H-5′), 6.97 (d, J = 8.8 Hz, 1H; H-7), 7.43 (s, 1H; H-2), 7.60 (d, J = 8.8 Hz, 1H; H-6); ^{13}C NMR (63 MHz, $CDCl_3$): δ = 21.88 ($CH(CH_3)_2$), 21.98 ($CH(CH_3)_2$), 55.06 (OCH_3), 55.57 (OCH_3), 62.76 (CH_2OH), 72.73 ($CH(CH_3)_2$), 73.46 ($CH(CH_3)_2$), 91.32, 94.05, 105.66, 109.82, 118.94, 121.31, 122.43, 124.61, 128.01, 135.62, 137.44, 138.41, 147.96, 154.94, 155.78, 155.84, 157.21, 160.73, 182.40 (C=O), 186.23 (C=O); MS (70 eV): *m*/*z* (%): 586/584 (54/54) [M^+], 543/541 (44/39) [$M^+ - C_3H_6^+$], 495/493 (20/19) [$M^+ - CH_4O_2^+$], 453/451 (100/100) [$M^+ - C_7H_{17}O_2^+$]; elemental analysis (%): calcd for $C_{29}H_{25}O_8Br$ (585.45): C 59.50, H 4.99; found: C 59.59, H 4.74.

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High-Temperature Synthesis of an Open-Framework Compound, $Na_2Cs_2Cu_3(P_2O_7)_2Cl_2$ (CU-4), by Molten-Salt Methods**

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Porous materials have stimulated much interest for their applications in catalysis, ion-exchange, separation, sensor, and molecular recognition.[1] Transition metal containing microporous (TMCM) solids have attracted particular attention because of their unique functions, such as redox catalysis,[2]

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magnetic ordering,[3] and cathodic electrolysis,[4] attributed to the utility of d electrons. Traditionally, the porous solids are prepared by low-temperature, hydrothermal (or solvothermal) methods. Conventional synthesis using organic as well as organometallic templates have given some insights into tailoring porous structures.[5, 6] Reaction mechanisms through which the pore structures are constructed, however, remain uncertain.

Prior to this study, we reported a series of new TMCM compounds synthesized by employing molten-salt methods at high temperatures well above those commonly employed in hydrothermal syntheses.[7] This compound series was designated as CU-2 (*C*lemson *U*niversity no. *2*) and contains large channels filled with a water-soluble salt.[8] The large pore is built around a column of close-packed $(K,Cs)^+/Cl^-$ ions in a squarelike lattice with a cross section of roughly 6×6 Å. For instance, for CU-2-CuPO, the chloride ions are bonded to the Cu^{2+} ions and, in turn, direct the orientation of otherwise square-planar CuO_4 in the construction of the Cu-P-O micropore structure.

Further studies on the "salt templating" effect have resulted in a new solid derived from different combinations of alkali metal chlorides, namely, $Na_2Cs_2Cu_3(P_2O_7)_2Cl_2$. This is the second example of a new family of open-framework compounds prepared by a conventional high-temperature, solid-state route. This new open-framework solid is designated as CU-4 and can be considered as structurally related to CU-2. Herein we report the synthesis and structure of CU-4 and compare it with CU-2. This work reaffirms the utility of molten salts for the high-temperature synthesis of microporous solids.

Crystals of the $Na_2Cs_2Cu_3(P_2O_7)_2Cl_2$ phase were grown at 750 °C by employing the salt CsCl. Compared with an idealized composition of CU-2-CuPO, $K_2Cs_3Cu_3(P_2O_7)_2Cl_3$, the current compound contains the smaller Na^+ ion and less cesium chloride. The new phase can also be synthesized at 550 °C in air by using stoichiometric amounts of the corresponding materials.[9]

With respect to the Cu-P-O framework, the CU-4 structure contains 8-ring and 16-ring micropores (Figure 1), which are 5.3×5.3 Å and 4.9×17.2 Å, respectively, measured from copper to copper.[10] CU-2 and CU-4 have the same connectivity (Figure 2), thus one phase can be converted to the other by a chemical modification. For instance, the CU-2 phase can be prepared by an ion-exchange reaction of CU-4 by using the KCl/CsCl eutectic salts at 600 °C.

The CsCl salt resides in the small channel. As in the CU-2 structure, the CsCl salt exists in a linear array of Cs^+-Cl^--Cs^+; the Cs–Cl distance is 3.31 Å ($\equiv$¼*c*). Each chlorine atom Cl(1) is bonded to four copper atoms Cu(1) (Cu(1)–Cl(1) 2.862(1) Å).

The 16-ring channel, which shows an unusually elongated window (Figure 1), is composed of eight CuO_4 and eight P_2O_7 polyhedra. The two different polyhedral units are alternately arranged and interconnected through vertex-sharing oxygen atoms (Figure 3). The 8-ring window is constructed in the same fashion with half as many CuO_4 and P_2O_7 units. The planes of the square-planar CuO_4 units all face the center of the pores. The axial positions of each unit are occupied by the

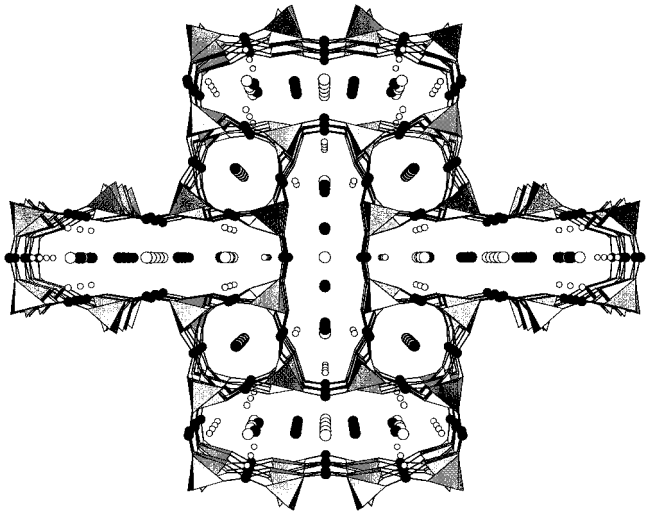

Figure 1. Projected view of the $Na_2Cs_2Cu_3(P_2O_7)Cl_2$ framework. The alternating CuO_4 (ball-and-stick) and P_2O_7 (polyhedral) units are interlinked through corner-sharing oxygen atoms. The mixed-salt contains Na^+ (small open circle), Cs^+, and Cl^- (nonbonded solid and open circles, respectively) ions.

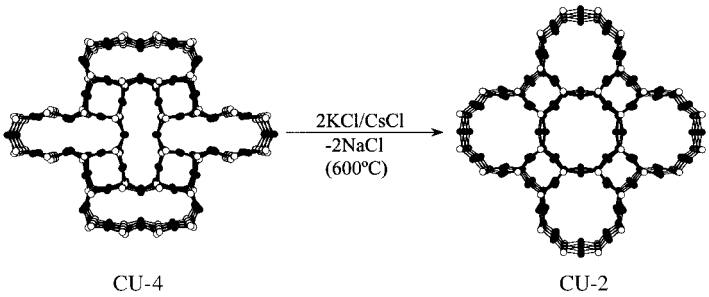

Figure 2. Microporous structures of CU-4 (left) and CU-2 (right). The frameworks are outlined by interconnecting copper metal (solid circles) and phosphorus cations (open circles). The oxygen atoms, as well as the salt, are omitted for clarity.

Cl^- ions residing in the channels. In $Cu(1)O_4Cl_2$, for example, the Cu(1) atom forms long bonds to two Cl atoms, namely, 2.86 Å to Cl(1) in the 8-ring, and 3.00 Å to Cl(2) in the 16-ring. Both these distances are significantly longer than 2.54 Å (derived from the sum of the Shannon radii of six-coordinate Cu^{2+} (0.87 Å) and Cl^- (1.67 Å)).[11] Also, as shown in the side view of CU-4 (Figure 3b), the copper atoms shared between the neighboring 16-rings, Cu(2) and Cu(3), are stacked alternately along the channel (*c* axis). These copper atoms are each five-coordinate, surrounded by four O atoms and a Cl atom; the Cu–Cl bond lengths are shorter than those mentioned above for Cu(1), that is, 2.44 Å for Cu(2)–Cl(4) and 2.60 Å for Cu(3)–Cl(3). This indicates a stronger Cu–Cl interaction, and gives rise to the "indented" structure at the waist of the elliptical framework (Figure 2). Taking into account the short Cu–Cl bonds, the elliptical pore can be alternatively viewed as a fused structure made of two 9-rings sharing a common Cu-Cl-Cu bond.

The formation of the large pore is likely attributed to the incorporation of multiple salts. In the elliptical pore, ions form an ordered lattice $[Na_2CsCl]^{2+}$ (Figure 4). Cl(2) is tetrahe-

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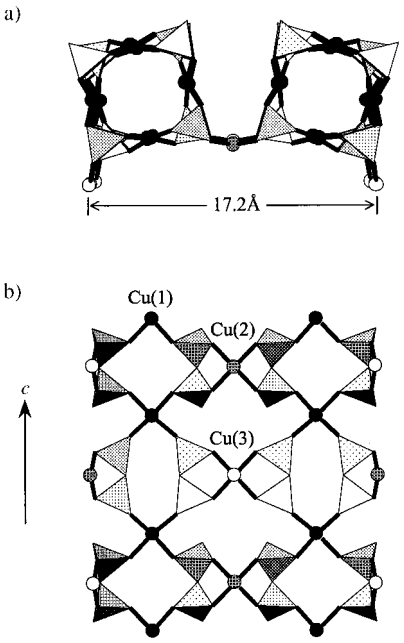

Figure 3. a) A partial structure of two large (half) and two small (full) micropores viewed along the channel, and b) a side view of the large pore in CU-4. The P_2O_7 units are drawn in fused PO_4 tetrahedra and three independent Cu^{2+} ions are labled (see text for details).

drally coordinated to three Na and one Cs, that is $Cl(2)Na(1)_2$-$Na(2)Cs(2)$ (Figure 4), while Cl(3) and Cl(4) are octahedrally coordinated to four Cs and two Cu atoms (not shown), that is, $Cl(3)Cs(2)_4Cu(3)_2$ and $Cl(4)Cs(2)_4Cu(2)_2$. Cs(3) primarily interacts with oxide ions since the corresponding Cs(3)–Cl(2,3) distances are long (4.69 and 4.56 Å). The two Na(1) ions reside above and below the plane of the $[Na_2CsCl]^{2+}$ lattice. Each is directly bonded to the chloride ions Cl(2) (Na(1)–Cl(2) 2.72 and 2.75 Å). In any event, the $[Na_2CsCl]^{2+}$ ionic lattice is tightly bonded to the $[Cu_3(P_2O_7)_2]^{2-}$ covalent framework judging from the short Cu–Cl distances mentioned above (2.44 and 2.60 Å) at the waist of the elliptical ring. This explains why the new compound does not behave like the CU-2 phase in terms of the ion-exchange properties in aqueous solution.

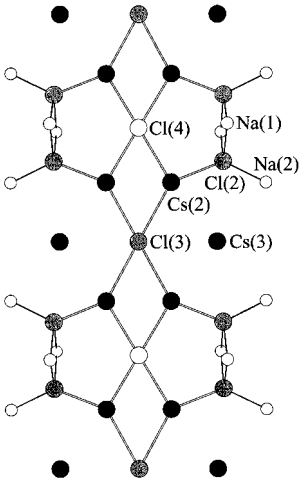

Figure 4. The ball-and-stick model of the $[Na_2CsCl]^{2+}$ lattice in the large pore (see text for details).

It should be noted here that porous solids containing large elliptical channel structures have been synthesized exclusively by employing organic templating agents. This is attributed to the anisotropic nature of the long-chain organic molecules and, of course, the versatility of the host lattice. The most studied mixed-metal phosphates, for example, have demonstrated a wide variety of elliptical channel structures.[12] To the best of our knowledge, the title compound represents the first open-framework structure that possesses large elliptical channels in the absence of organic templates.

In summary, the isolation of CU-4 has demonstrated the utility of molten salts in tailoring large open-framework structures. The CU-2 and CU-4 phases, in fact, are the first copper-based TMCM solids that contain channels circumscribed by 16-rings and have free diameters larger than 10 Å. We speculate that a salt structure that exists at the molten state is responsible for the formation of the porous framework. It is possible that an intermediate species, such as a Cu–Cl phase, also exists. Our preliminary differential thermal analysis studies of the reaction mixture[13] show an exotherm at about 380 °C; that is, below the melting points of CsCl (645 °C) and P_2O_5 (580–585 °C). This low-temperature thermal event may correspond to the formation of a precursor phase. In light of the functions of salt, we anticipate that more new phases with even larger pore diameters are yet to come. Moreover, the use of molten-salt methods would allow the search of microporous solids in a temperature regime at which thermally stable phases are commonly found.[14]

Experimental Section

Crystals of CU-4 were grown by employing a molten-salt reaction in a fused silica ampoule under vacuum. Na_2O (1.0 mmol, 86%, Alfa), CuO (3.0 mmol, 99.999%, Strem), P_2O_5 (2.0 mmol, 98+ %, Aldrich), and CsCl (1.0 mmol, 99%, Aldrich) were mixed and ground in a nitrogen-blanketed dry box. The reaction mixture was heated up to 750 °C at 3 K min^{-1}, kept at that temperature for five days, then slowly cooled to 400 °C at 0.1 K min^{-1}, and finally furnace-cooled to room temperature. Colorless, transparent column crystals (65% yield) were obtained along with some light blue crystals of $Na_6Cu_9(PO_4)_8$ and an unidentified yellow-greenish powder, according to the powder X-ray diffraction patterns.

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12.7 Å, in which the CsCl and mixed KCl/CsCl salt reside, respectively. The salt can be removed by washing at room temperature to give the microporous compound $Cs_2Cu_3(P_2O_7)_2 \cdot 8.5\,H_2O$.

[9] Using a stoichiometric mixture of $Na_2O/2\,CsCl/3\,CuO/2\,P_2O_5$, reactions by both slow cooling and quenching were studied after heating at 550 °C for a day. The quenched reaction gave a high-yield product (ca. 80 %) of CU-4, while the slow-cooled reaction gave a mixture of the CU-4 phase (ca. 50 %) and unknown products. The thermogravimetric analysis results show that the CU-4 phase decomposes at ~560 °C, and further studies suggest that the temperature window in which the CU-4 phase exists is ca. 500 – 550 °C.

[10] Crystal data of $Na_2Cu_3(P_2O_7)_2 \cdot 2\,CsCl$: colorless column crystal ($0.53 \times 0.18 \times 0.14$ mm^3), $M_r = 921.2$, tetragonal $P4_2/mnm$ (no. 136), $a = b = 15.868(2)$, $c = 13.238(2)$ Å, $V = 3333.1(8)$ Å^3, $Z = 8$, $\rho_{calcd} = 3.671$ g cm^{-3}, $\mu = 89.24$ cm^{-1}. Data collection: Nicolet R3mV diffractometer, ω-2θ scan mode, $Mo_{K\alpha}$ ($\lambda = 0.71073$ Å) radiation, $T = 295$ K. A total of 2119 unique reflections measured, of which 1715 ($F > 4.0\sigma(F)$) were used for the structure solution. Lorentz, polarization and empirical absorption corrections based on three azimuthal scans ($2\theta = 18.19°$, 22.01°, 24.72°) were applied to the intensity data (transmission factors: 0.43 – 0.62). The SHELXTL-Plus software package was used for crystal structure solution and refinement. The structure was solved by direct methods using the SHELXS-86 program and refined on $|F|$ by least-squares, full-matrix techniques. Final $R/R_W = 0.032/0.040$, GOF = 1.14 for 145 parameters. The final Fourier difference synthesis showed minimum and maximum peaks of -1.49 and $+1.88$ e Å^{-3}. Further details on the crystal structure investigation may be obtained from the Fachinformationszentrum Karlsruhe, 76344 Eggenstein-Leopoldshafen, Germany (fax: (+49) 7247-808-666; e-mail: crysdata@fiz-karlsruhe.de), on quoting the depository number CSD-411491. TEXSAN: Single Crystal Structure Analysis Software, Version 1.6b, Molecular Structure Corp., The Woodlands, TX, **1993**; "Scattering Factors for Non-Hydrogen Atoms": D. T. Cromer, J. T. Waber, *International Tables for X-ray Crystallography*, *Vol. IV*, Kynoch Press, Birmingham, **1974**, Table 2.2 A, pp. 71 – 98; G. M. Sheldrick in *Crystallographic Computing 3* (Eds.: G. M. Sheldrick, C. Krüger, R. Goddard), Oxford University Press, London, **1985**, pp. 175 – 189; G. M. Sheldrick, SHELXS-93, Göttingen, Germany, **1993**.

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[12] a) An *N*,*N*,*N*′,*N*′-tetramethylethylenediamine-templated gallium phosphate, $[Me_2NH(CH_2)_2NHMe_2]^{2+}[Ga_4P_5O_{20}H]^{2-} \cdot H_2O$, contains a 6.65×16.50 Å pore that is made of 16 Ga/P atoms: A. M. Chippindale, R. I. Walton, C. Turner, *J. Chem. Soc. Chem. Commun.* **1995**, 1261 – 1262. b) An aluminophosphate known as JDF-20, $[Al_5P_6O_{24}H]^{2-}2\,[N(C_2H_5)_3H]^+ \cdot 2\,H_2O$, exhibits 20-rings with 6.2×14.5 Å elliptical apertures: Q. Huo, R. Xu, S. Li, Z. Ma, J. M. Thomas, R. H. Jones, A. M. Chippindale, *J. Chem. Soc. Chem. Commun.* **1992**, 875 – 876. c) A novel TMCM solid of mixed-valence vanadium(III/IV) phosphate, $(H_2en)_3[V^{III}(H_2O)_2(V^{IV}O)_8(OH)_4(HPO_4)_4(PO_4)_4(H_2O)_2] \cdot 2\,H_2O$, shows 7×18 Å elliptical channels due to the incorporation of the ethylenediamine (en) molecule: V. Soghomonian, Q. Chen, R. C. Haushalter, J. Zubieta, *Angew. Chem.* **1993**, *105*, 601 – 603; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 610 – 612.

[13] Differential thermal analysis of the stoichiometric mixture shows two exotherms at 380 °C and 630 °C.

[14] A relevant article entitled "Fascinating Alkali Halide Structures of Different Dimensionalities Incorporated in Host Lattices" appeared after the submission of the present paper: R. Vaidhyanathan, S. Neeraj, P. A. Prasad, S. Natarajan, C. N. R. Rao, *Angew. Chem.* **2000**, *112*, 3612 – 3615; *Angew. Chem. Int. Ed.* **2000**, *39*, 3470 – 3473.

The Biosynthesis of Vancomycin-Type Glycopeptide Antibiotics—New Insights into the Cyclization Steps**

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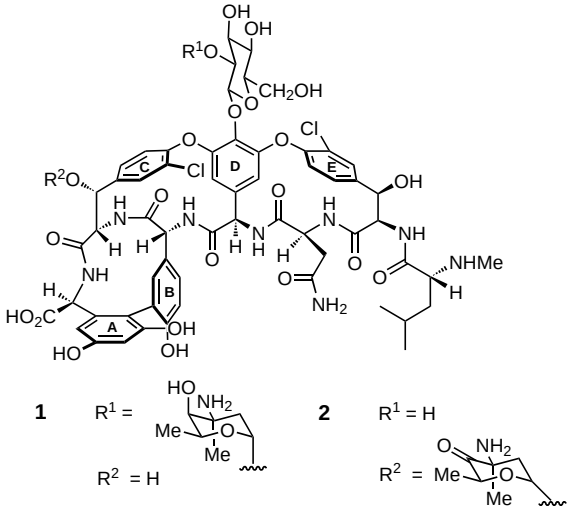
Over recent years, vancomyin (**1**) (Scheme 1)[1] has emerged as an antibiotic of last resort against infections of methicillin-resistant *Staphylococcus aureus* (MRSA) strains.[2] The antibiotic activity of the vancomycin-related glycopeptides is based on the high specificity of the aglycon cavity



Scheme 1. Structures of the glycopeptide antibiotics vancomycin (**1**) and balhimycin (**2**).

towards the *N*-acyl-D-Ala-D-Ala-peptide motif of bacterial cell-wall precursors.[3] Besides its pharmaceutical significance, work on the total synthesis of vancomycin has attracted the attention of synthetic chemists on account of the highly challenging stereochemical requirements encountered in the synthesis of the tricyclic aglycon. Chemical and biological aspects of glycopeptide antibiotics have been extensively reviewed recently.[4]

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