

University of Groningen

Sugar transport in the thermoacidophilic archaeon *Sulfolobus solfataricus*

Albers, Sonja-Verena

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2001

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Albers, S-V. (2001). *Sugar transport in the thermoacidophilic archaeon Sulfolobus solfataricus*. s.n.

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

References

- Akita, M., Sasaki, S., Matsuyama, S., and Mizushima, S. (1990) SecA interacts with secretory proteins by recognizing the positive charge at the amino terminus of the signal peptide in *Escherichia coli* *J. Biol. Chem.* **265**: 8164-8169.
- Albers, S.V., Elferink, M.G.L., Charlebois, R.L., Sensen, C.W., Driessen, A.J.M., and Konings, W.N. (1999a) Glucose transport in the extremely thermoacidophilic *Sulfolobus solfataricus* involves a high-affinity membrane-integrated binding protein. *J. Bacteriol.* **181**: 4285-4291.
- Albers, S.V., Konings, W.N., and Driessen, A.J. (1999b) A unique short signal sequence in membrane-anchored proteins of Archaea. *Mol. Microbiol.* **31**: 1595-1596.
- Andersson, H., von Heijne, G. (1994) Membrane protein topology: effects of $\Delta\mu H^+$ on the translocation of charged residues explain the 'positive inside' rule *EMBO J.* **13**: 2267-2272.
- Bairoch, A., Bucher, P., and Hofman, K. (1997) The PROSITE database, its status in 1997. *Nucleic acid research* **24**: 217-221.
- Bayley, D.P., Florian, V., Klein, A., and Jarrell, K.F. (1998) Flagellin genes of *Methanococcus vannielii*: amplification by the polymerase chain reaction, demonstration of signal peptides and identification of major components of the flagellar filament. *Mol. Gen. Genet.* **258**: 639-645.
- Bayley, D.P., Jarrell, K.F. (1998) Further evidence to suggest that archaeal flagella are related to bacterial type IV pili *J. Mol. Evol.* **46**: 370-373.
- Bayley, D.P., Jarrell, K.F. (1999) Overexpression of *Methanococcus voltae* flagellin subunits in *Escherichia coli* and *Pseudomonas aeruginosa*: a source of archaeal preflagellin *J. Bacteriol.* **181**: 4146-4153.
- Berks, B.C. (1996) A common export pathway for proteins binding complex redox cofactors? *Mol. Microbiol.* **22**: 393-404.
- Beveridge, T.J., Choquet, C.G., Patel, G.B., and Sprott, G.D. (1993) Freeze-fracture planes of methanogen membranes correlate with the content of tetraether lipids *J. Bacteriol.* **175**: 1191-1197.
- Bhuiyan, S.H., Gowda, K., Hotokezaka, H., and Zwieb, C. (2000) Assembly of archaeal signal recognition particle from recombinant components *Nucleic Acids Res.* **28**: 1365-1373.
- Blöchl, E., Rachel, R., Burggraf, S., Hafenbradl, D., Jannasch, H.W., and Stetter, K.O. (1997) *Pyrolobus fumarii*, gen. and sp. nov., represents a novel group of archaea, extending the upper temperature limit for life to 113°C *Extremophiles* **1**: 14-21.
- Boos, W. and H. Shuman (1998) Maltose/maltodextrin system of *Escherichia coli*: transport, metabolism, and regulation. *Microbiol. Mol. Biol. Rev.* **62**: 204-229.
- Briggs, M.S., Cornell, D.G., Dluhy, R.A., and Gierasch, L.M. (1986) Conformations of signal peptides induced by lipids suggest initial steps in protein export *Science* **233**: 206-208.
- Brock, T.D., Brock, K.M., Belly, R.T., and Weiss, R.L. (1972) *Sulfolobus*: a new genus of sulfur-oxidizing bacteria living at low pH and high temperature. *Arch. Microbiol.* **84**: 54-68.
- Bult, C.J., White, O., Olsen, G.J., Zhou, L., Fleischmann, R.D., Sutton, G.G., Blake, J.A., FitzGerald, L.M., Clayton, R.A., Gocayne, J.D., Kerlavage, A.R., Dougherty, B.A., Tomb, J.F., Adams, M.D., Reich, C.I., Overbeek, R., Kirkness, E.F., Weinstock, K.G., Merrick, J.M., Glodek, A., Scott, J.L., Geoghagen, N.S.M., and Venter, J.C. (1996) Complete genome sequence of the methanogenic archaeon, *Methanococcus jannaschii* *Science* **273**: 1058-1073.
- Burns, D.L. (1999) Biochemistry of type IV secretion *Curr. Opin. Microbiol.* **2**: 25-29.

- Carlos, J.L., Paetzel, M., Brubaker, G., Karla, A., Ashwell, C.M., Lively, M.O., Cao, G., Bullinger, P., and Dalbey, R.E. (2000) The role of the membrane-spanning domain of type I signal peptidases in substrate cleavage site selection *J.Biol.Chem.* **275**: 38813-38822.
- Choquet, C.G., Patel, G.B., Beveridge, T.J., and Sprott, G.D. (1992) Formation of unilamellar liposomes from total polar lipid extracts of methanogens *Appl. Environ. Microbiol.* **58**: 2894-2900.
- Choquet, C.G., Patel, G.B., Beveridge, T.J., and Sprott, G.D. (1994) Stability of pressure-extruded liposomes made from archaeobacterial ether lipids *Appl. Microbiol. Biotechnol.* **42**: 375-384.
- Correia, J.D., Jarrell, K.F. (2000) Posttranslational processing of *Methanococcus voltae* preflagellin by preflagellin peptidases of *M. voltae* *J Bacteriol* **182**: 855-858.
- Cubellis, M.V., Rozzo, C., Montecucchi, P., and Rossi, M. (1990) Isolation and sequencing of a new β -galactosidase-encoding Archaeobacterial gene. *Gene* **94**: 89-94.
- Cusdin, F.S., M.J. Robinson, G.D. Holman, D.W. Hough, and M.J. Danson (1996) Characterisation of glucose transport in the hyperthermophilic Archaeon *Sulfolobus solfataricus*. *FEBS Lett.* **387**: 193-195.
- Dalbey, R.E., Lively, M.O., Bron, S., and van Dijk, J.M. (1997) The chemistry and enzymology of the type I signal peptidases *Protein Sci.* **6**: 1129-1138.
- Dalbey, R.E., von Heijne, G. (1992) Signal peptidases in prokaryotes and eukaryotes--a new protease family *Trends Biochem. Sci.* **17**: 474-478.
- D'Auria, S., Morana, A., Febbraio, F., Vaccaro, C., De Rosa, M., and Nucci, R. (1996) Functional and structural properties of the homogeneous beta- glycosidase from the extreme thermoacidophilic archaeon *Sulfolobus solfataricus* expressed in *Saccharomyces cerevisiae*. *Protein Expr Purif* **7**: 299-308.
- Davidson, A.L., and Nikaido, H. (1990) Overproduction, solubilization, and reconstitution of the maltose transport system from *Escherichia coli* *J.Biol.Chem.* **265**: 4524-4260.
- De Rosa, M., Trincone, A., Nicolaus, B., and Gambacorta, A. (1991) Archaeobacteria: lipids, membrane structures, and adaptations to environmental stresses. In *Life under extreme conditions*. di Prisco, G. (ed). Berlin Heidelberg: Springer-Verlag, pp. 61-87.
- de Vrije, G.J., Batenburg, A.M., Killian, J.A., and de Kruijff, B. (1990) Lipid involvement in protein translocation in *Escherichia coli* *Mol. Microbiol.* **4**: 143-150.
- Deckert, G., Warren, P.V., Gaasterland, T., Young, W.G., Lenox, A.L., Graham, D.E., Overbeek, R., Snead, M.A., Keller, M., Aujay, M., Huber, R., Feldman, R.A., Short, J.M., Olsen, G.J., and Swanson, R.V. (1998) The complete genome of the hyperthermophilic bacterium *Aquifex aeolicus* *Nature* **392**: 353-358.
- Detmers, F.J., Lanfermeijer, F.C., Abele, R., Jack, R.W., Tampe, R., Konings, W.N., and Poolman, B. (2000) Combinatorial peptide libraries reveal the ligand-binding mechanism of the oligopeptide receptor OppA of *Lactococcus lactis* *Proc. Natl. Acad. Sci. U.S.A* **97**: 12487-12492.
- Diederichs, K., Diez, J., Grellner, G., Muller, C., Breed, J., Schnell, C., Vonrhein, C., Boos, W., and Welte, W. (2000) Crystal structure of MalK, the ATPase subunit of the trehalose/maltose ABC transporter of the archaeon *Thermococcus litoralis* *EMBO J* **19**: 5951-5961.
- Diez, J., Diederichs, K., Grellner, G., Horlacher, R., Boos, W. and Welte, W. (2001) The crystal structure of a liganded trehalose/maltose-binding protein from the hyperthermophilic archaeon *Thermococcus litoralis* at 1.85 Å *J. Mol. Biol.* **305**: 905-915.
- DiRuggiero, J., Dunn, D., Maeder, D.L., Holley-Shanks, R., Chatard, J., Horlacher, R., Robb, F.T., Boos, W., and Weiss, R.B. (2000) Evidence of recent lateral gene transfer among hyperthermophilic archaea *Mol Microbiol* **38**: 684-693.
- Ehrmann, M., Ehrle, R., Hofmann, E., Boos, W., and Schlosser, A. (1998) The ABC maltose transporter of *E. coli* *Mol. Microbiol.* **29**: 685-694.

- Elferink, M.G.L., De Wit, J.G., Demel, R., Driessen, A.J.M., and Konings, W.N. (1992) Functional reconstitution of membrane proteins in monolayer liposomes from bipolar lipids of *Sulfolobus acidocaldarius* *J. Biol. Chem.* **267**: 1375-1381.
- Elferink, M.G.L., De Wit, J.G., Driessen, A.J.M., and Konings, W.N. (1993) Energy-transducing properties of primary proton pumps reconstituted into archaeal bipolar lipid vesicles *Eur. J. Biochem.* **214**: 917-925.
- Elferink, M.G.L., De Wit, J.G., Driessen, A.J.M., and Konings, W.N. (1994) Stability and proton-permeability of liposomes composed of Archaeal tetraether lipids *Biochim. Biophys. Acta* **1193**: 247-254.
- Elferink, M.G.L., Albers, S.-V., Konings, W.N., and Driessen, A.J.M. (2001) Sugar transport in *Sulfolobus solfataricus* is mediated by two families of binding-protein-dependent ABC transporters *Mol. Microbiol.* **39**: 1494-1503.
- Erra-Pujada, M., Debeire, P., Duchiron, F., and O'Donohue, M.J. (1999) The type II pullulanase of *Thermococcus hydrothermalis*: molecular characterization of the gene and expression of the catalytic domain. *Bacteriol.* **181**: 3284-3287.
- Essenberg, R.C., C. Candler, and S.K. Nida (1997) *Brucella abortus* strain 2308 putative glucose and galactose transporter gene: cloning and characterization. *Microbiology* **143**: 1549-1555.
- Evdokimov, A.G., Anderson, D.E., Routzahn, K.M. and Waugh, D.S. (2001) Structural basis for oligosaccharide recognition by *Pyrococcus furiosus* maltodextrin-binding protein *J. Mol. Biol.* **305**: 891-904.
- Faguy, D.M., Bayley, D.P., Kostyukova, A.S., Thomas, N.A., and Jarrell, K.F. (1996) Isolation and characterization of flagella and flagellin proteins from the Thermoacidophilic archaea *Thermoplasma volcanium* and *Sulfolobus shibatae*. *J. Bacteriol.* **178**: 902-905.
- Faguy, D.M., Jarrell, K.F., Kuzio, J., and Kalmokoff, M.L. (1994) Molecular analysis of archaeal flagellins: similarity to the type IV pilin-transport superfamily widespread in bacteria. *Can. J. Microbiol.* **40**: 67-71.
- Fiala, G., Stetter, K.O. (1986) *Pyrococcus furiosus* sp. nov. represents a novel genus of marine heterotrophic archaeobacteria growing optimally at 100°C *Arch. Microbiol.* **145**: 56-61.
- Forest, K.T., Dunham, S.A., Koomey, M., and Tainer, J.A. (1999) Crystallographic structure reveals phosphorylated pilin from *Neisseria*: phosphoserine sites modify type IV pilus surface chemistry and fibre morphology *Mol. Microbiol.* **31**: 743-752.
- Fox, P.F. and J.R. Whitaker (1977) Isolation and characterization of sheep pepsin. *Biochem. J.* **161**: 389-398.
- Gilson, E., Alloing, G., Schmidt, T., Claverys, J.P., Dudler, R., and Hofnung, M. (1988) Evidence for high affinity binding-protein dependent transport systems in gram-positive bacteria and in *Mycoplasma* *EMBO J.* **7**: 3971-3974.
- Greene, R.V., MacDonald, R.E. (1984) Partial purification and reconstitution of the aspartate transport system from *Halobacterium halobium* *Arch. Biochem. Biophys.* **229**: 576-584.
- Greller, G., Horlacher, R., DiRuggiero, J., and Boos, W. (1999) Molecular and biochemical analysis of MalK, the ATP-hydrolyzing subunit of the trehalose/maltose transport system of the hyperthermophilic archaeon *Thermococcus litoralis* *J. Biol. Chem.* **274**: 20259-20264.
- Grogan, D.W. (1989) Phenotypic characterization of the archaeobacterial genus *Sulfolobus*: comparison of five wild-type strains. *J. Bacteriol.* **171**: 6710-6719.
- Grogan, D.W. (1996) Organization and interactions of cell envelope proteins of the extreme thermoacidophile *Sulfolobus acidocaldarius*. *Can. J. Microbiol.* **42**: 1163-1171.
- Grogan, D.W. (1996) Isolation and fractionation of cell envelope from the extreme thermoacidophile *Sulfolobus acidocaldarius* *J. Microbiol. Methods* **26**: 35-43.

- Gropp,R., Gropp,F., and Betlach,M.C. (1992) Association of the halobacterial 7S RNA to the polysome correlates with expression of the membrane protein bacterioopsin *Proc.Natl.Acad.Sci.U.S.A* **89**: 1204-1208.
- Haseltine, C., M. Rolfmeier, and P. Blum (1996) The glucose effect and regulation of α -Amylase synthesis in the hyperthermophilic archaeon *Sulfolobus solfataricus* *J.Bacteriol.* **178**: 945-950.
- Haseltine, C., Montalvo-Rodriguez, R., Bini, E., Carl, A., and Blum, P. (1999) Coordinate transcriptional control in the hyperthermophilic archaeon *Sulfolobus solfataricus*. *J Bacteriol* **181**: 3920-3927.
- Hekstra,D., Tommassen,J. (1993) Functional exchangeability of the ABC proteins of the periplasmic binding protein-dependent transport systems Ugp and Mal of *Escherichia coli* *J.Bacteriol.* **175**: 6546-6552.
- Hettmann,T., Schmidt,C.L., Anemuller,S., Zahringer,U., Moll,H., Petersen,A., and Schafer,G. (1998) Cytochrome b558/566 from the archaeon *Sulfolobus acidocaldarius*. A novel highly glycosylated, membrane-bound b-type hemoprotein *J Biol Chem* **273**: 12032-12040.
- Higgins C.F. (1992) ABC transporters: from microorganisms to man. *Annu Rev Cell Biol* **8**: 67-113.
- Hobbs, M. and Mattick, J.S. (1993) Common components in the assembly of type 4 fimbriae, DNA transfer systems, filamentous phage and protein-secretion apparatus: a general system for the formation of surface-associated protein complexes. *Mol. Microbiol.* **10**: 233-243.
- Hofnung,M., Hatfield,D., and Schwartz,M. (1974) malB region in *Escherichia coli* K-12: characterization of new mutations *J.Bacteriol.* **117**: 40-47.
- Hopfner,K.P., Karcher,A., Shin,D.S., Craig,L., Arthur,L.M., Carney,J.P., and Tainer,J.A. (2000) Structural biology of Rad50 ATPase: ATP-driven conformational control in DNA double-strand break repair and the ABC-ATPase superfamily *Cell* **101**: 789-800.
- Horlacher, R., K.B. Xavier, H. Santos, J. DiRuggiero, M. Kossmann, and W. Boos (1998) Archaeal binding protein-dependent ABC transporter: molecular and biochemical analysis of the trehalose/maltose transport system of the hyperthermophilic archaeon *Thermococcus litoralis*. *J.Bacteriol.* **180**: 680-689.
- Huddleston, S., C.A. Yallop, and B.M. Charalambous (1995) The identification and partial characterization of a novel inducible extracellular thermostable esterase from the archaeon *Sulfolobus shibatae*. *Biochem.Biophys.Res.Comm.* **216**: 495-500.
- Hung,L.W., Wang,I.X., Nikaido,K., Liu,P.Q., Ames,G.F., and Kim,S.H. (1998) Crystal structure of the ATP-binding subunit of an ABC transporter *Nature* **396**: 703-707.
- Hunke,S., Landmesser,H., and Schneider,E. (2000) Novel missense mutations that affect the transport function of MalK, the ATP-binding-cassette subunit of the *Salmonella enterica* serovar *typhimurium* maltose transport system *J. Bacteriol.* **182**: 1432-1436.
- Hunke,S., Mourez,M., Jehanno,M., Dassa,E., and Schneider,E. (2000) ATP modulates subunit-subunit interactions in an ATP-binding cassette transporter (MalFGK2) determined by site-directed chemical cross-linking *J.Biol.Chem.* **275**: 15526-15534.
- Jackson, P. (1994) High-resolution polyacrylamide gel electrophoresis of fluorophore-labeled reducing saccharides. *Meth Enzymol* **230**: 250-265.
- Jacobs, M.H., T. Van der Heide, A.J.M. Driessen, and W.N. Konings (1996) Glutamate transport in *Rhodobacter sphaeroides* is mediated by a novel binding protein-dependent secondary transport system. *Proc.Natl.Acad.Sci.U.S.A.* **93**:12786-12790.
- Jarrell, K.F., Bayley, D.P., and Kostyukova, A.S. (1996) The archaeal flagellum: a unique motility structure. *J. Bacteriol.* **178**: 5057-5064.

- Jarrell, K.F., Correia, J.D., and Thomas, N.A. (1999) Is the processing and translocation system used by flagellins also used by membrane-anchored secretory proteins in archaea? *Mol. Microbiol.* **34**: 395-398.
- Jones, C.J., Aizawa, S. (1991) The bacterial flagellum and flagellar motor: structure, assembly and function *Adv. Microb. Physiol* **32**: 109-172.
- Kalmokoff, M.L. and K.F. Jarrell (1991) Cloning and sequencing of a multigene family encoding the flagellins of *Methanococcus voltae*. *J. Bacteriol.* **173**: 7113-7125.
- Kamo, N., Wakamatsu, Y., Kohno, K., and Kobatake, Y. (1988) On the glutamate transport through cell envelope vesicles of *Halobacterium halobium* *Biochem Biophys Res Commun* **152**: 1090-1096.
- Kandler, O., Hippe, H. (1977) Lack of peptidoglycan in the cell walls of *Methanosarcina barkeri* *Arch. Microbiol.* **113**: 57-60.
- Kato, M., Miura, Y., Kettoku, M., Shindo, K., Iwamatsu, A., and Kobayashi, K. (1996) Purification and characterization of new trehalose-producing enzymes isolated from the hyperthermophilic archaea, *Sulfolobus solfataricus* KM1. *Biosci Biotechnol Biochem* **60**: 546-550.
- Kawarabayasi, Y., M. Sawada, H. Horikawa, Y. Haikawa, Y. Hino, S. Yamamoto, M. Sekine, S. Baba, H. Kosugi, A. Hosoyama, Y. Nagai, M. Sakai, K. Ogura, R. Otsuka, H. Nakazawa, M. Takamiya, Y. Ohfuku, T. Funahashi, T. Tanaka, Y. Kudoh, J. Yamazaki, N. Kushida, A. Oguchi, K. Aoki, and H. Kikuchi (1998) Complete sequence and gene organization of the genome of a hyper- thermophilic archaeobacterium, *Pyrococcus horikoshii* OT3. *DNA Res.* **5**: 55-76.
- Kengen S.W.M., Stams.A.J.M., and de Vos, W.M. (1996) Sugar metabolism of hyperthermophiles. *FEMS Microbiol Rev* **18**: 119-137.
- Kim, R, Sandler, S. J., Goldman, S, Yokota, H, Clark, A. J., and Kim, S.-H. (1998) Overexpression of archaeal proteins in *Escherichia coli*. *Biotechnology Letters* **20**: 207-210.
- Klenk, H.P., Clayton, R.A., Tomb, J.F., White, O., Nelson, K.E., Ketchum, K.A., Dodson, R.J., Gwinn, M., Hickey, E.K., Peterson, J.D., Richardson, D.L., Kerlavage, A.R., Graham, D.E., Kyrpides, N.C., Fleischmann, R.D., Quackenbush, J., Lee, N.H., Sutton, G.G., Gill, S., Kirkness, E.F., Dougherty, B.A., McKenney, K., Adams, M.D., Loftus, B., and Venter, J.C. (1997) The complete genome sequence of the hyperthermophilic, sulphate-reducing archaeon *Archaeoglobus fulgidus* *Nature* **390**: 364-370.
- Knol, J., Veenhoff, L., Liang, W.-J., Henderson, P.J.F., Leblanc, G., and Poolman, B. (1996) Unidirectional reconstitution into detergent-destabilized liposomes of the purified lactose transport system of *Streptococcus thermophilus* *J. Biol. Chem.* **271**: 15358-15366.
- Kobayashi, K., Kato, M., Miura, Y., Kettoku, M., Komeda, T., and Iwamatsu, A. (1996) Gene cloning and expression of new trehalose-producing enzymes from the hyperthermophilic archaeum *Sulfolobus solfataricus* KM1. *Biosci Biotechnol Biochem* **60**: 1882-1885.
- Koenig, H. (1988) Archaeobacterial cell envelopes. *Can. J. Microbiol.* **34**: 395-406.
- Koning, S.M., Elferink, M.G.L., Konings, W.N., Driessen, A.J.M. (2001) Cellobiose uptake in the hyperthermophilic archaeon *Pyrococcus furiosus* is mediated by an inducible, high affinity ABC transporter. Submitted.
- Konisky, J., Lynn, D., Hoppert, M., Mayer, F., and Haney, P. (1994) Identification of the *Methanococcus voltae* S-layer structural gene *J. Bacteriol.* **176**: 1790-1792.
- Krueger, R.D., Harper, S.H., Campbell, J.W., and Fahrney, D.E. (1986) Kinetics of phosphate uptake, growth, and accumulation of cyclic diphosphoglycerate in a phosphate-limited continuous culture of *Methanobacterium thermoautotrophicum* *J Bacteriol* **167**: 49-56

- Kuhnau, S., Reyes, M., Sievertsen, A., Shuman, H.A., and Boos, W. (1991) The activities of the *Escherichia coli* MalK protein in maltose transport, regulation, and inducer exclusion can be separated by mutations *J Bacteriol* **173**: 2180-2186.
- Kurr, M., Huber, R., Koenig, H., Jannasch, H.W., Fricke, H., Trincone, A., Kristjansson, J.K., and Stetter, K.O. (1991) *Methanopyrus kandleri* new genus new species, represents a novel group of hyperthermophilic methanogens, growing at 110°C *Arch.Microbiol.* **156**: 239-247.
- Lanfermeijer, F.C., Detmers, F.J., Konings, W.N. and Poolman, B. (2000) On the binding mechanism of the peptide receptor of the oligopeptide transport system of *Lactococcus lactis* *EMBO J* **19**:3649-3656.
- Langworthy, T.A., Pond, J.L. (1986) Archaeobacterial ether lipids and chemotaxonomy *Syst.Appl.Microbiol* **7**: 235-257.
- Lanzetta, P.A., Alvarez, L.J., Reinach, P.S., and Candia, O.A. (1979) An improved assay for nanomole amounts of inorganic phosphate *Anal Biochem* **100**: 95-97.
- Lechner, J., and Sumper, M. (1987) The primary structure of a procaryotic glycoprotein. Cloning and sequencing of the cell surface glycoprotein gene of halobacteria. *J.Biol.Chem* **262**: 9724-9729.
- Linton, K.J., Higgins, C.F. (1998) The *Escherichia coli* ATP-binding cassette (ABC) proteins *Mol.Microbiol.* **28**: 5-13.
- Lippincott, J., Traxler, B. (1997) MalFGK complex assembly and transport and regulatory characteristics of MalK insertion mutants *J.Bacteriol.* **179**: 1337-1343.
- Liu, C.E., Liu, P.Q., and Ames, G.F.L. (1997) Characterization of the adenosine triphosphatase activity of the periplasmic histidine permease, a traffic ATPase (ABC transporter) *J.Biol.Chem.* **35**: 21883-21891.
- Macnab, R.M. (1999) The bacterial flagellum: reversible rotary propellor and type III export apparatus *J.Bacteriol.* **181**: 7149-7153.
- Mattar, S., Scharf, B., Kent, S.B., Rodewald, K., Oesterhelt, D., and Engelhard, M. (1994) The primary structure of halocyanin, an archaeal blue copper protein, predicts a lipid anchor for membrane fixation *J. Biol. Chem.* **269**: 14939-14945.
- Mattick, J.S. and Alm, R.A. (1995) Common architecture of type 4 fimbriae and complexes involved in macromolecular traffic. *Trends Microbiol Sci* 411-413.
- Miroux, B., Walker, J.E. (1996) Over-production of proteins in *Escherichia coli*: mutant hosts that allow synthesis of some membrane proteins and globular proteins at high levels *J. Mol. Biol.* **260**: 289-298.
- Moll, R. and G. Schäfer (1988) Chemiosmotic H⁺ cycling across the plasma membrane of the thermoacidophilic archaeobacterium *Sulfolobus acidocaldarius* . *FEBS Lett.* **232**:359-363.
- Moll, R., Schmidtke, S., and Schafer, G. (1999) Domain structure, GTP-hydrolyzing activity and 7S RNA binding of *Acidianus ambivalens* ffh-homologous protein suggest an SRP-like complex in archaea *Eur.J.Biochem.* **259**: 441-448.
- Munoz, F.J., Miller, K.W., Beers, R., Graham, M., and Wu, H.C. (1991) Membrane topology of *Escherichia coli* prolipoprotein signal peptidase (signal peptidase II) *J.Biol.Chem.* **266**: 17667-17672.
- Murzin, A.G. (1993) OB(oligonucleotide/oligosaccharide binding)-fold: common structural and functional solution for non-homologous sequences *EMBO J.* **12**: 861-867.
- Nelson, K.E., Clayton, R.A., Gill, S.R., Gwinn, M.L., Dodson, R.J., Haft, D.H., Hickey, E.K., Peterson, J.D., Nelson, W.C., Ketchum, K.A., McDonald, L., Utterback, T.R., Malek, J.A., Linher, K.D., Garrett, M.M., Stewart, A.M., Cotton, M.D., Pratt, M.S., Phillips, C.A., Richardson, D., Heidelberg, J., Sutton, G.G., Fleischmann, R.D., Eisen, J.A., and Fraser, C.M.

- (1999) Evidence for lateral gene transfer between Archaea and bacteria from genome sequence of *Thermotoga maritima*. *Nature* **399**: 323-329.
- Nichols,P.D., Franzmann,P.D. (1992) Unsaturated diether phospholipids in the Antarctic methanogen *Methanococcoides burtonii* *FEMS Microbiol.Lett.* **98**: 205-208.
- Nielsen, H., Engelbrecht, J., Brunak, S., and von Heijne, G. (1997) Identification of prokaryotic and eukaryotic signal peptides and prediction of their cleavage sites. *Protein Eng* **10**: 1-6.
- Nielsen, H., Brunak, S., and von Heijne, G. (1999) Machine learning approaches for the prediction of signal peptides and other protein sorting signals *Prot Engng* **12**: 3-9.
- Nouwen,N., Stahlberg,H., Pugsley,A.P., and Engel,A. (2000) Domain structure of secretin PulD revealed by limited proteolysis and electron microscopy *EMBO J.* **19**: 2229-2236.
- Nunn, D.N. and Lory, S. (1991) Product of the *Pseudomonas aeruginosa* gene pilD is a prepilin leader peptidase. *Proc Natl Acad Sci U S A* **88**: 3281-3285.
- Nunn,D. (1999) Bacterial type II protein export and pilus biogenesis: more than just homologies? *Trends Cell Biol.* **9**: 402-408.
- Olendzenski,L., Liu,L., Zhaxybayeva,O., Murphey,R., Shin,D.G., and Gogarten,J.P. (2000) Horizontal Transfer of Archaeal Genes into the Deinococcaceae: Detection by Molecular and Computer-Based Approaches *J Mol Evol* **51**: 587-599.
- Paetzel,M., Dalbey,R.E. (1997) Catalytic hydroxyl/amine dyads within serine proteases *Trends Biochem.Sci.* **22**: 28-31.
- Panagiotidis,C.H., Boos,W., and Shuman,H.A. (1998) The ATP-binding cassette subunit of the maltose transporter MalK antagonizes MalT, the activator of the *Escherichia coli* mal regulon *Mol.Microbiol.* **30**: 535-546.
- Panagiotidis,C.H., Reyes,M., Sievertsen,A., Boos,W., and Shuman,H.A. (1993) Characterization of the structural requirements for assembly and nucleotide binding of an ATP-binding cassette transporter. The maltose transport system of *Escherichia coli* *J.Biol.Chem.* **268**: 23685-23696.
- Pao, S.S., I.T. Paulsen, and M.H. Saier, Jr. (1998) Major facilitator superfamily. *Microbiol.Mol.Biol.Rev.* **62**:1-34.
- Parge,H.E., Forest,K.T., Hickey,M.J., Christensen,D.A., Getzoff,E.D., and Tainer,J.A. (1995) Structure of the fibre-forming protein pilin at 2.6 Å resolution *Nature* **378**: 32-38.
- Paulsen,I.T., Nguyen,L., Sliwinski,M.K., Rabus,R., and Saier,M.H.J. (2000) Microbial genome analyses: comparative transport capabilities in eighteen prokaryotes *J Mol Biol* **301**: 75-100.
- Pegden,R.S.,Larson,M.A.,Grant,R.J., and Morrison,M. (1998) Adherence of the gram-positive bacterium *Ruminococcus albus* to cellulose and identification of a novel form of cellulose-binding protein which belongs to the Pil family of proteins *J Bact* **180**: 5921-5927.
- Pohlschroder,M., Prinz,W.A., Hartmann,E., and Beckwith,J. (1997) Protein translocation in the three domains of life: variations on a theme *Cell* **91**: 563-566.
- Polekhina,G., Thirup,S., Kjeldgaard,M., Nissen,P., Lippmann,C., and Nyborg,J. (1996) Helix unwinding in the effector region of elongation factor EF-Tu-GDP *Structure.* **4**: 1141-1151.
- Preston,C.M., Wu,K.Y., Molinski,T.F., and Delong,E.F. (1996) A psychrophilic crenarchaeon inhabits a marine sponge: *Cenarchaeum symbiosum* gen. nov., sp. nov *Proc.Natl.Acad.Sci.USA* **93**: 6241-6246.
- Pugsley,A.P. (1993) The complete general secretory pathway in gram-negative bacteria *Microbiol Rev* **57**: 50-108.
- Quioco, F.A., and Vyas,, N.K. (1984) Novel stereospecificity of the L-arabinose-binding protein. *Nature* **310**: 381-386.

- Quioco,F.A., Ledvina,P.S. (1996) Atomic structure and specificity of bacterial periplasmic receptors for active transport and chemotaxis: variation of common themes *Mol Microbiol* **20**: 17-25.
- Relini,A., Cassinadri,D., Fan,Q., Gulik,A., Mirghani,Z., De Rosa,M., and Gliozzi,A. (1996) Effect of physical constraints on the mechanisms of membrane fusion: bolaform lipid vesicles as model systems *Biophys.J.* **71**: 1789-1795.
- Richarme, G. and A. Kepes (1983) Study of binding protein-ligand interaction by ammonium sulphate assisted adsorption on cellulose ester filters. *Biochim.Biophys.Acta* **742**:16-24.
- Richarme,G., el Yaagoubi,A., and Kohiyama,M. (1993) The MglA component of the binding protein-dependent galactose transport system of *Salmonella typhimurium* is a galactose-stimulated ATPase *J Biol Chem* **268**: 9473-9477.
- Richet,E., Raibaud,O. (1987) Purification and properties of the MalT protein, the transcription activator of the Escherichia coli maltose regulon *J.Biol.Chem.* **262**: 12647-12653.
- Rolfsmeier, M., and Blum, P. (1995) Purification and characterization of a maltase from the extremely thermophilic crenarchaeote *Sulfolobus solfataricus*. *J Bacteriol* **177**: 482-485.
- Rolfsmeier, M., Haseltine, C., Bini, E., Clark, A., and Blum, P. (1998) Molecular characterization of the alpha-glucosidase gene (malA) from the hyperthermophilic archaeon *Sulfolobus solfataricus*. *J Bacteriol* **180**: 1287-1295.
- Ruepp, A., Graml, W., Santos-Martinez, M.L., Koretke, K.K., Volker, C., Mewes, H.W., Frishman, D., Stocker, S., Lupas, A.N., and Baumeister, W. (2000) The genome sequence of the thermoacidophilic scavenger *Thermoplasma acidophilum*. *Nature* **407**: 508-513.
- Scatchard, G (1949) The attraction of proteins for small molecules and ions. *Ann.NY Acad.Sci.* **51**:660-672.
- Schaegger, H. and G. von Jagow (1991) Blue native electrophoresis for isolation of membrane protein complexes in enzymatically active form. *Anal.Biochem.* **199**:223-231.
- Schafer,G., Engelhard,M., and Muller,V. (1999) Bioenergetics of the Archaea *Microbiol Mol Biol Rev* **63**: 570-620.
- Schleper,C., Holz,I., Janekovic,D., Murphy,J., and Zillig,W. (1995) A multicopy plasmid of the extremely thermophilic archaeon *Sulfolobus* effects its transfer to recipients by mating *J Bacteriol* **177**: 4417-4426.
- Schleper,C., Pühler,G., Holz,I., Gambacorta,A., Janekovic,D., Santarius,U., Klenk,H.-P., and Zillig,W. (1995) *Picrophilus* gen.nov., fam. nov.: a novel aerobic, heterotrophic, thermoacidophilic genus and family comprising archaea capable of growth around pH 0 *J.Bacteriol.* **177**: 7050-7059.
- Schmees,G., Schneider,E. (1998) Domain structure of the ATP-binding-cassette protein MalK of *Salmonella typhimurium* as assessed by coexpressed half molecules and LacK'-MalK chimeras *J.Bacteriol.* **180**: 5299-5305.
- Schmees,G., Stein,A., Hunke,S., Landmesser,H., and Schneider,E. (1999) Functional consequences of mutations in the conserved 'signature sequence' of the ATP-binding-cassette protein MalK *Eur J Biochem* **266**: 420-430.
- Schoenheit, P. and T. Schaefer (1995) Metabolism of hyperthermophiles. *World J.Microbiol.Biotechnol.* **11**:26-57.
- Schwartz,M. (1967) Phenotypic expression and genetic localization of mutations affecting maltose metabolism in Escherichia coli K 12 *Ann.Inst.Pasteur (Paris)* **112**: 673-698.
- Sensen, C.W., R.L. Charlebois, C. Chow, I.G. Clausen, B. Curtis, W.F. Doolittle, M. Duguet, R.A. Garrett, T. Gaasterland, G. Erauso, I. Heikamp de Jong, A.C. Jeffries, C. Kozera, Medina N., A. De Moors, J. van der Oost, H. Phan, M.A. Ragan, M.E. Schenk, Q. She, R.K. Singh, and

- N. Tolstrup (1998) Completing the sequence of the *Sulfolobus solfataricus* P2 genome. *Extremophiles* **2**:305-312.
- Shaw, J.G., M.J. Hamblin, and D.J. Kelly (1991) Purification, characterization and nucleotide sequence of the periplasmic C4-dicarboxylate-binding protein (DctP) from *Rhodobacter capsulatus*. *Mol Microbiol* **5**:3055-3062.
- Sleigh, S.H., Seavers, P.R., Wilkinson, A.J., Ladbury, J.E., and Tame, J.R. (1999) Crystallographic and calorimetric analysis of peptide binding to OppA protein *J.Mol.Biol.* **291**: 393-415.
- Sleytr, U.B., Beveridge, T.J. (1999) Bacterial S-layers *Trends Microbiol.* **7**: 253-260.
- Smith, D.R., Doucette-Stamm, L.A., Deloughery, C., Lee, H., Dubois, J., Aldredge, T., Bashirzadeh, R., Blakely, D., Cook, R., Gilbert, K., Harrison, D., Hoang, L., Keagle, P., Lumm, W., Pothier, B., Qiu, D., Spadafora, R., Vicaire, R., Wang, Y., Wierzbowski, J., Gibson, R., Jiwani, N., Caruso, A., Bush, D., and Reeve, J.N. (1997) Complete genome sequence of *Methanobacterium thermoautotrophicum* deltaH: functional analysis and comparative genomics *J Bacteriol* **179**: 7135-7155.
- Smith, R.L., Gottlieb, E., Kucharski, L.M., and Maguire, M.E. (1998) Functional similarity between archaeal and bacterial CorA magnesium transporters *J.Bacteriol.* **180**: 2788-2791.
- Strom, M.S., Nunn, D.N., and Lory, S. (1993) A single bifunctional enzyme, PilD, catalyzes cleavage and N-methylation of proteins belonging to the type IV pilin family. *Proc Natl Acad Sci U S A* **90**: 2404-2408.
- Strom, M.S., Lory, S. (1991) Amino acid substitutions in pilin of *Pseudomonas aeruginosa*. Effect on leader peptide cleavage, amino-terminal methylation, and pilus assembly *J Biol Chem* **266**: 1656-1664.
- Strom, M.S., Nunn, D.N., and Lory, S. (1994) Posttranslational processing of type IV prepilin and homologs by PilD of *Pseudomonas aeruginosa* *Methods Enzymol* **235**: 527-540.
- Sumper, M., Berg, E., Mengele, R., and Strobel, I. (1990) Primary structure and glycosylation of the S-layer protein of *Haloferax volcanii*. *J Bacteriol* **172**: 7111-7118.
- Tamano, K., Aizawa, S., Katayama, E., Nonaka, T., Imajoh-Ohmi, S., Kuwae, A., Nagai, S., and Sasakawa, C. (2000) Supramolecular structure of the Shigella type III secretion machinery: the needle part is changeable in length and essential for delivery of effectors *EMBO J.* **19**: 3876-3887.
- Tawara, E., and Kamo, N. (1991) Glucose transport of *Haloferax volcanii* requires the Na(+)-electrochemical potential gradient and inhibitors for the mammalian glucose transporter inhibit the transport. *Biochim Biophys Acta* **1070**: 293-299.
- Thomas, N.A., Bardy, S.L., and Jarrell, K. (2001) The archaeal flagellum: a different kind of prokaryotic motility structure *FEMS Microbiol. Rev.* **25**: 147-174.
- Tjalsma, H., Bolhuis, A., Jongbloed, J.D., Bron, S., and van Dijk, J.M. (2000a) Signal peptide-dependent protein transport in *Bacillus subtilis*: a genome-based survey of the secretome *Microbiol.Mol.Biol.Rev.* **64**: 515-547.
- Tjalsma, H., Stover, A.G., Driks, A., Venema, G., Bron, S., and van Dijk, J.M. (2000b) Conserved serine and histidine residues are critical for activity of the ER-type signal peptidase SipW of *Bacillus subtilis* *J.Biol.Chem.* **275**: 25102-25108.
- Tjalsma, H., Bolhuis, A., van Roosmalen, M.L., Wiegert, T., Schumann, W., Broekhuizen, C.P., Quax, W.J., Venema, G., Bron, S., and van Dijk, J.M. (1998) Functional analysis of the secretory precursor processing machinery of *Bacillus subtilis*: identification of a eubacterial homolog of archaeal and eukaryotic signal peptidases *Genes Dev.* **12**: 2318-2331.
- Van de Vossenberg, J.L.C.M., Driessen, A.J.M., and Konings, W.N. (1998) The essence of being extremophilic: the role of the unique archaeal membrane lipids *Extremophiles* **2**: 163-170.

- Van de Vossenberg, J.L.C.M., Ubbink-Kok, T., Elferink, M.G.L., Driessen, A.J.M., and Konings, W.N. (1995) Ion permeability of the cytoplasmic membrane limits the maximum growth temperature of bacteria and archaea *Mol. Microbiol.* **18**: 925-932.
- Van der Does, C., den Blaauwen, T., De Wit, J.G., Manting, E.H., Groot, N.A., Fekkes, P., and Driessen, A.J. (1996) SecA is an intrinsic subunit of the *Escherichia coli* preprotein translocase and exposes its carboxyl terminus to the periplasm *Mol. Microbiol.* **22**: 619-629.
- Van der Heide, T., and Poolman, B. (2000) Osmoregulated ABC-transport system of *Lactococcus lactis* senses water stress via changes in the physical state of the membrane *Proc Natl Acad Sci U S A* **97**: 7102-7106.
- Van der Vlag, J., Postma, P.W. (1995) Regulation of glycerol and maltose uptake by the IIAGlc-like domain of IINag of the phosphotransferase system in *Salmonella typhimurium* LT2 *Mol. Gen. Genet.* **248**: 236-241.
- Van Dijk, J.M., de Jong, A., Vehmaanpera, J., Venema, G., and Bron, S. (1992) Signal peptidase I of *Bacillus subtilis*: patterns of conserved amino acids in prokaryotic and eukaryotic type I signal peptidases *EMBO J.* **11**: 2819-2828.
- Verdon, G., Albers, S.V., Driessen, A.J.M., and Thunnissen, A.M.W.H. (2001) manuscript in preparation.
- Von Heijne G. (1990) The signal peptide. *J Membr Biol* **115**: 195-201.
- Von Heijne, G. (1985) Signal sequences. The limits of variation *J Mol Biol* **184**: 99-105.
- Vyas, N.K., Vyas, M.N., and Quiococho, F.A. (1991) Comparison of the periplasmic receptors for L-arabinose, D-glucose/D-galactose, and D-ribose. Structural and Functional Similarity *J. Biol. Chem.* **266**: 5226-5237.
- Walker, J.E., Saraste, M., Runswick, M.J., and Gay, N.J. (1982) Distantly related sequences in the alpha- and beta-subunits of ATP synthase, myosin, kinases and other ATP-requiring enzymes and a common nucleotide binding fold *EMBO J.* **1**: 945-951.
- Wall, D., Kaiser, D. (1999) Type IV pili and cell motility *Mol. Microbiol.* **32**: 1-10.
- Wanner, C., and Soppa, J. (1999) Genetic identification of three ABC transporters as essential elements for nitrate respiration in *Haloferax volcanii*. *Genetics* **152**: 1417-1428.
- Wardi, A.H. and G.A. Michos (1972) Alcian blue staining of glycoproteins in acrylamide disc electrophoresis. *Anal. Biochem.* **49**: 607-609.
- Wassenberg, D., Liebl, W. and Jaenicke, R. (2000) Maltose-binding protein from the hyperthermophilic bacterium *Thermotoga maritima*: stability and binding properties. *J. Mol. Biol.* **295**: 279-288.
- Wolfgang, M., van Putten, J.P., Hayes, S.F., Dorward, D., and Koomey, M. (2000) Components and dynamics of fiber formation define a ubiquitous biogenesis pathway for bacterial pili *EMBO J.* **19**: 6408-6418.
- Xavier, K.B., Martins, L.O., Peist, R., Kossmann, M., Boos W. and Santos, H. (1996) High-affinity maltose/trehalose transport system in the hyperthermophilic archaeon *Thermococcus litoralis*. *J. Bacteriol.* **178**: 4773-4777.
- Yallop, C.A. and B.M. Charalambous (1996) Nutrient utilization and transport in the thermoacidophilic archaeon *Sulfolobus shibatae* *Microbiology* **142**: 3373-3380.
- Yeats, S., McWilliam, P., and Zillig, W. (1982) A plasmid in the archaebacterium *Sulfolobus acidocaldarius* *EMBO J* **1**: 1035-1038.
- Zahringer, U., Moll, H., Hettmann, T., Knirel, Y.A., and Schafer, G. (2000) Cytochrome b558/566 from the archaeon *Sulfolobus acidocaldarius* has a unique Asn-linked highly branched hexasaccharide chain containing 6-sulfoquinovose. *Eur. J. Biochem.* **267**: 4144-4149.

- Zillig, W., Stetter, K. O., Wunderl, S., Schulz, W., Priess, H., and Scholz, I. (1980) The *Sulfolobus* - "Caldariella" Group: Taxonomy on the Basis of the Structure of DNA-Dependent RNA Polymerases. *Archives of Microbiology* 125, 259-269.
- Zillig, W., Kletzin, A., Schleper, C., Holz, I., Janekovic, D., Hain, J., Lanzendoerfer, M., and Kristjansson, J.K. (1994) Screening for *Sulfolobales*, their plasmids and their viruses in Icelandic solfataras *Systematic and Applied Microbiology* **16**: 609-628.

