F. Mathey, *Angew. Chem.* **1996**, *108*, 1204; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1125.

[5] a) C. Ganter, L. Brassat, C. Glinsböckel, B. Ganter, *Organometallics* **1997**, *16*, 2862; b) C. Janiak, K. C. H. Lange, U. Versteeg, D. Lentz, P. M. H. Budzelaar, *Chem. Ber.* **1996**, *129*, 1517.

[6] T. Douglas, K. H. Leopold, B. S. Haggerty, A. L. Rheingold, *Polyhedron* **1990**, *9*, 329.

[7] D. Carmichael, L. Ricard, F. Mathey, *J. Chem. Soc. Chem. Commun.* **1994**, 1167.

[8] The bicyclic skeleton of the dimer is isostructural with a known analogue[15] prepared from the monomer of 3,4-dimethylphosphole. The *tert*-butyl groups in dimer **3** induce very little distortion of the bicyclic skeleton; the P–P and C–C distances lie within the statistical errors of the known compound.[15]

[9] The ab initio calculations were performed with the TURBOMOLE[16] package using TZVP[17] (**2**) or SVP (**5**) basis sets.[18] Geometries were optimized by using the RI-DFT module [19] (BP-86-Functional[20]) in the C_s point group. NMR chemical shifts were calculated at the SCF level,[21] using geometries optimized at the RI-DFT level. **2**: $E = -2730.201229$ au, Ga–P 266.2, Ga–C 256.7 and 253.4, P–C 179, C–C 138.1, C–C 142.2 pm, C-P-C 90.9, P-C-C 110.4, C-C-C 114.1°. **5**: $E = -4346.064324$ au, Ga–P 249.9, Ga–C 246.3 and 242.1, Ga–Cr 241.4, P–C 184.9, C–C 138.7, C–C 143.4 pm, C-P-C 88.9°, P-C-C 110.9°, C-C-C 114.6°.

[10] P. Jutzi, B. Neumann, G. Reumann, H.-G. Stammler, *Organometallics* **1998**, *17*, 1305–1314.

[11] Comparison between the Ga–C and Ga–P distances of the calculated phospholylgallium(I) and the chromium pentacarbonyl adduct show the same trends. The Ga–P length decreases by 16 pm, whilst Ga–C decreases by 11 pm.

[12] C. Üffing, A. Ecker, R. Köppe, H. Schnöckel, *Organometallics* **1998**, *17*, 2373.

[13] Qing Ju, A. Purath, A. Donchev, H. Schnöckel, *J. Organomet. Chem.*, in press.

[14] Whilst the preparation of the Ga^I halide solutions requires rather sophisticated equipment, the compound described here should be accessible through more classical techniques. One possible approach, by analogy with the successful synthesis of GaCp*,[10] involves the reduction of the corresponding phospholylgallium dihalide with potassium. Further synthetic investigations and preliminary CVD experiments aimed at the formation of GaP are in progress.

[15] G. de Lauzon, C. Charrier, H. Bonnard, F. Mathey, *J. Chem. Soc. Chem.Commun.* **1982**, 1272–1273.

[16] R. Ahlrichs, M. Bär, M. Häser, C. Kölmel, *Chem. Phys. Lett.* **1989**, *162*, 165–169.

[17] A. Schäfer, R. Ahlrichs, *J. Phys. Chem.* **1993**, *100*, 589–591.

[18] A. Schäfer, R. Horn, R. Ahlrichs, *J Chem. Phys.* **1992**, *97*, 2571–2577.

[19] K. Eichkorn, O. Treutler, H. Öhm, M. Häser, R. Ahlrichs, *Chem. Phys. Lett.* **1995**, *240*, 283–290.

[20] A. D. Becke, *Phys. Rev.* **1988**, *A 38*, 3098–4003.

[21] M. Häser, R. Ahlrichs, H. P. Baron, P. Weis, H. Horn, *Theor. Chim. Acta* **1992**, *83*, 455.

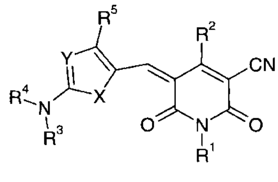
Design, Synthesis, and Evaluation of a Dye Library: Glass-Forming and Solid-State Luminescent Merocyanines for Functional Materials**

Frank Würthner,* Rüdiger Sens, Karl-Heinz Etzbach, and Günther Seybold

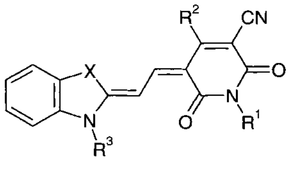
Dedicated to Professor Hans-Jürgen Quadbeck-Seeger on the occasion of his 60th birthday

In the development of functional dyes, after the identification of a suitable chromophore extensive variations of the substituents usually have to be carried out before a satisfactory product is obtained for the desired area of application. This optimization of the lead structure traditionally takes place according to combinatorial rather than rational principles, as stability, solubility, affinity, and compatibility properties are hard to predict.

Recently we reported on the dyes **1**–**4**,[1] which possess a very interesting chromogenic system for several high-technology applications.[2] These chromophores with an electronic structure at the mesomeric center between neutral and zwitterionic electron distribution have high polarizabilities, high dipole moments, and exhibit absorption spectra with sharp bands ($\varepsilon_{max} > 100000\ \mathrm{L\,mol^{-1}\,cm^{-1}}$, half widths $\Delta\tilde{\nu}_{1/2} < 1500\ \mathrm{cm^{-1}}$) that give rise to exceptionally brilliant magenta hues.[3] This resulted in hitherto unattainable refractive index modulations in photorefractive materials[1] as well as brilliant hues in thermal dye transfer printing and in electrophotography (color copiers).[2]



1: X = O, Y = CH
2: X = S, Y = CH
3: X = S, Y = N



4: X = CMe$_2$
5: X = S
6: X = O

High concentrations of colorant are necessary in photorefractive materials, ribbons for thermal dye transfer printing, and toners for color copiers, which leads to problems due to

---

[*] Dr. F. Würthner,[+] Dr. R. Sens, Dr. K.-H. Etzbach, Dr. G. Seybold
BASF Aktiengesellschaft
ZDT – Farbenlaboratorium
D-67056 Ludwigshafen (Germany)

[+] New Address:
Abteilung Organische Chemie II der Universität
Albert-Einstein-Allee 11, D-89081 Ulm (Germany)
Fax: (+49) 731-50-22840
E-mail: frank.wuerthner@chemie.uni-ulm.de

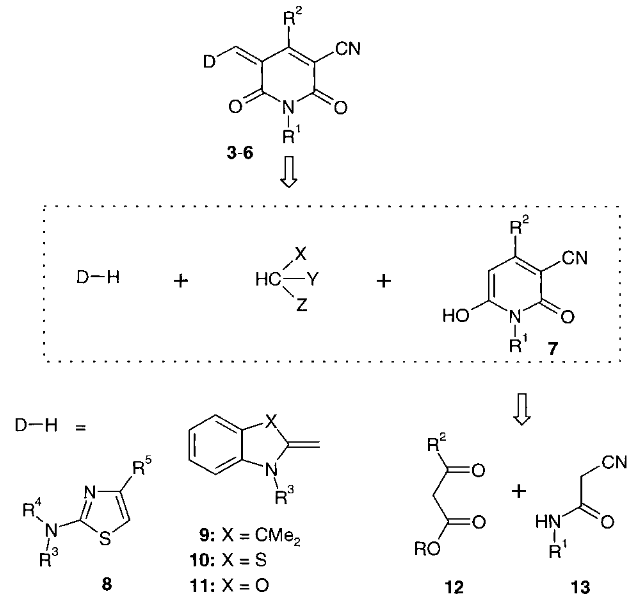
[**] We thank Mr. K.-H. Frieß and Mr. J. Manz for their committed work in the laboratory and Mrs E. Tewes for carrying out the calorimetric measurements. We are grateful to Prof. Dr. P. Bäuerle for helpful discussions in the field of combinatorial chemistry. F.W. thanks the Fonds der Chemischen Industrie and the Bundesministerium für Bildung und Forschung for a Liebig stipend for "new materials", as well as the Volkswagen-Stiftung for financial support.

Supporting information for this article is available on the WWW under http://www.wiley-vch.de/home/angewandte/ or from the author.

the marked tendency of these dipolar chromophores to aggregate and crystallize. Our aim was now to optimize these properties, which are hard to predict, by variation of the substituents in a combinatorial fashion. It was advantageous that in terms of their molecular properties the lead structures **1**–**6** developed by rational concepts were all similarly well suited to the desired applications;[1] thus, further treatment of the furan and thiophene dyes **1** and **2**, respectively, which are less easily accessible in view of their precursors, became unnecessary.

Readily accessible starting materials, which can be produced in one-pot syntheses from industrially available precursors by simple alkylation or multicomponent condensation reactions,[4] include the dialkylamino thiazoles **8**,[5] the methylene bases **9**–**11**,[6] and the hydroxypyridones **7**.[7] Their further reaction, usually consisting of a Vilsmeier formylation of the donor bases **8**–**11** and subsequent condensation with **7**, is, however, troublesome and requires prior purification of **8**–**11**, which is only possible by means of time-consuming chromatography in the case of longer chain alkyl substituents R^3–R^5. Therefore our aim was to find a method with which a wide variety of structurally variable, unpurified starting materials **7**–**11** would react in a simple sequence leading directly to the dyes **3**–**6** and with which the pure products could be isolated directly from the reaction mixtures.

Prompted by the recent description of a formylation–condensation sequence for the synthesis of merocyanines in which orthoformates[8] were used, we examined a series of formic acid derivatives in diverse solvents for their suitability for the synthesis of the dyes **3** and **4** from the reactants **7** and **8** or **9**, respectively (Scheme 1).[9] Indeed, we were able to obtain almost quantitative yields with orthoformates and some other activated formic acid derivatives as long as the starting material was pure. Impure, and in particular not completely anhydrous, donor components **8** or **9**, on the other hand, led to rapid hydrolysis of the formylating agent and thus to impure products and losses in yield. Finally, the little-known formylating agent dimethylformamide in acetic anhydride[10] proved to be the ideal reagent, since it is extremely tolerant towards the use of impure starting materials.[11]



Scheme 1. Retrosynthesis of the merocyanine dyes **3**–**6**.

Simple heating of equimolar amounts of the starting materials in acetic anhydride in the presence of 1.5 equivalents of dimethylformamide [Eq. (1)] led to the formation of the merocyanine dyes **3** and **4** in almost quantitative yield (HPLC) (Tables 1 and 2). Even the synthesis of derivatives

$$\mathbf{8,9} + \mathrm{HC(O)NMe_2} + \mathbf{7} \xrightarrow[90^\circ\mathrm{C,\ 3\ h}]{\mathrm{Ac_2O}} \mathbf{3,4} \qquad (1)$$

Table 1. Thiazole dyes **3** and their optical and thermal properties.[a]

	R^1	R^2	$R^3=R^4$	R^5	λ_{max} [nm][b]	Color of the solid	Luminescence of the solid[c]	DSC (type, m.p., T_G [°C])[d]
3a	Me	Me	Bu	Ph	536	red	+	D, 229
3b	Bu	Me	Bu	Ph	536	green[e]	0	A, 182, –
3c	hex	Me	Bu	Ph	536	green[e]	0	A, 140, –
3d	Me	Me	Bu	chex	529	red	0	B, 182, 24
3e	Bu	Me	Bu	chex	529	red	+	A, 162, –
3f	Bu	Ph	Bu	chex	530	red	+	A, 205, –
3g	Bu	Me	Bu	*i*Pr	528	red	0	B, 154, 10
3h	Me	Me	Bu	*t*Bu	533	light red	+	A, 170, –
3i	Bu	Me	Bu	*t*Bu	534	orange	++	A, 173, –
3j	Me	Me	Et	neop	526	red	0	D, 244
3k	Bu	Me	Bu	neop	530	orange	++	A, 146, –
3l	Bu	Me	Bu	*o*-MeC_6H_4	529	red	(+)	B, 174, 28
3m	Bu	Me	Bu	*p*-$MeOC_6H_4$	542	green[e]	0	B, 183, 33
3n	Bu	Me	Bu	2-furyl	565	brass-colored[e]	0	A, 204, –
3o	Bu	Me	Bu	2-thienyl	555	green[e]	0	A, 203, –
3p	Bu	Me	Bu	3-thienyl	542	bronze-colored[e]	0	A, 178, –

[a] hex = *n*-hexyl, chex = cyclohexyl, neop = neopentyl. [b] In dichloromethane. All alkyl-substituted derivatives are characterized by a single, extremely narrow absorption band, for example **3g** ($\varepsilon_{max} = 110000\ \mathrm{L\,mol^{-1}\,cm^{-1}}$, $\Delta\tilde{\nu}_{1/2} = 1250\ \mathrm{cm^{-1}}$). Substituents capable of conjugation in the 4-position at the thiazole ring, on the other hand, lead to bathochromic shifts and broader bands, for example **3b** ($\varepsilon_{max} = 89000\ \mathrm{L\,mol^{-1}\,cm^{-1}}$, $\Delta\tilde{\nu}_{1/2} = 1800\ \mathrm{cm^{-1}}$), **3o** ($\varepsilon_{max} = 64000\ \mathrm{L\,mol^{-1}\,cm^{-1}}$, $\Delta\tilde{\nu}_{1/2} = 2200\ \mathrm{cm^{-1}}$). [c] After excitation with UV light of 366 nm: 0 no, (+) weak, + distinct, + + intense luminescence. [d] The DSC measurements were carried out with heating and cooling rates of $10\ \mathrm{K\,min^{-1}}$. A: Recrystallization upon cooling; B: Glass formation upon cooling, but recrystallization during the second heating cycle; C: Glass formation upon cooling and no recrystallization during the second heating cycle; D: Decomposition upon melting. [e] Bronze shiny colors.

Table 2. Indoline **4**, benzothiazole **5**, and benzoxazole dyes **6**, as well as their optical and thermal properties.[a]

	R^1	R^2	R^3	X	λ_{max} [nm][b]	Color of the solid	Luminescence of the solid[c]	DSC (type, m.p., T_G [°C])[d]
4a	Me	Me	Me	CMe_2	522	light red	(+)	D, 310
4b	Bu	Me	Me	CMe_2	522	red	(+)	A, 253, –
4c	hex	Me	Me	CMe_2	523	red	+	B, 204, 64
4d	*p*-MeC_6H_4	Me	Me	CMe_2	524	red-brown	(+)	D, >300
4e	BnOPr	Me	Me	CMe_2	525	red	(+)	B, 171, 55
4f	Bu	Me	Bu	CMe_2	527	red	+	B, 196, 46
4g	Bu	Me	*i*Pent	CMe_2	527	red	++	A, 218, –
4h	Ethex	Me	Bu	CMe_2	526	red	+	B, 162, 37
4i	Bu	Pr	Bu	CMe_2	528	red	++	B, 160, 30
4j	Bu	Me	*i*Pr	CMe_2	526	red	(+)	B, 221, 73
4k	Ethex	Me	*i*Pr	CMe_2	526	red	+	C, 161, 58
5a	Bu	Me	Et	S	533	red	+	D, 310
5b	Ethex	Me	Et	S	533	red	+	D, 278
6	Bu	Me	Et	O	495	orange	+	D, 286

[a] hex = *n*-hexyl, BnOPr = $(CH_2)_3OCH_2Ph$, Ethex = 2-ethylhexyl, *i*Pent = isopentyl. [b] In dichloromethane. All dyes are characterized by one single, extremely narrow absorption band, for example **4f** ($\varepsilon_{max} = 130000\,L\,mol^{-1}\,cm^{-1}$, $\Delta\tilde{\nu}_{1/2} = 1300\,cm^{-1}$), **5a** ($\varepsilon_{max} = 137000\,L\,mol^{-1}\,cm^{-1}$, $\Delta\tilde{\nu}_{1/2} = 1150\,cm^{-1}$), **6a** ($\varepsilon_{max} = 145000\,L\,mol^{-1}\,cm^{-1}$, $\Delta\tilde{\nu}_{1/2} = 1150\,cm^{-1}$). [c, d] See footnotes of Table 1.

with sterically demanding substituents, such as neopentyl- and *tert*-butylthiazoles, was possible without complications. When the reactions were carried out in concentrated solutions, almost all dyes crystallized upon cooling in >80% yield, and analytically pure products were obtained through simple washing with alcohol.[12] With the strongly basic and oxidation-sensitive methylene bases **10** and **11** it proved effective to start from the more stable hydroiodides and to convert these in an analogous way to dyes **5** and **6**, after addition of 1 equivalent of potassium acetate.

Tables 1 and 2 provide an overview of the structural variations we carried out on the dyes **3**–**6**, the extension of which to a large library displaying a diverse range of substituents should be readily accessible by an automated parallel synthesis. In terms of our objective, that is the identification of positions in the chromophore and substituents that lead to as low a tendency as possible to crystallize, the compounds presented herein that contain the "standard" substituents methyl and *n*-butyl and in general one varied position should be sufficient.

Differential scanning calorimetry (DSC)[13] was used to characterize the crystallization behavior, wherein the dyes were first melted and then examined for recrystallization or formation of an amorphous glass during the subsequent cooling and a second heating cycle. Figure 1 shows the results of two typical DSC experiments. Whereas most low molecular weight compounds recrystallize from the melt on cooling, compounds **4c** and **4k** form amorphous glasses. Besides the absence of exothermic recrystallization during the cooling cycle (not shown), the course of the DSC plot is characterized by a glass transition at 64 °C (**4c**) and 58 °C (**4k**), respectively, on reheating. In the case of **4c**, recrystallization occurs at a higher temperature, which can be interpreted as the expression of a noticeable tendency to crystallize. This tendency is completely suppressed in **4k**; thus, once melted, the substance only alternates between the melted and the glassy state without recrystallizing even in repeated heating–cooling cycles. This behavior is exceptional for dyes, which are among the substances most prone to crystallization because of their high dipole moments and a pronounced tendency towards π–π stacking.

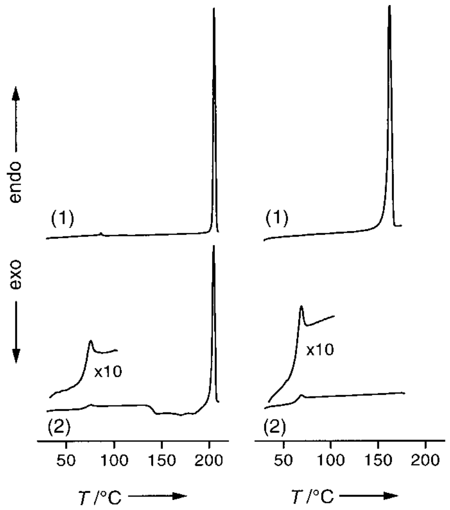


Figure 1. DSC measurements on **4c** (left) and **4k** (right). The heat flows for the first (1) and the second heating cycle (2) are shown. The heating and the cooling rates were 10 K min^{-1} each. The glass transitions are clearly visible in the magnified section. endo: heat absorption, exo: heat emission.

Tables 1 and 2 summarize the DSC results for all the dyes. The colorants were divided into A) crystallizing, B) glass-forming, recrystallizing, and C) glass-forming, non-recrystallizing substances. In accordance with earlier findings for other classes of compounds,[14] the only dye of the C type, **4k**, is characterized by several sterically demanding substituents that prevent the ordered stacking of the π faces. This interpretation is also supported by the high solubility of the compound in all organic solvents and its almost identical color in solution and in the solid state. The tendency to glass formation is already apparent for the parent skeletal structure, as demonstrated by a number of other indoline dyes **4**, in which one or two *n*-alkyl chains already suffice for amorphous solidification (type B). In contrast, only a few thiazole dyes **3** form glasses upon cooling (**3d**, **g**, **l**, **m**). No systematic trend is apparent, especially as the compounds with sterically demanding *tert*-butyl and neopentyl substituents crystallize readily (type A).

Another property listed in Tables 1 and 2 is the very intense photoluminescence exhibited by some of the dyes in the solid state. This finding was surprising to us as solutions of **3**–**6** do not fluoresce. For many fluorophores the opposite behavior is typical, that is despite intensive fluorescence in solution, radiationless deactivation takes place in the crystalline state. Evidently, these properties are also influenced considerably by packing effects, which have a decisive influence on the relaxation paths for the excitation energy. Many of the nonluminescent dyes listed in Table 1 are planar molecules whose bronze or green colors in the solid state indicate strong $\pi-\pi$ interactions in the crystal. The dyes with sterically demanding substituents, on the other hand, form red crystals that shine intensively in numerous cases.[15,16]

The dye library obtained through a highly efficient multicomponent synthesis led us to colorants with glass-forming and solid-state photoluminescent properties. Sterically demanding substituents proved crucial to both properties by determining the packing of the functional π systems, thus paving the way for the exploitation of these interesting dyes in new materials.

Experimental Section

Typical procedure for the synthesis of the merocyanine dyes **3** and **4**: A thiazole **8** (0.05 mol) or a methylene base **9** (0.05 mol), respectively, a hydroxypyridone **7** (0.05 mol), and dimethylformamide (0.075 mol, 5.5 g) were heated to 90 °C in acetic anhydride (20–30 mL) for about 3 h. The solid which precipitated upon cooling to room temperature was filtered off, washed thoroughly with 2-propanol and/or aqueous ethanol until the color of the filtrate changed from violet to red, and subsequently dried in a vacuum-drying cabinet at 50 °C.

For the physical characterization, the dyes were recrystallized from acetic anhydride, toluene, or toluene/hexane mixtures.

Received: November 17, 1998 [Z12673IE]
German version: *Angew. Chem.* **1999**, *111*, 1753–1757

Keywords: combinatorial chemistry · dyes · luminescence · multicomponent reactions · polymethines

---

[1] F. Würthner, R. Wortmann, R. Matschiner, K. Lukaszuk, K. Meerholz, Y. DeNardin, R. Bittner, C. Bräuchle, R. Sens, *Angew. Chem.* **1997**, *109*, 2933–2936, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2765–2768.

[2] P. Gregory, *High-Technology Applications of Organic Colorants*, Plenum, New York, **1991**.

[3] Brilliant hues are obtained when only one absorption band, which additionally has to be as narrow as possible, appears in the visible spectral range. For four-color printing, a medium color component—magenta—with an absorption band between 520 and 550 nm is required.

[4] R. W. Armstrong, A. P. Combs, P. A. Tempest, S. D. Brown, T. A. Keating, *Acc. Chem. Res.* **1996**, *29*, 123–131.

[5] a) G. Seybold (BASF), DE-A 3227329, **1984** [*Chem. Abstr.* **1984**, *100*, 122768k]; b) A. J. Schmidt, R. Sens, K.-H. Etzbach (BASF), DE-A 4440066, **1994** [*Chem. Abstr.* **1996**, *125*, P60959].

[6] I. Gruda, R. M. Leblanc, *Can. J. Chem.* **1976**, *54*, 576–580.

[7] J. Guareschi, *Ber. Dtsch. Chem. Ges. Bd. 4 (Referate, Patente, Nekrologe)* **1896**, *29*, 654–656.

[8] C. Reidlinger, R. Dworczak, W. M. F. Fabian, H. Junek, *Dyes Pigm.* **1994**, *24*, 185–204.

[9] F. Würthner, unpublished results.

[10] a) F. Eiden, *Angew. Chem.* **1960**, *72*, 77; b) F. Eiden, *Arch. Pharmaz.* **1962**, *295*, 516–523.

[11] In numerous reactions, starting materials with purities (NMR, GC) <80% were used and nevertheless very good yields were obtained and pure products isolated. Difficulties were encountered with the most readily soluble dyes when these did not crystallize from the reaction mixtures in the presence of solubility-promoting impurities or when greater amounts of 2-propanol, which became necessary in the washing procedure, led to losses in yield.

[12] Because of the high influence of the purity on the investigated properties (see Tables 1 and 2), the dyes were recrystallized once more.

[13] H. K. Cammenga, M. Epple, *Angew. Chem.* **1995**, *107*, 1284–1301, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1171.

[14] Although the glassy state is regarded as a typical feature of polymeric substances, great progress was recently achieved by using low molecular weight organic glasses in the development of photoconductive and electroluminescent materials: a) K.-Y. Law, *Chem. Rev.* **1993**, *93*, 449–486; b) J. Salbeck, *Ber. Bunsen-Ges. Phys. Chem.* **1996**, *100*, 1667–1677.

[15] Compounds of the structural types **4**–**6** also show intensive luminescence in solid solutions, that is in textile dyeing on polyester. A detailed discussion of the competition between radiationless deactivation and photoluminescence, which is evidently strongly dependent on the rigidity of the matrix, should become possible based on the emission spectra of solid samples and dyed textile fibers as well as on crystal structure analyses.

[16] As extremely small concentrations of impurities already function as traps in the solid state, the data given in Tables 1 and 2 should not be overinterpreted. Especially the substances marked (+) could show better emission properties given a higher purity.

Total Synthesis of (−)-Bafilomycin A_1: Application of Diastereoselective Crotylboration and Methyl Ketone Aldol Reactions[**]

Karl A. Scheidt, Akihiro Tasaka, Thomas D. Bannister, Michael D. Wendt, and William R. Roush*

Bafilomycin A_1 (**1**), a member of the hygrolide family of macrolide antibiotics that includes the concanamycins[1] and the hygrolidins,[2] is a potent vacuolar ATPase inhibitor that displays broad antibiotic activity.[3] First isolated in 1983 by Werner et al. from a culture of *Streptomyces griseus* sp. *sulphurus*,[4] the stereochemistry of the bafilomycins was proposed based on NMR data[5] and was subsequently verified

---

[*] Prof. W. R. Roush, K. A. Scheidt, A. Tasaka, T. D. Bannister, M. D. Wendt
Department of Chemistry, University of Michigan
Ann Arbor, MI, 48109 (USA)
Fax: (+1) 734-647-9279
E-mail: roush@umich.edu

[**] Financial support has been provided by the National Institute of General Medical Sciences (GM 38436). We thank Dr. Timothy Barden of American Cyanamid—Agriculture Research Division, for providing a comparative sample of natural bafilomycin A_1, and Professor S. Hanessian for providing comparative NMR data.

Supporting information for this article is available on the WWW under http://www.wiley-vch.de/home/angewandte/ or from the author.