partially resolved EtOAc molecules ($C_{120.75}H_{64}N_2O_{20}$, $M_r = 1862.74$): Triclinic space group $P\bar{1}$, $Z = 4$, $\rho_{calcd} = 1.368\,g\,cm^{-3}$, $a = 14.218(7)$, $b = 25.562(13)$, $c = 25.916(13)$ Å, $\alpha = 84.18(3)$, $\beta = 74.84(3)$, $\gamma = 89.81(4)°$, $V = 9042(8)$ Å^3. The structure was solved starting with a single fullerene oriented by PATTSEE orientation search and subsequent tangent expansion in $P1$. Refinement by full-matrix least-squares analysis (SHELXTL PLUS; heavy atoms anisotropic, H atoms fixed, whereby H positions are based on stereochemical considerations) to give $R(1) = 0.0964$ and $R_w(2) = 0.2564$ for 2554 variables, 756 restraints, and 18545 observed reflections with $I > 2\sigma(I)$ and $1.74 \leq \theta \leq 50.01$. b) X-ray crystal data for **1**:[16c] Yellow rhomboid crystals ($0.1 \times 0.1 \times 0.015$ mm) were obtained by slow diffusion of hexane into a solution of **1** in EtOAc/PhH and contained a large amount of unresolved solvent molecules ($C_{200.5}H_5N_2O_{20}P_2PtS$, $M_r = 3050.16$): Monoclinic space group $P2(1)/c$, $Z = 4$, $\rho_{calcd} = 1.580\,g\,cm^{-3}$, $a = 29.17(2)$, $b = 17.986(9)$, $c = 27.37(2)$ Å, $\alpha = 90$, $\beta = 116.75(5)$, $\gamma = 90°$, $V = 12821(13)$ Å^3. The structure was solved by Patterson methods and refined by full-matrix least-squares analysis (SHELXTL PLUS; heavy atoms isotropic, bond distances and angles of the partially disordered diethyl malonate groups constrained by SHELX-DFIX-instructions) to give $R = 0.109$ and $R_w = 0.092$ (based on F) for 756 variables and 5549 observed reflections with $I > 2\sigma(I)$ and $1.70 \leq \theta \leq 35.10$. c) Data collection at $T = 293$ K: Picker–Stoe diffractometer, $Cu_{K\alpha}$ radiation using ω scans, $\lambda = 1.54178$ Å. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-101112. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

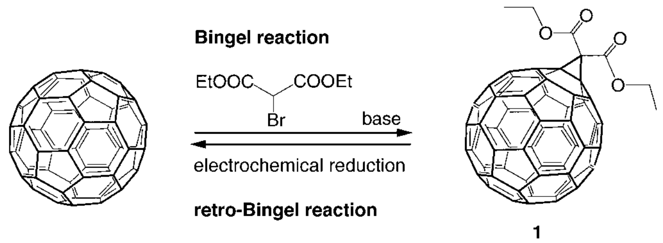
[17] F. Cardullo, P. Seiler, L. Isaacs, J.-F. Nierengarten, R. F. Haldimann, F. Diederich, T. Mordasini-Denti, W. Thiel, C. Boudon, J.-P. Gisselbrecht, M. Gross, *Helv. Chim. Acta* **1997**, *80*, 343–371.

Preparation of Enantiomerically Pure C_{76} with a General Electrochemical Method for the Removal of Di(alkoxycarbonyl)methano Bridges from Methanofullerenes: The Retro-Bingel Reaction**

Roland Kessinger, Jeanne Crassous, Andreas Herrmann, Markus Rüttimann, Luis Echegoyen,* and François Diederich*.

Since its discovery in 1993, the Bingel reaction[1] has been widely used as a mild, versatile method to introduce one or more methano bridges into C_{60}[2] and the higher fullerenes.[3] Cyclopropanation of a fullerene, according to the original Bingel protocol, occurs by treating the carbon allotrope with 2-bromomalonate esters in the presence of base. Modified procedures allowing in situ formation of the 2-bromo- or 2-iodomalonates have also been reported.[4, 5] Cyclopropane rings fused to fullerenes are highly stable and cannot be removed thermally or by wet-chemical methods, although mass spectrometric fragmentation occurs rather readily.[6]

The majority of methanofullerenes are also known to be very stable under the conditions of cyclic (CV) and steady-state voltammetry (SSV).[7] A notable exception was reported by Haddon, Wudl, and co-workers[8] for the monoanion of 1,2-methano[60]fullerene-61,61-dinitrile, which was unstable under CV conditions and, based upon voltammetric observations, was reported to revert back to C_{60}.[9] Also, the electrochemistry group of M. Gross at Strasbourg had noted a decomposition of dianions of specific bis(methano)fullerenes with a *cis-2* addition pattern during CV and SSV, and this observation provided the impetus for the work reported here.[7c, 10] In this paper, we describe the retro-Bingel reaction (Scheme 1) as a general, preparative electrochemical method[11, 12] for the removal of di(alkoxycarbonyl)methano bridges from methanofullerenes and illustrate its power with the preparation of the pure enantiomers of C_{76}.[13, 14]



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Scheme 1. The Bingel and retro-Bingel reactions.

Electrochemical investigations on diethyl 1,2-methano[60]fullerene-61,61-dicarboxylate (**1**) and similar C_{60} monoadducts have shown that the first two reduction steps are electrochemically and chemically reversible on the voltammetric time scale at a scan rate of $100\,mV\,s^{-1}$.[7b, 8] Our CV data are in agreement with these earlier findings (Figure 1). Chemical irreversibility of the second reduction is only evident at very slow scan rates. We reduced **1** electrochemically in CH_2Cl_2 containing 0.1 M Bu_4NPF_6 at 293 K at controlled potential, initially to its monoanionic state (at −1.2 V versus a Ag wire pseudo reference electrode).[15] The charge transferred corresponded exactly to one electron per molecule, and the resulting anion was very stable under these conditions, with no apparent decomposition after 30 min. The formation of the dianion (at −1.55 V versus Ag) by controlled potential electrolysis (CPE, Figure 1), on the other hand, was surprising, because the charge transferred corresponded to four electrons per molecule and not just one. Clear changes in the CV indicated that some chemical reaction had taken place. After 30 min of electrolysis, reoxidation of the solution at 0 V (versus Ag), followed by column chromatography (SiO_2, toluene) yielded pure C_{60} in over 80% yield (Table 1). It must be stressed that the two first reduction steps are perfectly reversible on the CV time scale at a scan rate of

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[*] Prof. Dr. L. Echegoyen
Department of Chemistry, University of Miami
Coral Gables, FL 33124, USA
Fax: (+1)305-284-4571
E-mail: lechegoyen@umiami.ir.miami.edu

Prof. Dr. F. Diederich, Dr. J. Crassous, Dr. A. Herrmann,
Dipl.-Chem. R. Kessinger, Dipl.-Chem. M. Rüttimann
Laboratorium für Organische Chemie, ETH-Zentrum
Universitätstrasse 16, CH-8092 Zürich (Switzerland)
Fax: (+41)1-632-1109
E-mail: diederich@org.chem.ethz.ch

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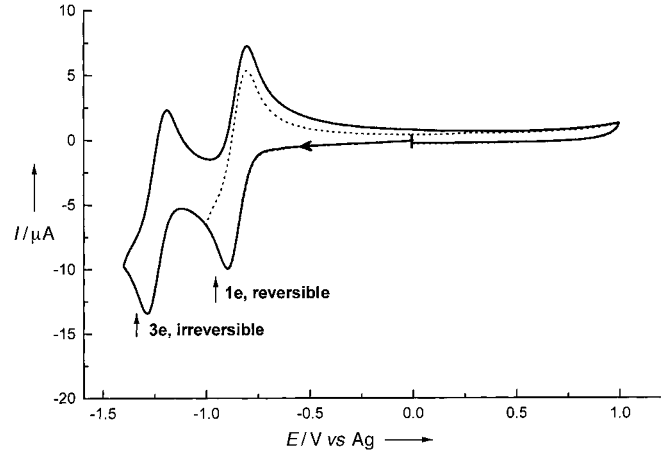


Figure 1. CV of **1** in CH_2Cl_2 containing 0.1 M Bu_4NPF_6, with a scan rate of 100 mV s^{-1}. The working electrode was a glassy carbon mini-electrode. The dotted line corresponds to a scan with a switching potential of −1 V versus the Ag wire pseudo reference electrode, and the solid line to one with a switching potential of −1.4 V. Shown are the potentials applied in the controlled potential coulometry.

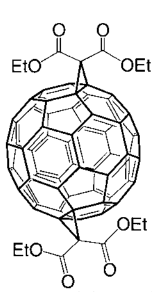
Table 1. Results of the retro-Bingel reaction by CPE in CH_2Cl_2.

Starting material	Product	Yield[%]
1	C_{60}	82
2	C_{60}	75
3	C_{60}	75
4	C_{70}	70
5	C_{76}	5[a]
6	*ent*-C_{76}	9[a]

[a] Not optimized.

100 mV s^{-1} (Figure 1). It was thus surprising to see that controlled potential bulk electrolysis at the second reduction potential led to complete chemical irreversibility yielding predominantly C_{60}. The mechanism of this reaction, which we call the retro-Bingel reaction, is not yet fully understood but is under investigation in our laboratory.

The generality of the retro-Bingel reaction was proven by CPE (under the conditions described above) of the bis-Bingel adducts[2] **2**[16] and **3**[7c], which were converted cleanly and in over 75 % yield into C_{60} (Table 1). As in the case of **1**, CPE was conducted at the second reduction potential, but the number of electrons transferred per molecule was approximately six instead of four. The reaction is not limited to C_{60} derivatives and was shown to work also for the C_{70} monoadduct **4**,[17a] which reacted cleanly to give C_{70} in 70 % yield.



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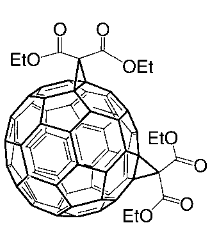
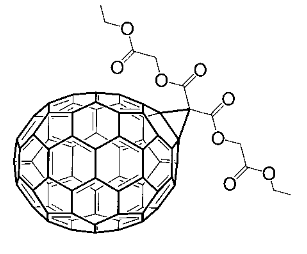


3 (*e*)



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We monitored the retro-Bingel reaction of **4** by CV. The first reduction step is fully reversible (Figure 2a), whereas the second reduction process in this case is electrochemically irreversible (Figure 2b), and, not surprisingly, bulk electrolysis at the potential corresponding to the irreversible second reduction process (−1.3 V versus Ag) led to a net charge transfer of four electrons per molecule, transforming **4** into C_{70}. This conversion occurs stepwise since new waves between 0 and −0.5 V (versus Ag) started appearing during electrolysis (Figure 2c), providing evidence for the formation of intermediates. These intermediates eventually disappeared when the conversion into pure C_{70} was complete (Figure 2d). These intermediate species are under current investigation as possible clues to the mechanism of the retro-Bingel reaction.

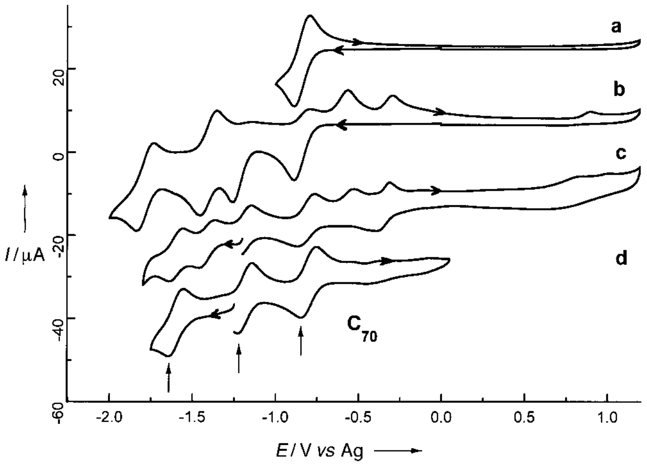
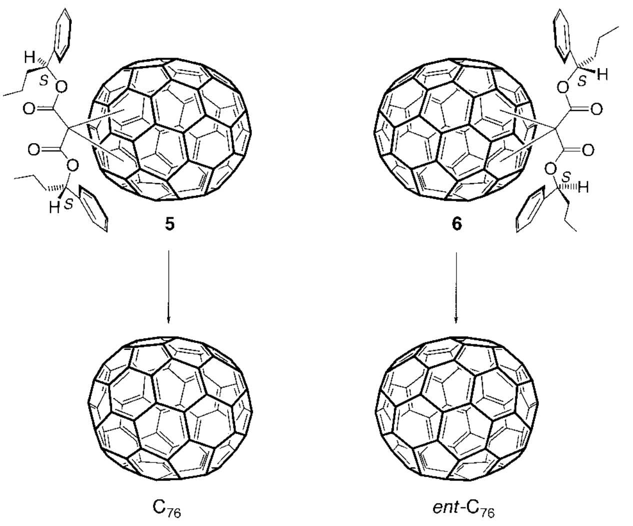


Figure 2. CV data for **4** in CH_2Cl_2 containing 0.1 M Bu_4NPF_6, with a glassy carbon working electrode and a scan rate of 100 mV s^{-1}. a) Initial scan showing the reversibility of the first reduction process. b) Scan with a switching potential of −2 V (versus Ag), clearly showing the irreversibility of subsequent reductions, even the second one. c) Voltammogram recorded after electrolyzing the solution with a net charge corresponding to a four-electron transfer per molecule. The scan was started at the rest potential, around −1.25 V (versus Ag). d) Same as in (c), but after waiting approximately 30 min. Notice the almost exclusive observation of the first three reduction waves of pure C_{70}.

Hawkins and Meyer had performed the kinetic optical resolution on a small scale of the inherently chiral fullerene D_2-C_{76} by employing the asymmetric Sharpless osmylation reaction.[14a] A comparison of the circular dichroism (CD) spectra reported by Hawkins and Meyer for the C_{76} enantiomers[14a] to those of a variety of optically active, covalent derivatives of C_{76} prepared by us[18] had revealed a large, unexpected difference in the magnitude of the Cotton effects. Whereas the covalent C_{76} derivatives displayed bands whose $\Delta\varepsilon$ values can be up to 250 $M^{-1}cm^{-1}$, the enantiomers of the pure fullerene displayed bands with $\Delta\varepsilon$-values up to only 32 $M^{-1}cm^{-1}$.[14a, 19] In order to reinvestigate the chiroptical properties of C_{76}, we applied the retro-Bingel reaction to the preparation of the enantiomerically pure higher fullerene (Scheme 2). When the optically active, diastereoisomerically pure C_{76} monoadducts **5** and **6**, with enantiomeric carbon cores,[18] were submitted to CPE and subsequent purification by HPLC,[20] the two enantiomers, C_{76} and (*ent*-C_{76}) were



Scheme 2. Retro-Bingel reaction of the diastereoisomerically pure, optically active C_{76} monoadducts **5** and **6**. The location of the malonate addend is not exactly known although tentative constitutional assignments have been made. The CD spectra, however, provide unambiguous evidence that the two compounds are associated pairs of diastereoisomers.[18, 21]

obtained in low yields (about 5–10%) which have not yet been optimized because of the limited availability of the starting materials.

The CD spectra of C_{76} and *ent*-C_{76} displayed the expected mirror image shapes (Figure 3, Table 2) with band positions in full agreement with those reported by Hawkins and Meyer.[19] In contrast, however, the Cotton effects in our spectra are almost a full magnitude larger than those previously reported. The $\Delta\varepsilon$ values can be as large as $210\,\mathrm{M^{-1}cm^{-1}}$ and are therefore much more in agreement with the values measured for optically pure C_{76} derivatives such as **5** and **6**.[21] Two possible reasons may account for the noticeably low values reported by Hawkins and Meyer: Either the enantiomeric purity of their samples was not very high or their concentrations were not accurately determined.[22]

We now intend to apply the retro-Bingel reaction also to the formation of other enantiomerically pure higher fullerenes such as D_3-C_{78} or D_2-C_{84}, starting from diastereoisomerically pure malonate adducts. Furthermore, the sequence of the Bingel followed by the retro-Bingel reaction also permits the introduction of the cyclopropane ring as a new protecting group in fullerene chemistry, which should be selectively removable in the presence of many other addends. With the capability of selectively reversing both fullerene cyclopropanation and, by an indirect method,[7c, 23] the Diels–Alder addition, our tether-directed remote functionalization,[2c] which introduces both cyclopropane and cyclohexene rings, should now lead to an even greater diversity of hitherto unknown multiple addition patterns on the fullerene surface that are not available by other methods.

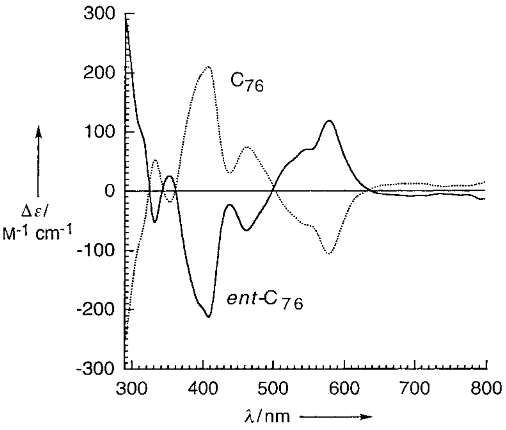


Figure 3. CD Spectra of C_{76} and *ent*-C_{76} in toluene (see Table 2).

Table 2. Circular dichroism spectra of C_{76} ($c = 3.4\times10^{-6}$ M in toluene) and *ent*-C_{76} ($c = 8.0\times10^{-6}$ M in toluene) in the range 290–800 nm. Both compounds were prepared from the retro-Bingel reaction.

C_{76}		*ent*-C_{76}	
λ [nm]	$\Delta\varepsilon$ [$\mathrm{M^{-1}cm^{-1}}$]	λ [nm]	$\Delta\varepsilon$ [$\mathrm{M^{-1}cm^{-1}}$]
315	−73[a]	316	+80[a]
331	+53.4	331	−52.3
352	−18.8	351	+23.7
391	+186[a]	391	−186[a]
406	+210.4	407	−215.5
463	+74.1	462	−66.0
519	−32[a]	520	+45[a]
541	−55.8	549	+69.5
578	−106.3	578	+117.0
629	−6[a]	629	+6[a]
694	+9.7	700	−9.7

[a] Shoulders; $\Delta\varepsilon$ values have greater uncertainties.

Experimental Section

Fullerene monoadduct **1** (11 mg, 12.5 μmol) and supporting electrolyte Bu_4NPF_6 (0.8 g) were added into a home-built electrochemical cell,[12b] and the cell was degassed and pumped to 10^{-6} Torr before the dried CH_2Cl_2 (17 mL), which had also been degassed and pumped to the same pressure, was vapor-transferred directly into the cell. CPE at 293 K on a Pt mesh working electrode (100 mesh, 6.5 cm^2) at −1.55 V versus a Ag wire pseudo reference electrode, separated from the solution by a Vycor tip, was performed for 30 min after which the solution was reoxidized at 0 V versus Ag for the same length of time. The electrolyte was removed by passing the mixture through a short column of SiO_2, and elution with toluene yielded pure C_{60} (7.4 mg, 82%).

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[1] C. Bingel, *Chem. Ber.* **1993**, *126*, 1957–1959.

[2] a) A. Hirsch, I. Lamparth, H. R. Karfunkel, *Angew. Chem.* **1994**, *106*, 453–455; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 437–438; b) I. Lamparth, G. Schick, A. Hirsch, *Liebigs Ann.Chem./Recueil* **1997**, 253–258; c) F. Diederich, C. Thilgen *Science* **1996**, *271*, 317–323; L. Isaacs, F. Diederich, R. F. Haldimann, *Helv. Chim. Acta* **1997**, *2*, 317–342.

[3] C. Thilgen, A. Herrmann, F. Diederich, *Angew. Chem.* **1997**, *109*, 2362–2374; *Angew. Chem. Int. Ed .Engl.* **1997**, *36*, 2268–2280.

[4] a) C. Bingel, presentation at the conference *New Perspectives in Fullerene Chemistry and Physics*, Rome, **1994**; b) J.-F. Nierengarten, V. Gramlich, F. Cardullo, F. Diederich, *Angew. Chem.* **1996**, *108*, 2242–2244; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2101–2103.

[5] X. Champs, A. Hirsch, *J. Chem. Soc. Perkin Trans. 1* **1997**, 1595–1596.

[6] For a hint that the Bingel-addend may be removed at very high temperatures, see A. Hirsch, I. Lamparth, T. Grösser, H. R. Karfunkel, *J. Am. Chem. Soc.* **1994**, *116*, 9385–9386.

[7] a) D. M. Guldi, H. Hungerbühler, K.-D. Asmus, *J. Phys. Chem.* **1995**, *99*, 9380–9385; b) C. Boudon, J.-P. Gisselbrecht, M. Gross, L. Isaacs, H. L. Anderson, R. Faust, F. Diederich, *Helv. Chem. Acta* **1995**, *78*, 1334–1344; c) F. Cardullo, P. Seiler, L. Isaacs, J.-F. Nierengarten, R. F. Haldimann, F. Diederich, T. Mordasini-Denti, W. Thiel, C. Boudon, J.-P. Giesselbrecht, M. Gross, *Helv. Chim. Acta* **1997**, *80*, 343–371.

[8] M. Keshavarz-K., B. Knight, R. C. Haddon, F. Wudl, *Tetrahedron* **1996**, *52*, 5149–5159.

[9] For the ring opening of cyclopropanes by electrochemical reduction, see J. Y. Becker in *The Chemistry of the Cyclopropyl Group, Part 2* (ed.: Z. Rappoport), Wiley, Chichester, **1987**, pp. 915–958.

[10] R. Kessinger, M. Gómez-López, C. Boudin, J.-P. Gisselbrecht, M. Gross, L. Echegoyen, F. Diederich, *J. Am. Chem. Soc.*, submitted.

[11] For the loss of fullerene addends (H, Cl, Pt, or Pd) by electrochemical reduction during CV, see a) P. Boulas, F. D'Souza, C. C. Henderson, P. A. Cahill, M. Thomas Jones, K. M. Kadish, *J. Phys. Chem.* **1993**, *97*, 13435–13437; b) T. F. Guarr, M. S. Meier, V. K. Vance, M. Clayton, *J. Am. Chem. Soc.* **1993**, *115*, 9862–9863; c) F. N. Tebbe, J. Y. Becker, D. B. Chase, L. E. Firment, E. R. Holler, B. S. Malone, P. J. Krusic, E. Wasserman, *J. Am. Chem. Soc.* **1991**, *113*, 9900–9901; d) S. A. Lerke, B. A. Parkinson, D. H. Evans, P. J. Lerke, D. H. Evans, P. J. Fagan, *J. Electroan. Chem.* **1995**, *383*, 127–132; e) S. A. Lerke, B. A. Parkinson, D. H. Evans, P. J. Fagan, *J. Am. Chem. Soc.* **1992**, *114*, 7807–7813. f) H. Nagashima, M. Nakazawa, T. Furukawa, K. Itoh, *Chem. Lett.* **1996**, 405–406.

[12] For electrochemical synthesis of fullerene adducts, see a) C. Caron, R. Subramanian, F. D'Souza, J. Kim, W. Kutner, M. T. Jones, K. M. Kadish, *J. Am. Chem. Soc.* **1993**, *115*, 8505–8506; b) P. L. Boulas, Y. Zuo, L. Echegoyen, *Chem. Commun.* **1996**, 1547–1548.

[13] R. Ettl, I. Chao, F. Diederich, R. L. Whetten, *Nature* **1991**, *353*, 149–153.

[14] a) J. M. Hawkins, A. Meyer, *Science* **1993**, *260*, 1918–1920; b) J. M. Hawkins, M. Nambu, A. Meyer, *J. Am. Chem. Soc.* **1994**, *116*, 7642–7645.

[15] All controlled potential electrolyses were executed in a home-built electrochemical cell,[12b] and all electrochemical experiments were performed with an EG&G Princeton Applied Research model 263 A potentiostat/galvanostat.

[16] J.-F. Nierengarten, T. Habicher, R. Kessinger, F. Cardullo, F. Diederich, V. Gramlich, J.-P. Gisselbrecht, C. Boudon, M. Gross, *Helv. Chim. Acta* **1997**, *80*, 2238–2276.

[17] a) A. Herrmann, M. Rüttimann, C. Thilgen, F. Diederich, *Helv. Chim. Acta* **1995**, *78*, 1673–1704; b) C. Bingel, H. Schiffer, *Liebigs. Ann.* **1995**, 1551–1553.

[18] A. Herrmann, F. Diederich, *Helv. Chim. Acta* **1996**, *79*, 1741–1756.

[19] CD spectrum of enantiomerically pure C_{76} ($c = 3.8\times10^{-5}$ M) in toluene:[14a] λ[nm] ($\Delta\varepsilon$ [$\mathrm{M^{-1}cm^{-1}}$]: 315 (−11.7), 330 (+8.9), 354 (−4.2), 394 (+29.4), 405 (+31.6), 460 (+12.6), 541 (−11.1), 573 (−18.2), 639 (+2.5).

[20] Preparative HPLC on a Regis Buckyclutcher I Trident-Tri-DNP (10 mm) 500 mm × 21.1 mm column with an n-hexane/toluene (60/40) mobile phase at 8 mL min^{-1}.

[21] The chiroptical properties of both functionalized inherently chiral fullerene derivatives and derivatives with an inherently chiral addition pattern are largely determined by the chirality of the carbon sphere and not by the chirality of the addends.[17a, 18]

[22] We determined the concentrations of the enantiomeric solutions based on their known UV/Vis absorptions (see reference [13] and A. Herrmann, doctoral dissertation, ETH Zürich, **1997**).

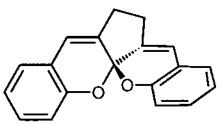
[23] a) Y.-Z. An, G. A. Ellis, A. L. Viado, Y. Rubin, *J. Org. Chem.* **1995**, *60*, 6353–6361; b) F. Cardullo, L. Isaacs, F. Diederich, J.-P. Gisselbrecht, C. Boudon, M. Gross, *Chem. Commun.* **1996**, 797–799.

Enantiomeric Enrichment of Stereolabile Chiral Spiro Compounds by Dynamic HPLC on Chiral Stationary Phases[**]

Klaus Lorenz, Eiji Yashima, and Yoshio Okamoto[*]

Chromatographic enantioseparation on chiral stationary phases (CSPs)[1–5] has become a very useful method for the analysis of chiral compounds and the preparative separation of enantiomers because of recent progress in the development of CSPs with high chiral recognition ability. In addition, the newly developed dynamic high-performance liquid chromatography (DHPLC) has received considerable attention as a powerful tool for investigating dynamic processes of interconverting enantiomers;[6–11] kinetic data and enantiomerization barriers for stereolabile compounds can be obtained from a series of temperature-dependent plateaus and peak shapes by chiral DHPLC. Here, we focus on the influence of CSPs on the equilibrium of interconverting enantiomers which will result in nonracemic mixtures. In the case of interconverting enantiomers, the use of CSPs opens the possibility for combining separation techniques and equilibrium shift in one step. By employing quite simple new chromatographic procedures we may, in principle, obtain one enantiomerically pure enantiomer in 100% yield from a racemate with standard HPLC equipment.

We investigated the racemic spiro compounds **1** and **2** as model compounds. Both enantiomerize thermally and photochemically through an electrocyclic [1,6]-ring opening of the C–O bond next to the spiro center and consecutive ring closure.[12]



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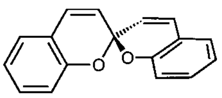

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Figure 1a shows a standard HPLC chromatogram for the resolution of **1** on Chiralcel OD.[13] Compound **1** can be completely resolved at 20 °C without any enantiomerization. However, at higher temperatures (ca. 50 °C), the enantiomerization processes described in Scheme 1 (DHPLC on CSPs)[14,15] lead to plateaulike elution profiles[16] (Figure 1b). In the heterogeneous system (CSP/mobile phase) the adsorbed enantiomer showing a longer retention time (B) should be enriched, whereas the eluent may contain a racemic mixture under equilibrium conditions.

According to the kinetic differential equations describing the enantiomerization processes during DHPLC, only race-

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[*] Prof. Y. Okamoto, Dr. K. Lorenz, Dr. E. Yashima
Department of Applied Chemistry, Graduate School of Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464–8603 (Japan)
Fax: (+81) 52-789-3188
E-mail: okamoto@apchem.nagoya-u.ac.jp

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