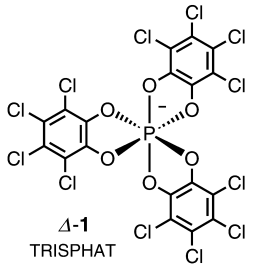
Efficient Enantioselective Extraction of Tris(diimine)ruthenium(II) Complexes by Chiral, Lipophilic TRISPHAT Anions**

Jérôme Lacour,* Catherine Goujon-Ginglinger, Sonya Torche-Haldimann, and Jonathan J. Jodry

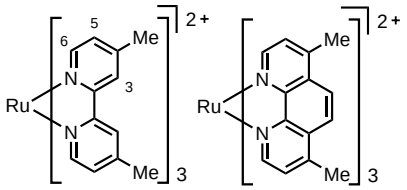
Chiral tris(diimine)ruthenium(II) complexes have been extensively studied because of their photochemical, photophysical, and biological properties.[1] The complexes are commonly synthesized in racemic form and obtained enantiopure by resolution procedures that separate the Δ and Λ enantiomers. Traditionally, resolution of the chiral cationic complexes is realized by the formation of diastereomeric ion pairs with anionic chiral-resolving agents. Selective crystallization[2] or ion-pair chromatography[3] may then result in the separation of the diastereomeric salts. We now report a novel enantioselective method of resolution based on the asymmetric extraction of racemic, water-soluble $[Ru(diimine)_3]Cl_2$ complexes with lipophilic, tris(tetrachlorobenzenediolato)phosphate(v) (TRISPHAT) salts. Phase separation allows the isolation of the Δ and Λ enantiomers of the ruthenium complexes with selectivity ratios up to 49:1.



The resolution of racemic substrates by preferential extraction of one enantiomer from water into immiscible organic solvents has been well studied.[4] The extraction and the subsequent selectivity arise from the preferential binding in the organic phase of one enantiomer of the substrate to a chiral lipophilic selector. The racemic substrates are traditionally ammonium salts or zwitterionic amino acids.[5] Crown ethers with chiral elements in or around the backbone are usually used to ensure the asymmetric discrimination. Selectivity ratios as high as 99:1 have been obtained.[5g] Recent studies have described the use of novel selectors, such as, lanthanide tris(β-diketonates) and polymeric columnar aggregates of deoxyguanosine.[6] Of most relevance to our current work is the observation by Lindoy, Everett, and co-workers that chiral Co^{III} amine complexes can be extracted from aqueous layers into $CHCl_3$ using Lasalocid A as the chiral host with a diastereomeric ratio (d.r.) of up to 2.6:1.[7]

We recently reported the synthesis and resolution of TRISPHAT anion **1**[8] which has D_3 symmetry. This anion is an efficient NMR chiral shift reagent and a chiral inducer onto iron(II) tris(diimine) complexes.[8] The Λ enantiomer of **1** is isolated as the tri(*n*-butyl)ammonium (**2**) salt ([**2**][Λ-**1**]) and is soluble in pure $CHCl_3$. The Δ enantiomer of **1** is prepared as the cinchonidinium (**3**) salt ([**3**][Δ-**1**]) and is soluble in more polar solvent mixtures (>7.5% DMSO in $CHCl_3$). More importantly, we observed that the lipophilic[9] TRISPHAT anion confers an affinity for organic solvents on these salts and, once dissolved, [**2**][Λ-**1**] and [**3**][Δ-**1**] do not partition in aqueous layers. We thus considered using the anions **1** as chiral selectors in asymmetric extraction procedures of chiral cations.

We selected the complexes $[Ru(4,4'\text{-}Me_2bpy)_3]^{2+}$ (**4**) and $[Ru(4,7\text{-}Me_2phen)_3]^{2+}$ (**5**) (4,4′-Me_2bpy = 4,4′-dimethylbipyridine; 4,7-Me_2phen = 4,7-dimethylphenanthroline) as chiral substrates because of their solubility in water as dichloride salts. The racemic salts [**4**][PF_6]$_2$ and [**5**][PF_6]$_2$ were prepared



in a single step from $[Ru(dmso)_4]Cl_2$ and three equivalents of the respective ligand.[10] The solubilization of [**4**][PF_6]$_2$ and [**5**][PF_6]$_2$ in water in the presence of Dowex 1X8 afforded the dichloride salts [**4**]Cl_2 and [**5**]Cl_2, respectively, in quantitative yield. The simple and efficient extraction of the cations **4** and **5** by the TRISPHAT anion **1** was then demonstrated. Solutions of the salts [**2**][Λ-**1**] in $CHCl_3$ or [**3**][Δ-**1**] in 7.5–10% DMSO/$CHCl_3$ were prepared (10^{-3} M, 1 equiv) and added to the orange solutions of racemic [**4**]Cl_2 or [**5**]Cl_2 in water (1 equiv). Upon vigorous stirring of the biphasic mixtures, a partial transfer of color from the aqueous to the organic layer occurred.[11] Several experiments demonstrated that stirring for 10 min is sufficient to complete the extraction.

The organic and aqueous phases were separated, concentrated in vacuo and the resulting orange solid residues analyzed by ^{1}H NMR spectroscopy. The residue from the aqueous layer contained the chloride complexes that had not been extracted and the cations **2** or **3** that had been transferred from the organic layer during the extraction; no trace of **1** (^{31}P NMR) was observed in the aqueous layer. The residue from the organic layer contained the extracted ruthenium complexes **4** and **5** with two equivalents of the counterion **1** ([**4**][**1**]$_2$ or [**5**][**1**]$_2$). In the experiments performed with the salt [**2**][Λ-**1**], we often observed traces of the cation **2** (0–15%) in the organic layer. Cation **2** is associated with a chloride anion and could be removed by washing the organic layer several times with water.

The selectivity of the extraction was readily determined by ^{1}H NMR spectroscopy. In the organic phases, the enantiopure anions Λ-**1** or Δ-**1**, associated with the cations **4** or **5**, behave as efficient NMR chiral shift reagents.[8a] With cation **4**, two sets of signals are observed, which correspond to the Δ and Λ enantiomers (Figure 1); the d.r. of ≥8.7:1 was measured by

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[**] This work was supported by the Swiss National Science Foundation. We thank A. Pinto, J.-P. Saulnier, W. Kloeti, and E. Sandmeyer for NMR and MS measurements. TRISPHAT = tris(tetrachlorobenzenediolato)phosphate(v).

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

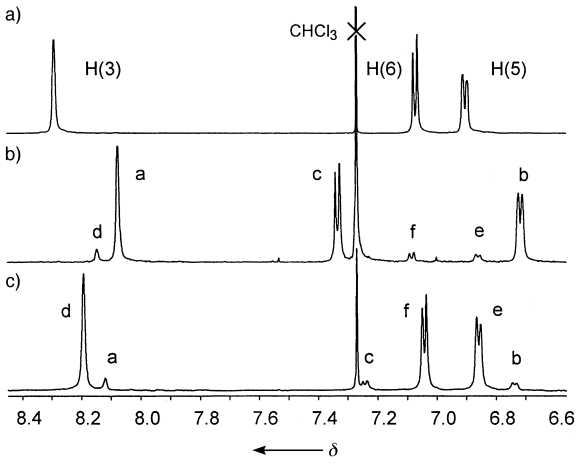


Figure 1. Extraction of [*rac*-**4**]Cl_2 with [**2**][*Λ*-**1**]. ^{1}H NMR spectra (δ = 8.45 – 6.6; [D_6]DMSO/$CDCl_3$ (20/80)) of a) *rac*-**4**-Cl_2, b) the organic layer (d.r. = 8.7:1), and c) the aqueous layer + 2.7 equiv of [**2**][*Λ*-**1**] (e.r. = 8.4:1). Signals a – c and d – f correspond to the hydrogens H(3), H(5), and H(6) in [*Λ*-**4**][*Λ*-**1**]$_2$ and [*Δ*-**4**][*Λ*-**1**]$_2$, respectively.

integration of the respective signals (Table 1, entries 1 and 2). When the cation **5** was used we could detect the signals of a single diastereomer by ^{1}H NMR spectroscopy. This result indicates that the diastereoselectivity of the extraction of **5** is excellent (d.r. $\geq$ 49:1). In both examples with the cations **4** and **5** the diastereoselectivity is largely independent of the source of the TRISPHAT anion.

Table 1. Results of the asymmetric extraction of complexes [**4**]Cl_2 or [**5**]Cl_2 by [**2**][*Λ*-**1**] or [**3**][*Δ*-**1**].

Entry	Cation	S[a]	EY[b] [%]	OLC[c]	d.r.$_{org}$[d]	ALC[e]	e.r.$_{aq}$[f]
1[g]	**4**	*Λ*	48	*Λ*	8.7:1	*Δ*	8.4:1
2[h]	**4**	*Δ*	46	*Δ*	12.3:1	*Λ*	–
3[g]	**5**	*Λ*	45	*Λ*	> 49:1	*Δ*	35:1
4[i]	**5**	*Δ*	48	*Δ*	49:1	*Λ*	–

[a] S is the configuration of the anion **1** in the chiral selector used. [b] EY is the extraction yield. [c] OLC is the configuration of the most abundant enantiomer of the cation in the organic layer. [d] d.r.$_{org}$ the diastereomeric ratio. [e] ALC is the configuration of the most abundant enantiomer of the cation in the aqueous layer. [f] e.r.$_{aq}$ the enantiomeric ratio. [g] Organic layer: $CHCl_3$. [h] Organic layer: 7.5% DMSO in $CHCl_3$. [i] Organic layer: 10% DMSO in $CHCl_3$.

The absolute configurations of the complexes **4** or **5** extracted in the organic layers—*Λ* and *Δ* for the experiments with [**2**][*Λ*-**1**] and [**3**][*Δ*-**1**], respectively— were assigned by circular dichroism (CD) in 1% DMSO in CH_2Cl_2.[3a, 12] Homochiral diastereomers ([*Λ*$^+$][*Λ*$^-$]$_2$ and [*Δ*$^+$][*Δ*$^-$]$_2$) are thus preferentially extracted.[13] The CD spectra of the salts [**4**]Cl_2 and [**5**]Cl_2 which remained in the aqueous layer after the extraction and phase separation showed, as expected, opposite Cotton effects.

In the extraction experiments performed with the salt [**2**][*Λ*-**1**], we also determined the enantiomeric purity of the complexes [**4**]Cl_2 and [**5**]Cl_2, that remained in the aqueous layer after the phase separation (Table 1).[8a, 14] Enantiomeric ratios of 8.4:1 and 35:1 were measured for complexes [**4**]Cl_2 (Figure 1) and [**5**]Cl_2, respectively. The diastereomeric and enantiomeric ratios—in the organic layer and aqueous layer—are thus quasi identical. This is an important feature of this extraction procedure. In many examples of asymmetric extraction, an excess of the racemic substrate (5- to 35-fold) is used in the presence of the chiral selector. The enantiomeric purity of the substrate that remains in the aqueous layer is then low, even if the diastereoselectivity of the extraction is very high.

Experimental Section

Full details of the experimental and extraction procedures can be found in the Supporting Information.

In a flask (25 mL) equipped with a magnetic stirrer, a solution of either [**4**]Cl_2 or [**5**]Cl_2 (10 μmol) in water (10 mL) was added to a solution of [*n*Bu_3NH][*Λ*-**1**] (10 μmol) in $CHCl_3$ (10 mL) or [cinchonidinium][*Δ*-**1**] (10 μmol) in 7.5 – 10% DMSO in $CHCl_3$.[15] After 10 min of vigorous stirring the reaction mixture was left to stand for 5 min. The two phases were separated and the organic layer was washed with water. The organic phase was dried (Na_2SO_4), filtered, and concentrated in vacuo to afford an orange solid. The diastereomeric purity of this extracted adduct was measured directly by ^{1}H NMR analysis. The aqueous layer was concentrated in vacuo and dried at 50 °C for 12 h to afford an orange solid. In the experiments performed with [*n*Bu_3NH][*Λ*-**1**], the enantiomeric purity of the complexes [**4**]Cl_2 and [**5**]Cl_2 that remained in the aqueous phases was determined by ^{1}H NMR analysis after the addition of 2 – 3 equiv of the NMR chiral shift reagent [*n*Bu_3NH][*Λ*-**1**].

Received: February 3, 2000
Revised: May 12, 2000 [Z 14645]

[1] a) A. von Zelewsky, P. Belser, P. Hayoz, R. Dux, X. Hua, A. Suckling, H. Stoeckli-Evans, *Coord. Chem. Rev.* **1994**, *132*, 75 – 85; b) J. K. Barton, *Science* **1986**, *233*, 727 – 734; c) J. K. Barton, *Pure Appl. Chem.* **1989**, *61*, 563 – 564; d) I. Ortmans, C. Moucheron, A. Kirsch-De Mesmaeker, *Coord. Chem. Rev.* **1998**, *168*, 233 – 271.

[2] a) F. P. Dwyer, E. C. Gyarfas, *J. Proc. R. Soc. N.S.W.* **1949**, *83*, 174 – 176; b) F. P. Dwyer, E. C. Gyarfas, *J. Proc. R. Soc. N.S.W.* **1949**, *83*, 170 – 173; c) R. D. Gillard, R. E. E. Hill, *J. Chem. Soc. Dalton Trans.* **1974**, 1217 – 1236; d) G. B. Porter, R. H. Sparks, *J. Photochem.* **1980**, *13*, 123 – 131.

[3] a) T. J. Rutherford, P. A. Pellegrini, J. Aldrich-Wright, P. C. Junk, F. R. Keene, *Eur. J. Inorg. Chem.* **1998**, 1677 – 1688; b) B. T. Patterson, F. R. Keene, *Inorg. Chem.* **1998**, *37*, 645 – 650; c) N. C. Fletcher, P. C. Junk, D. A. Reitsma, F. R. Keene, *J. Chem. Soc. Dalton Trans.* **1998**, 133 – 138; d) T. J. Rutherford, M. G. Quagliotto, F. R. Keene, *Inorg. Chem.* **1995**, *34*, 3857 – 3858; e) F. R. Keene, *Coord. Chem. Rev.* **1997**, *166*, 121 – 159; f) J. Lacour, S. Torche-Haldimann, J. J. Jodry, C. Ginglinger, F. Favarger, *Chem. Commun.* **1998**, 1733 – 1734.

[4] E. L. Eliel, S. H. Wilen, *Stereochemistry of Organic Compounds*, Wiley, New York, **1994**, pp. 416 – 421.

[5] a) E. B. Kyba, K. Koga, L. R. Sousa, M. G. Siegel, D. J. Cram, *J. Am. Chem. Soc.* **1973**, *95*, 2692 – 2693; b) R. C. Helgeson, J. M. Timko, P. Moreau, S. C. Peacock, J. M. Mayer, D. J. Cram, *J. Am. Chem. Soc.* **1974**, *96*, 6762 – 6763; c) S. M. Peacock, D. J. Cram, *J. Chem. Soc. Chem. Commun.* **1976**, 282 – 285; d) J.-M. Lehn, J. Simon, A. Moradpour, *Helv. Chim. Acta* **1978**, *61*, 2407 – 2418; e) D. S. Lingenfelter, R. C. Helgeson, D. J. Cram, *J. Org. Chem.* **1981**, *46*, 393 – 406; f) V. Prelog, Z. Stojanac, K. Kovacevic, *Helv. Chim. Acta* **1982**, *65*, 377 – 384; g) A. Galán, D. Andreu, A. M. Echavarren, P. Prados, J. de Mendoza, *J. Am. Chem. Soc.* **1992**, *114*, 1511 – 1512; h) K. Maruyama, H. Sohmiya, H. Tsukube, *Tetrahedron* **1992**, *48*, 805 – 818; i) M. V. Martínez-Díaz, J. de Mendoza, T. Torres, *Tetrahedron Lett.* **1994**, *35*, 7669 – 7672; j) Y. Abe, Q. Wang, T. Shoji, S. Fukui, M. Suzuki, T. Kamiyama, M. Kobayashi, H. Nishizawa, *Chem. Pharm. Bull.* **1996**, *44*, 1250 – 1251; k) A. Metzger, K. Gloe, H. Stephan, F. P. Schmidtchen, *J. Org. Chem.* **1996**, *61*, 2051 – 2055; l) H. Tsukube, J. Uenishi, T. Kanatani, H. Itoh, O. Yonemitsu, *Chem. Commun.* **1996**,

  1433-7851/00/3920-3696 $ 17.50+.50/0

477 – 478; m) M. Nazhaoui, J. P. Joly, S. Kitane, M. Berrada, *J. Chem. Soc. Perkin Trans. 1* **1998**, 3845 – 3850.
[6] a) H. Tsukube, S. Shinoda, J. Uenishi, T. Kanatani, H. Itoh, M. Shiode, T. Iwachido, O. Yonemitsu, *Inorg. Chem.* **1998**, *37*, 1585 – 1591; b) V. Andrisano, G. Gottarelli, S. Masiero, E. H. Heijne, S. Pieraccini, G. P. Spada, *Angew. Chem.* **1999**, *111*, 2543 – 2544; *Angew. Chem. Int. Ed.* **1999**, *38*, 2386 – 2388.
[7] a) P. S. K. Chia, L. F. Lindoy, G. W. Walker, G. W. Everett, *J. Am. Chem. Soc.* **1991**, *113*, 2533 – 2537; b) P. S. K. Chia, L. F. Lindoy, G. W. Walker, G. W. Everett, *Pure Appl. Chem.* **1993**, *65*, 521 – 526.
[8] a) J. Lacour, C. Ginglinger, F. Favarger, S. Torche-Haldimann, *Chem. Commun.* **1997**, 2285 – 2286; b) C. Ginglinger, D. Jeannerat, J. Lacour, S. Jugé, J. Uziel, *Tetrahedron Lett.* **1998**, *39*, 7495 – 7498; c) J. Lacour, J. J. Jodry, C. Ginglinger, S. Torche-Haldimann, *Angew. Chem.* **1998**, *110*, 2522 – 2524; *Angew. Chem. Int. Ed.* **1998**, *37*, 2379 – 2380.
[9] J. Lacour, S. Barchéchath, J. J. Jodry, C. Ginglinger, *Tetrahedron Lett.* **1998**, *39*, 567 – 570.
[10] a) I. P. Evans, A. Spencer, G. Wilkinson, *J. Chem. Soc. Dalton Trans.* **1973**, 204 – 209; b) L. F. Cooley, C. E. L. Headford, C. M. Elliot, D. F. Kelley, *J. Am. Chem. Soc.* **1988**, *110*, 6673 – 6682.
[11] In the absence of TRISPHAT salts, no transfer of color from the aqueous to the organic layer is observed.
[12] a) A. J. McCaffery, S. F. Mason, B. J. Norman, *J. Chem. Soc. (A)* **1969**, 1428 – 1441; b) M. Ziegler, A. von Zelewsky, *Coord. Chem. Rev.* **1998**, *177*, 257 – 300.
[13] Chiral discriminations occur among three-bladed propellers. For leading references see: a) J. Breu, K. J. Range, *Monatsh. Chem.* **1994**, *125*, 141 – 151; b) J. Breu, C. R. A. Catlow, *Inorg. Chem.* **1995**, *34*, 4504 – 4510; c) H. Sato, A. Yamagishi, S. Kato, *J. Am. Chem. Soc.* **1992**, *114*, 10933 – 10940; d) A. Yamagishi, Y. Goto, M. Taniguchi, *J. Phys. Chem.* **1996**, *100*, 1827 – 1832; e) I. Dance, M. Scudder, *J. Chem. Soc. Dalton Trans.* **1998**, 1341 – 1350; f) J. Breu, A. J. Stoll, *Acta Crystallogr. Sect. C* **1996**, *52*, 1174 – 1177; g) J. Breu, P. Belser, H. Yersin, *Acta Crystallogr. Sect. C* **1996**, *52*, 858 – 861.
[14] In the experiments performed with [**3**][*Δ*-**1**], the signals for the aromatic protons of cation **3** overlap with the signals of the $[Ru(diimine)_3]^{2+}$ ions. Our protocol of NMR enantiomeric determination by addition of [**2**][*Λ*-**1**][8a] cannot be used.
[15] The solutions of [**3**][*Δ*-**1**] are prepared by dissolution of the salt in DMSO and then dilution with $CHCl_3$.

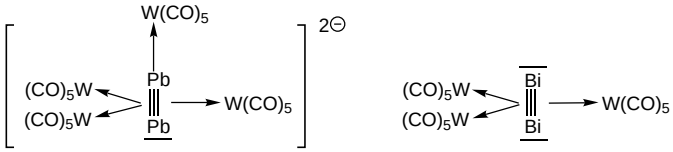
Pb_2^{2-} as Ligand in $[Ph_4P]_2[\{W(CO)_5\}_4Pb_2]$**

Peter Rutsch and Gottfried Huttner*

Dedicated to Professor Hans Brintzinger on the occasion of his 65th birthday

The heavy element homologues of dinitrogen are only stable at high temperature in the gas phase.[1] In the condensed phase such compounds can be stabilized by coordination to organometallic building blocks.[2, 3] For the element dimers As_2, Sb_2, and Bi_2 the coordination of the diatomic molecules to three side-on-bound 16-valence-electron complex fragments has proven to be particularly appropriate as a method for stabilizing such units.[3] In the cartwheel-shaped compounds $[\{W(CO)_5\}_3X_2]$ (X = As, Sb, Bi (**2**)) the distances between the main group elements X are only slightly longer than in the free particles X_2 (cf. d(Bi–Bi) 2.66 Å in $Bi_{2(g)}$[1] and 2.82 Å in $[\{W(CO)_5\}_3Bi_2]$[3d]). The three $W(CO)_5$ building blocks, which symmetrically surround the X_2 unit in the axis of the molecule, can therefore be considered as an organometallic matrix, within which these units are trapped.

As an isoelectronic analogue of Bi_2 it should also be possible to stabilize Pb_2^{2-} in this way.[4] All attempts, however, to construct this fragment, which is also isoelectronic to C_2^{2-}, and to integrate it in a stabilizing matrix have thus far been unsuccessful. We report here on **1**, which was synthesized from $[K_2W_2(CO)_{10}]$ and $Pb(NO_3)_2$ and was obtained as the tetraphenylphosphonium salt in the form of black, metallic shiny crystals. $[(Ph_4P)^+]_2$-**1** dissolves in THF to give an intense violet solution, the IR and ^{13}C NMR spectrum of this solution confirm the presence of two types of $W(CO)_5$ units in **1**. Thus, the known compound $[\{W(CO)_5\}_3Bi_2]$ (**2**) was prepared for comparison.[3d]



1 **2**

Compound **2** displays, as expected for a complex with three equivalent $W(CO)_5$ units, the spectroscopic signature of equivalent, coordinatively bound $W(CO)_5$ groups with a sharp band at 2054 cm^{-1} and a broad, intense absorption at 1963 cm^{-1}. The ν_{CO} band pattern in **1** is considerably more complex and its overall appearance and, in particular, the two shortwave bands at 2057 and 2034 cm^{-1} which display a ratio of intensities of 1:3, indicates that two different sets of $W(CO)_5$ groups are present in **1**. The anionic character of **1** is evident in a shift of the center of the $\tilde{\nu}_{CO}$ bands from 1980 cm^{-1} in the neutral compound **2** to 1928 cm^{-1} in **1**. The ^{13}C NMR spectrum of **1** shows an intense signal at $\delta = 202.9$ that has both ^{207}Pb and ^{183}W satellites ($^2J_{Pb,C} = 34$, $^1J_{W,C} = 124$ Hz). This signal is assigned to the equatorial carbonyl groups. The signal for the axial carbonyl groups of the side-on-coordinated $W(CO)_5$ units ($^2J_{Pb,C} = 26$ Hz) appears at $\delta = 206.5$. The weaker signal of the axial carbonyl group of the terminal $W(CO)_5$ unit occurs at $\delta = 208.4$ ($^2J_{Pb,C} = 20$, $^1J_{W,C} = 126$ Hz). The ratio of intensities and the positions of the signals support the given assigments. The fundamental similarity betweeen the bonding in **1** and **2** mirrors itself in the UV/Vis spectra. The longwave absorption of **2** (570 nm, $\varepsilon = 11700\,M^{-1}cm^{-1}$) corresponds to an absorption of **1** at 583 nm ($\varepsilon = 4500\,M^{-1}cm^{-1}$); the prominent absorptions at shorter wavelengths (428 nm ($\varepsilon = 12200\,M^{-1}cm^{-1}$) in **2**; 415 nm ($\varepsilon = 6600\,M^{-1}cm^{-1}$) in **1**) as well as the shoulders (340 nm ($\varepsilon = 13000\,M^{-1}cm^{-1}$) in **2**; 320 nm ($\varepsilon = 21000\,M^{-1}cm^{-1}$) in **1**) also correspond. These bands lie in a region, which is characteristic for Bi_2 or the isoelectronic PbTe in the gas phase.[1] The

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[**] This work was supported by the Fonds der Chemischen Industrie and by the Deutsche Forschungsgemeinschaft (SFB 247).