Enantiomerically Pure Quaternary Ammonium Salts with a Chiral Alkyl Chain N(CH₃)(*n*-C₃H₇)₂(*sec*-C₄H₉)I: Synthesis and Physical Studies

RUXANDRA GHEORGHE,¹ LISE-MARIE CHAMOREAU,¹ JOSEF KAPITAN,² NIKOLAÏ S. OVANESYAN,³ SERGEI M. ALDOSHIN,³ LUTZ HECHT,² LAURENCE D. BARRON,² CYRILLE TRAIN,¹ AND MICHEL GRUSELLE^{1*}

¹Laboratoire de Chimie Inorganique et Matériaux Moléculaires, UMR-CNRS 7071, IFR 2769,

Université Pierre et Marie Curie-Paris 6, F-75252 Paris Cedex 05, France

²WestCHEM, Department of Chemistry, University of Glasgow, Glasgow G12 8QQ, United Kingdom ³Institute of Problems of Chemical Physics, Russian Academy of Science, Moscow Region, 142432 Chernogolovka, Russia

Dedicated to the 160th Anniversary of Louis Pasteur's Discovery

ABSTRACT A pair of enantiomerically pure quaternary ammonium salts with a chiral side chain, methyl-(R)-(1-methylpropyl)di(n-propyl)ammonium iodide 1 and methyl-(S)-(1-methylpropyl)di(*n*-propyl)ammonium iodide **2**, and the related racemate, methyl-(*rac*)-(1-methylpropyl)di(n-propyl)ammonium iodide 3, were synthesized through a reductive alkylation procedure, starting from enantiomerically pure and, also, racemic forms of (rac)-(1-methylpropyl)amine. A spectroscopic chiroptical signature in solution was provided by the Raman optical activity spectra of compounds 1 and 2. The crystallographic structures of 1, 2, and 3 were examined by single crystal X-ray diffraction. 1 crystallizes in the tetragonal space group $P4_{3}2_{1}2$ (no. 96), a = b = 12.826 (2) Å, c = 17.730 (2) Å, V =2916.9 (5) Å³, Z = 8, Flack coefficient 0.04 (2). **2** crystallizes in the tetragonal space group $P4_{1}2_{1}2$ (no. 92), a = b = 12.842 (1) Å, c = 17.749 (2) Å, V = 2927.0 (5) Å³, Z = 8, Flack coefficient 0.05 (2). The crystal structures and space groups for 1 and 2 are enantiomorphs and the crystallographic investigation confirmed the absolute configuration of the stereocenter in both compounds. 3 crystallizes in the monoclinic space group $P_{2_1/n}(no.$ 14), a = 8.178 (1) Å, b = 14.309 (2) Å, c = 12.328 (2) Å, $\beta = 96.811$ (6)°, V = 1432.4 (2) Å³, Z = 4. Chirality 20:1085–1091, 2008. © 2008 Wiley-Liss, Inc.

KEY WORDS: chirality; ammonium salts; absolute configuration; Raman optical activity; X-ray diffraction

INTRODUCTION

Ammonium cations are a widely studied class of organic cations. During the last 10 years, there has been much interest in chiral ammonium cations that can behave either as asymmetric ionic liquids or phase transfer agents.^{1,2} The ability of tetraalkylammonium salts with four different alkyl chains to form mesophases has also been studied.³

Our interest in such cations is part of a general strategy to synthesize optically active hybrid molecular magnets.⁴ The ultimate goal of this approach is to measure magnetochiral dichroism⁵⁻⁸ in a ferromagnetically ordered material. We have focused our attention on the crystallization of optically active oxalate-based magnets of general formula $A^+[M(II)M'(III)(C_2O_4)_3]^-$. Because of the rapid racemization of tris(oxalato)metalate(III) in solution, we chose to develop enantioselective templated-assembly of these compounds starting from resolved template cations.⁴ By using resolved bis(bipyridine)phenylpyridineruthenium(II) monocations, we obtained enantiomerically pure three-dimensional bimetallic anionic networks.⁹⁻¹¹ Starting from resolved chiral ferrocenic ammonium cation, we were able to characterize optically active two dimensional © 2008 Wiley-Liss, Inc.

bimetallic anionic networks.^{10,11} The compounds were obtained as powders because the chiral moiety of the ammonium is lost by hydrolysis during the crystallization process.¹¹ We intend to extend our study by investigating the ability of other resolved and (configurationally) stable ammonium salts to act as templates in the formation of optically active systems.

Crystallographic data for the structures of **3**, **1**, and **2**, respectively reported in this paper have been deposited with the Cambridge Crystallographic Data (CCDC 666586, 666587, and 666588, respectively).

Contract grant sponsors: University Pierre et Marie Curie-Paris6, CNRS, EPSRC, Russian Academy of Sciences

Contract grant sponsors: DFG Schwerpunktprogramm Molekularer Magnetismus; Contract grant number: SPP 1137

Contract grant sponsor: CNRS/RAS Joint Research Program; Contract grant number: 16332

Contract grant sponsors: RFBR; Contract grant number: 05-03-33026

^{*}Correspondence to: Dr. Michel Gruselle, Laboratoire de Chimie Inorganique et Matériaux Moléculaires, UMR-CNRS 7071, IFR 2769, Université Pierre et Marie Curie-Paris 6, case courrie 42, 4 Place Jussieu, F-75252 Paris Cedex 05, France. E-mail: michel.gruselle@courriel.upmc.fr Received for publication 10 December 2007; Accepted 10 March 2008

DOI: 10.1002/chir.20577 Published online 12 May 2008 in Wiley InterScience

⁽www.interscience.wiley.com).

We report here the result of the first step we took in this investigation, namely the synthesis, the Raman and Raman optical activity (ROA) studies, as well as the crystallographic analysis of the cationic ammonium precursors. These are quaternary ammonium cations with a chiral alkyl side chain, methyl-(R)-(1-methylpropyl)di(*n*-propyl)-ammonium iodide **1** and methyl-(S)-(1-methylpropyl)di(*n*-propyl)ammonium iodide **2**. For comparison, the related racemate, methyl-(rac)-(1-methylpropyl)di(*n*-propyl)ammonium iodide **3** is also reported.

MATERIALS AND METHODS

All the chemicals used for the present study were purchased from commercial sources and used without any further purification. Elemental analyses were carried out at the SIARE-UPMC Paris (France) for C, H, and N. The infra red (IR) spectra were recorded in KBr pellets with a Bio-Rad IRFT spectrophotometer in the 4000–200 cm⁻¹ range. ¹H NMR spectra were recorded on a Bruker AC 300 spectrometer.

Synthesis

 $N(CH_3)(n-C_3H_7)_2((R)-sec-C_4H_9)I(1)$. Compound 1 was synthesized starting from the primary (*R*)-(1-methyl-propyl)amine, by adapting a three-step procedure already reported in the literature,³ as follows.

Synthesis of the secondary amine $NH(n-C_3H_7)((R)-sec C_4H_9$). A methanolic solution (5 ml) of propanal (1.6 ml, 22 mmol) was added dropwise to an ice-cooled solution of (R)-(1-methylpropyl)amine (2 ml, 20 mmol) in methanol (5 ml). After half an hour of stirring at room temperature, the resulting (*R*)-(1-methylpropyl)-*n*-propylimine was reduced with sodium borohydride (0.85 g, 22 mmol), which was added, in small portions, to the ice-cooled solution. The resulting mixture was stirred for 2 h at room temperature, to give (R)-(1-methylpropyl)(*n*-propyl)amine. The pH of the solution was set to 14 by adding 20 ml of 1 mol 1⁻¹ NaOH aqueous solution. The secondary amine was extracted with diethyl ether and purified by distillation (yield 70%).

¹H NMR (300 MHz, CDCl₃, TMS): δ /ppm = 2.51 (m, 3 H), 1.45 (m, 3 H), 1.24 (m, 1 H), 0.98 (d, ²*J*(H–H) = 6.4 Hz, 3 H), 0.90 (t, ²*J*(H–H) = 7.5 Hz, 3 H), 0.87 (t, ²*J*(H–H) = 7.5 Hz, 3 H).

Synthesis of the tertiary amine $N(n-C_3H_7)_2((R)-sec C_4H_9$). A methanolic solution (2.5 ml) of propanal (1.1 ml, 15.3 mmol) was added dropwise to an ice-cooled solution of (R)-(1-methylpropyl) (*n*-propyl) amine (1.59) g. 14 mmol) dissolved in a mixture of methanol (2.5 ml) and dichloromethane (5 ml). After half an hour of stirring at room temperature, sodium triacetoxyborohydride (3.53 g, 16.6 mmol) was added, in small portions, to the ice-cooled solution. After 15 min, three extra portions of propanal (each 0.04 ml, 0.04 equiv.) and NaBH(OAc)₃ (each 0.16 mg, 0.05 equiv.) were alternatively added over a total period of 1 h. The resulting mixture was stirred for 3 h at room temperature, to give (R)-(1-methylpropyl)di(n-propyl)amine. The pH of this solution was set to 14 by adding 36 ml of 1 mol l^{-1} NaOH aqueous solution. The tertiary Chirality DOI 10.1002/chir

amine was extracted with diethyl ether and purified by distillation (yield 60.5%).

¹H NMR (300 MHz, CDCl₃, TMS): δ/ppm = 2.54 (m, 1 H), 2.28 (m, 4 H), 1.38 (m, 5 H), 1.19 (m, 1 H), 0.87 (3t + 1d, 12 H).

Synthesis of the quaternary ammonium salt $N(CH_3)$ (n- C_3H_7)₂((R)-sec- C_4H_9)I. The resulting tertiary amine (1.33 g, 8.5 mmol) was quaternized using iodomethane (0.7 ml, 11 mmol) in toluene (20 ml) at 80°C over a period of 10 h. Methyl-(R)-(1-methylpropyl)di(n-propyl)ammonium iodide was isolated as a white crystalline powder (yield 76%).

¹H NMR (300 MHz, CDCl₃, TMS): δ /ppm = 3.56 (m, 1 H), 3.43 (m, 4 H), 3.20 (s, 3 H), 2.07 (m, 1 H), 1.82 (m, 4 H), 1.60 (m, 1 H), 1.46 (d, 3 H), 1.07 (m, 9 H).

Selected IR bands (KBr): v = 3008 (s), 2971 (vs), 2938 (s), 2976 (s), 1473 (s), 1394 (m), 1375 (w), 1330 (w), 1187 (w), 1120 (w), 1097 (m), 1036 (w), 990 (w), 980 (w), 949 (m), 935 (m), 884 (w), 844 (w), 753 (s).

Elemental analysis calcd (%) for $C_{11}H_{26}NI$: C 44.00%, H 8.66%, N 4.66%; found: C 42.3%, H 8.57%, N 4.62%.

Single crystals of **1** were obtained by slow diffusion of diethyl ether in a dichloromethane (1.5 ml) solution of methyl-(R)-(1-methylpropyl)di(n-propyl)ammonium iodide (50 mg).

The same synthetic procedures were applied in the cases of the other two compounds $N(CH_3)(n-C_3H_7)_2((S)-sec-C_4H_9)I(2)$ and $N(CH_3)(n-C_3H_7)_2((rac)-sec-C_4H_9)I(3)$.

Raman Optical Activity

The Raman and ROA spectra were measured in backscattering in the University of Glasgow using a ChiralRA-MAN instrument manufactured by BioTools, and described previously.¹² The ROA spectra are presented as scattered circular polarization intensity differences $I_{\rm R} - I_{\rm L}$ and the parent Raman spectra as scattered circular polarization intensity sums $I_{\rm R}$ + $I_{\rm L}$, where $I_{\rm R}$ and $I_{\rm L}$ are the Raman-scattered intensities with right- and left-circular polarization, respectively. The solutions were studied at concentrations ~ 250 mg/ml at ambient temperature $(\sim 20^{\circ} \text{C})$ in methanol. They were filtered through 0.22 μm Millipore filters into guartz microfluorescence cells, which were centrifuged gently prior to mounting in the ROA instrument. Residual visible fluorescence from traces of impurities, which can give large backgrounds in Raman spectra, was quenched by leaving the sample to equilibrate in the laser beam for a few hours before acquiring ROA data. Experimental conditions: laser wavelength 532 nm; laser power at the sample ~ 200 mW; spectral resolution $\sim 10 \text{ cm}^{-1}$; acquisition time $\sim 10 \text{ h}$.

Single Crystal X-Ray Diffraction

A single crystal of each compound was selected, mounted onto a glass fiber, and transferred in a cold nitrogen gas stream at 250 K. Intensity data were collected with a Bruker-Nonius Kappa-CCD with graphite-monochromated Mo–K α radiation. Unit-cell parameters determination, data collection strategy and integration were carried out with the Nonius EVAL-14 suite of programs.¹³ Multi-scan absorption correction was applied.¹⁴ The structures were solved by direct methods using the SHELXS-86, the SHELXS-97 or the SIR-92 programs.^{15–17} All were refined anisotropically by full-matrix least-squares methods using the SHELX-97 software package.¹⁷ For **3**, the occupancy factor of C(10) and C(10b) has been refined leading to 0.69:0.31 ratio. It was then fixed to 2:1.

RESULTS AND DISCUSSION

Two reductive alkylation reactions performed starting from the enantiomerically pure or the racemic forms of sec-butylamine, followed by a reaction of quaternization, lead to three iodide salts of quaternary ammonium cations with a chiral side chain: $N(CH_3)(n-C_3H_7)_2((R)-sec-C_4H_9)I$ 1, $N(CH_3)(n-C_3H_7)_2((S)-sec-C_4H_9)I$ 2 and $N(CH_3)(n-C_3H_7)_2((S)-sec-C_4H_9)I$ $C_{3}H_{7}$ ₂((*rac*)-*sec*- $C_{4}H_{9}$)I **3**. The reductive alkylation reactions can be performed with various aldehydes.^{3,18} On the contrary, the quaternization failed when other iodoalkanes are used because the bulky trialkylamine favors elimination reactions. Nevertheless, this synthetic strategy appears as a general one to obtain a wide variety of enantiomerically pure ammonium salts of both configurations. This last feature contrasts with the strategy that uses compounds from the "chiral pool" as starting materials.¹ Such species can be used for studying the influence of controlled chirality on the formation of mesophases³ as well as organic reactions using asymmetric ionic liquids¹ or asymmetric phase transfer reagents.² In the latter cases, working with either enantiomer of the ammonium cation allows to obtain either enantiomer of the target compound.

The IR spectra of compounds **1**, **2**, and **3** are basically identical. The group of four, strong to very strong, bands located between 2976 and 3008 cm⁻¹ are due to the C—H stretching vibrations of the alkyl branches. Another band of strong intensity, situated at around 1460 cm⁻¹, is assigned to the C—H bending vibrations.

The chemical shifts in the ¹H NMR spectra of compounds 1, 2, and 3 are identical and consistent with the formation of the ammonium salts. For instance, the ¹H NMR spectrum of **1** shows eight groups of protons. The signals assigned to the protons belonging to the methyl groups are a singlet located at 3.20 ppm (CH₃-N), a doublet at 1.46 ppm (CH₃-CH-; ${}^{2}J$ (H-H) = 6.4 Hz), and two triplets centered at 1.07 ppm (three CH3-CH2groups). The multiplet signals arising from the protons of the β -methylene groups of the two propyl branches are situated at 1.82 ppm, the ones from the α -methylene groups are at 3.43 ppm, and the two diastereotopic protons belonging to the methylene group from the sec-butyl chain appear at 1.60 and 2.07 ppm. The multiplet signal due to the proton linked to the carbon stereocenter is located at 3.56 ppm.

It is important to achieve the characterization of the enantiomeric purity and configurational stability of the products in solution. As they are aliphatic ammonium salts, the electronic spectroscopy for such species is dominated by $\sigma-\sigma^*$ transitions that take place at relatively large energies. Consequently, the natural circular dichroism in the 185–800 nm region, which is the most common technique for analyzing optically active compounds in solu-

tion, is not suitable in this case. To get a spectroscopic signature of the absolute configuration of our compounds in solution, we used a vibrational spectroscopy, namely ROA. This technique has been shown to be a powerful method for determining the absolute configuration of aliphatic alkanes.¹⁹ Figure 1 shows the Raman, where the contribution of the solvent (methanol) was subtracted, and ROA spectra of compounds 1 and 2. Because 1 and 2 are enantiomers, their ROA spectra are of opposite sign and approximately equal magnitude, as expected. A quantitative analysis of the ROA spectra is beyond the scope of this article, and in any event is not required here because the absolute configuration of the stereocenter is known a priori. A qualitative analysis of the ROA spectra²⁰ of compounds 1 and 2 focuses on vibrational coordinates of groups attached to the asymmetric carbon atom C(8) (cf. Fig. 2) because these are expected to generate the largest ROA signals. We expect groups attached to the nitrogen atom to make only minor contributions to the ROA, but that they will all contribute significantly to the parent Raman spectrum.

Normal modes of vibration involving various deformations of the methyl group linked to the asymmetric carbon atom C(8), together with those from the methylene fragment and the C(8)-H group probably dominate the ROA spectrum. One clear assignment is the 1451/1485 cm⁻ ROA couplet which originates in the C(8)-methyl antisymmetric deformations, the degeneracy of which is lifted by the chiral environment (no splitting is seen in the parent Raman spectrum; but it is revealed by the ROA couplet). The non-degenerate methyl symmetric deformation might be involved in the 1402 cm⁻¹ ROA band. There might also be some involvement of CH₂ deformations in both. Also C(8)—H deformations might be involved in the \sim 1285– 1331 cm⁻¹ ROA bands. C(8)-methyl rocking motions probably contribute to the \sim 1110–1174 cm⁻¹ and the \sim 880– 995 cm^{-1} ROA bands, with significant mixing with C(8) - C and $C(8) - N^+$ stretches.

From ~565 cm⁻¹ and below, the modes will be complicated mixtures of various skeletal deformations, together with methyl torsions at the lower wavenumber end. Although contributions from conformers associated with rotations around the C(8)—N⁺ bond and N⁺-propyl groups probably complicate the parent Raman spectra, it is possible they do not complicate the ROA so much, again because groups attached to N⁺ probably contribute little to the ROA.

Summarized crystallographic data and selected bond distances and angles for compounds **1**, **2**, and **3** are collected in Tables 1 and 2. The molecular structures of **1**, **2**, and **3** are shown in Figure 2, along with the atom numbering scheme. The two enantiomers, **1** and **2**, crystallize in two enantiomorphous tetragonal space groups, $P4_32_12$ (no. 96) and $P4_12_12$ (no. 92), respectively. The crystal structure of compound **3** is achiral in the centrosymmetric monoclinic space group $P2_1/n$ (no. 14). In **1** and **2**, the absolute configuration of the stereocenter was confirmed by the determination of the Flack coefficients.²¹ They are equal to 0.04(2) for compound **1**, and 0.05(2) for **2**. Compound **3** crystallizes in a space group containing symmetry opera-*Chirality* DOI 10.1002/chir

GHEORGHE ET AL.



Fig. 1. The Raman (methanol subtracted, baseline corrected) and ROA (baseline corrected) spectra of 1 (black) and 2 (gray/red) in methanol. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

tions of the second kind (rotoinversions and glide reflections) forcing the presence of an equal number of (R) and (S) molecules in the structure: a racemate is formed. The C(10) carbon atom is disordered over two positions, the occupancy factor being 2:1. Hence, it can be bonded to C(9) and C(11) carbon atoms. As a consequence, the two configurations of the carbon stereocenter can be present at the same molecular position.

Following the Wallach's rule,^{22–24} the density of the enantiomerically pure compounds 1 and 2 is lower by 1.93% than that of the racemate 3.

At the molecular level, we restrict ourselves to the description of the structure of **1**. Within experimental errors, the distances and angles in **2** are identical to those of **1** whereas only minor differences are observed between **1** and **3** (Table 2). The bond angles around the nitrogen atom are consistent with a tetrahedral environment (Table 2). The slightly higher values for the angles C(8)—



Fig. 2. Ortep view (30% probability) along with the atoms numbering scheme of the molecular crystal structures of quaternary ammonium cations in $N(CH_3)(n-C_3H_7)_2((R)-sec-C_4H_9)I 1$ (right) and its enantiomer $N(CH_3)(n-C_3H_7)_2((S)-sec-C_4H_9)I 2$ (left) (**a**) and $N(CH_3)(n-C_3H_7)_2((rac)-sec-C_4H_9)I 3$ (**b**). In the latter case, the C(10) atom is the most probable position whereas C(10b) is the less probable one (see text). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Chirality DOI 10.1002/chir

	1	2	3
Formula	C ₁₁ H ₂₆ NI	C ₁₁ H ₂₆ NI	$C_{11}H_{26}NI$
Formula weight	299.23	299.23	299.23
Crystal system	Tetragonal	Tetragonal	Monoclinic
Space group	$P 4_3 2_1 2$	$P4_{1}2_{1}2$	$P 2_1/n$
Temperature (K)	250 (2)	250 (2)	250 (2)
Unit cell dimensions			
a (Å)	12.826 (2)	12.842 (1)	8.178 (1)
b (Å)	12.826 (2)	12.842 (1)	14.309 (2)
<i>c</i> (Å)	17.730 (2)	17.749 (2)	12.328 (2)
β (°)			96.811(6)
$V(Å^3)$	2916.9 (5)	2927.0 (5)	1432.5 (2)
Ζ	8	8	4
$D_{\rm calc} ({\rm g \ cm^{-3}})$	1.363	1.358	1.387
$\mu (mm^{-1})$	2.165	2.157	2.204
F(000)	1216	1216	608
$\theta_{\min} - \theta_{\max}$ (°)	3.38-30.00	2.52-30.01	2.84-30.08
Flack coefficient	0.04 (2)	0.05 (2)	-
Reflexions collected/uniques	$22448/4252, R_{\rm int} = 0.0422$	$19051/4268, R_{\rm int} = 0.0512$	$27582/4179, R_{\rm int} = 0.0538$
Data/restraints/parameters	4252/0/124	4268/0/125	4179/1/132
Goodness-of-fit on F^2	1.016	1.006	1.014
Final $R_1, wR^2 [I > 2\sigma (I)]$	0.0275, 0.0502	0.0321, 0.0540	0.0359, 0.0740
R_1 , wR_2 (all data)	0.0578, 0.0573	0.0804, 0.0640	0.0827, 0.0866

TABLE 1. Crystallographic data for compounds 1, 2, and 3

N(1)—C(2) and C(8)—N(1)—C(5) formed by the N—C(sec-butyl) and the two N—C(propyl) bonds [110.27(15)° and 111.31(16)°)] are likely to be related to the larger steric hindrance between these groups when compared with the smaller methyl group. The two propyl branches have a staggered conformation. The sec-butyl chain has a gauche conformation, stabilizing the whole molecule by limiting the steric repulsion between the two alkyl groups of the sec-butyl branch and the -NMePr₂ fragment. The bond angles around the carbon stereocenter (in the range 106.9–112.1°) deviate slightly from the typical sp³ hybridization angle (109.3°) to optimize the steric repulsion between the four different substituents. The values of the

TABLE 2. Selected bond distances (Å) and angles (°)for compounds 1, 2, and 3

	1	2	3
N(1)-C(1)	1.509 (3)	1.510 (3)	1.510 (4)
N(1) - C(2)	1.522 (3)	1.517 (3)	1.519 (4)
N(1) - C(5)	1.533 (3)	1.529 (3)	1.522 (4)
N(1) - C(8)	1.550 (3)	1.554 (3)	1.549 (4)
C(2) - C(3)	1.521 (3)	1.527 (4)	1.510 (5)
C(3) - C(4)	1.511 (4)	1.511 (4)	1.525 (5)
C(5) - C(6)	1.526 (3)	1.526 (4)	1.498 (5)
C(6) - C(7)	1.539 (3)	1.543 (4)	1.479 (6)
C(8) - C(11)	1.529 (3)	1.533 (4)	1.519 (5)
C(8) - C(9)	1.535 (3)	1.533 (4)	1.512 (5)
C(9) - C(10)	1.532 (3)	1.539 (4)	1.486 (6)
C(1) - N(1) - C(2)	110.07 (17)	110.0 (2)	108.7 (2)
C(1) - N(1) - C(5)	108.50 (18)	108.4 (2)	109.7 (3)
C(2) - N(1) - C(5)	108.43 (18)	108.5 (2)	108.7 (2)
C(1) - N(1) - C(8)	108.25 (18)	108.1 (2)	108.9 (2)
C(2) - N(1) - C(8)	110.27 (15)	110.37 (19)	111.0 (3)
C(5) - N(1) - C(8)	111.31 (16)	111.4 (2)	109.8 (2)

bond lengths vary in a normal regime corresponding to simple C—C (1.51–1.54 Å) and C—N (1.51–1.55 Å) bonds.

The quaternary ammonium cations in 1 are related through a 4_3 axis (Fig. 3a). At the supramolecular level, the 4_3 axis generates a right-handed helix along the *c* axis (see Fig. 3). Because of the 2 axis, the ammonium cations form a second right-handed helix interwoven with the former one (Fig. 3b). In the case of 2, the ammonium ions are related through a 4_1 axis, leading to two intervoven left-handed helices along the *c* axis. Within the helix generated by the ammonium cations, the iodide anions are placed in a distorted zig-zag manner, the shortest I...I distance being 7.859(1) Å and the largest 14.797(1) Å. The shortest distance between the equivalent iodide ions "belonging" to neighbouring helices is 7.955(1) Å. The $I \cdots N$ distance is equal to 4.897(2) Å, stabilizing the supramolecular arrangement through electrostatic interactions. In the racemic crystal $\mathbf{3}$, the 2_1 axis generates supramolecular helices of the quaternary ammoniums (see Fig. 4). The glide plane generates a second supramolecular helix (see Fig. 4). Because of the location of the C(10) carbon atom mentioned above, a first family of helices is mainly composed (in a 2:1 ratio) of cations of the same configuration. In the family of helices generated by the glide plane, the proportion is reversed. Because X-ray diffraction is not sensitive to short-range order, it is not possible to figure out whether the helices are formed by long sequences of (R) molecules followed by long sequences of (S) molecules or by a rapid alternation between the (R) and (S)molecules. The iodine ions are positioned alternatively between the ammonium cations of the same helix, the distance between them being 7.244(2) Å. The shortest distance between the iodide ions "belonging" to helices of opposed chirality is 8.362(4) Å. The shortest distances $N \cdots I$ fall in the range 4.72–4.82 Å.



Fig. 3. Packing diagram for crystal 1 illustrating the interwoven helical arrangement of the quaternary ammonium cations at the supramolecular level: (a) along the c axis and (b) along the a axis. In (b), for clarity, the iodide ions are not shown and only the first carbon atom of the propyl chains is shown; moreover, the asymmetric carbon atom is colored in black for one helix and in white in the second one (see text). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The comparison between the structures of the enantiomerically pure compounds 1 and 2 and the racemate 3shows that the handedness of the supramolecular helices in 1 and 2 is indeed entirely determined by the configuration of the carbon stereocenter, whereas no control can be exerted in the case of 3.

Concluding Remarks

We have described the synthesis of the two enantiomers of methyl(1-methylpropyl)di(*n*-propyl)ammonium iodide starting from the resolved (1-methylpropyl)amine in a three-step procedure with an overall yield of 32%. The synthetic procedure we report can be extended to chiral ammoniums with longer alkyl chains that can be used as asymmetric ionic liquids or phase transfer agents. In contrast with the quaternary ammoniums obtained from the "chiral pool",¹ this strategy allows either enantiomer of the ammonium cation to be synthesized. Thus, it is possible to study the influence of the configuration of the stereocenter both on the chiroptical spectroscopic measurements, as exemplified here by ROA, as well as on the helical crystal packing of the molecular ions, as shown by single crystal X-ray diffraction.

The next step in our general approach of the template enantioselective self-assembly of hybrid 2D and 3D oxa-*Chirality* DOI 10.1002/chir



Fig. 4. Packing diagram for crystal 3 along the *a* axis. The configuration of the carbon stereocenters is determined by setting the C(10) atom at its most probable position (see text). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

late-based networks⁴ will be to test the ability of the resolved methyl(1-methylpropyl)di(*n*-propyl)ammonium cations to build optically active bimetallic honeycomb layers.

LITERATURE CITED

- Ding J, Armstrong DW. Chiral ionic crystals: synthesis and applications. Chirality 2005;17:281–292.
- Ooi T, Maruoka K. Recent advances in asymmetric phase-transfer catalysis. Angew Chem Int Ed 2007;46:4222–4266.
- Soulié C, Bassoul P, Tournilhac F. Cubic. Mesophase in an unsymmetrical alkyl ammonium salt. Synthesis and structural model. Chem Phys Chem 2002;3:1024–1030.
- Gruselle M, Train C, Boubekeur K, Gredin P, Ovanesyan N. Enantioselective self-assembly of chiral bimetallic oxalate-based network. Coord Chem Rev 2006;250:2491–2500.
- Barron LD, Vrbancich J. Magneto-chiral birefringence and dichroism. Mol Phys 1984;51:715–730.
- Rikken GLJA, Raupach E. Observation of magneto-chiral dichroism. Nature (London) 1997;390(6659):493–494.
- Rikken GLJA, Raupach E. Pure and cascaded magnetochiral anisotropy in optical absorption. Phys Rev E 1998;58:5081–5084.
- Raupach E, Rikken GLJA, Train C, Malézieux B. Modeling of magneto-chiral enantioselective photochemistry. Chem Phys 2006;26:373– 380.
- 9. Andres R, Brissard M, Gruselle M, Train C, Vaisserman J, Malezieux B, Jamet J-P, Verdaguer M. Rational design of three-dimensional (3D) optically active molecule-based magnets: synthesis, structure, optical and magnetic properties of {[Ru(bpy)₃]²⁺, ClO₄⁻, [Mn^{II}Cr^{III}(ox)₃]⁻}_n and {[Ru(bpy)₂ppy]⁺, [M^{II}Cr^{III}(ox)₃]⁻}_n, with M^{II} = Mn^{II}, Ni^{II}. X-ray structure of {[ΔRu(bpy)₃]²⁺, ClO₄⁻, [ΔMn^{II}ΔCr^{III}(ox)₃]⁻}_n and {[ΛRu(bpy)₂ppy]⁺, [ΛM^{II}ΔCr^{III}(ox)₃]⁻}_n. Inorg Chem 2001;40:4633–4640.
- Gruselle M, Thouvenot R, Malezieux B, Train C, Gredin P, Demeschik TV, Troitskaya LL, Sokolov VI. Enantioselective self-assembly of bimetallic [Mn^{II}(Δ)-Cr^{III}(C₂O₄)₃]⁻ and [Mn^{II}(Δ)-Cr^{III}(C₂O₄)₃]⁻ layered

anionic networks templated by the optically active (*Rp*)- and (*Sp*)-[1-CH₂N(n-C₃H₇)₃-2-CH₃-C₅H₃Fe-C₅H₅]⁺ ions. Chem Eur J 2004;10: 4763–4769;

- Shilov GV, Ovanesyan NS, Aldoshin SM, Gruselle M, Train C, Guyard-Duhayon C. J Coord Chem 2004;57:1165–1171.
- Barron LD, Zhu F, Hecht L, Tranter GE, Isaacs NW. Raman optical activity: an incisive probe of molecular chirality and biomolecular structure. J Molec Struct 2007;834–836:7–16.
- Duisenberg AJM, Kroon-Batenburg LMJ, Schreurs AMM. An intensity evaluation method: EVAL-14. J Appl Cryst 2003;36:220–229.
- Blessing RH. An empirical correction for absorption anisotropy. Acta Cryst. A 1995;51:33–38.
- 15. Sheldrick GM, SHELXS-86. Germany: University of Göttingen; 1986;
- Altomare A, Cascarano G, Giacovazzo C, Guagliardi A. Completion and refinement of crystal-structures with sir92. J Appl Cryst 1993;26: 343–350.
- 17. Sheldrick GM, SHELXL-97. Germany: University of Göttingen; 1997.
- Gruselle M, Malézieux B, Train C, Soulié C, Ovanesyan NS. Les cations ammoniums chiraux de type [R₁R₂R₃R₄N]⁺, de nouveaux templates pour les réseaux bimétalliques à pont oxalate. CR Chimie 2003;6:189–191.
- Haesler J, Schindelholz I, Riguet E, Bochet CG, Hug W. Absolute configuration of chirally deuterated neopentane. Nature 2007;446:526– 529.
- Barron LD. Molecular light scattering and optical activity. 2nd ed. Cambridge University Press; 2004.
- Flack HD. On enantiomorph-polarity estimation. Acta Crystallogr Sect A 1983;39:876–881.
- Wallach O. Zur Kenntniss der Terpene und der ätherischen Oele. Ueber gebromte Derivate der Carvonreihe. Liebigs Ann Chem 1895; 286:119–143.
- 24. Brock CP, Schweizer WB, Dunitz JD. On the validity of Wallach's rule: on the density and stability of racemic crystals compared with their chiral counterparts. J. Am Chem Soc 1991;113:9811–9820.