DNA (through the duplex major groove or minor groove).[8] Increased polarizability of the nucleobase is also unlikely to result in the destabilization as it is expected to enhance interbase stacking.[8] The observed destabilization may result from unfavorable dipole–dipole interactions with flanking bases in the case of NICS, and increased steric repulsion between the opposing sulfur atoms of the self-pairs of SICS and SNICS.

Sulfur substitution in SICS and SNICS results in self-pairs that are synthesized two orders of magnitude more efficiently than ICS and NICS. As described above, this increase in efficiency resulted from a modest increase in k_{cat} (3- to 5-fold) and a more substantial decrease in unnatural triphosphate binding (25-fold). Speculation about the potential origins of these effects may be based on the available structures of the type I DNA polymerases from *B. stearothermophilus* and *T. aquaticus*.[9,10] These polymerases are highly homologous to KF, both structurally and functionally. In these structures the triphosphate hydrogen bond acceptor, located at a position analogous to that of the C10 sulfur atom in the unnatural bases, interacts with the template base as well as a water molecule. Based on the structures, the aromatic ring of the unnatural triphosphate is also expected to pack with Tyr766. It therefore seems likely that sulfur substitution may increase the binding of the unnatural substrate through favorable sulfur–sulfur interactions or through electronic effects which favor hydrophobic packing.

The crystal structures also reveal information that may be relevant to the extension rates that are increased by an order of magnitude. The nucleobase at the primer terminus packs against the base of the incoming triphosphate, and along with the template base is tightly packed by hydrophobic side chains of the protein, which is thought to exert a geometrical selection against the aberrant structures of mispaired bases. The structures also reveal sequence-independent hydrogen bonds between the polymerase and the purine N3 or pyrimidine O2 atoms of the natural bases at the primer terminus. Failure of the unnatural DNA base pair to suitably engage the protein by any of these interactions may result in a misaligned 3′-OH primer terminus which is unable to act as an efficient nucleophile during the extension step. The higher extension efficiency that results from C10-thio substitution may therefore derive from improved packing interactions, structural or electronic changes owing to interpair sulfur–sulfur interactions, or altered hydrogen bonding with protein side chains in the developing minor groove.

Replication of DNA containing unnatural base pairs requires that the base pairs be stable as well as efficiently synthesized and then extended by a DNA polymerase. We have demonstrated that both of these steps may be optimized by heteroatom substitution. The SNICS self-pair is synthesized 55-fold more efficiently and 5-fold more selectively and is extended 12-fold more efficiently than its parent ICS self-pair. Not only does this represent significant progress towards a replicable unnatural base pair, it implies that further improvement in insertion and extension should be possible with further modification of the bases.

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Hierarchically Ordered Silica Mesophases Using Mixed Surfactant Systems as Templates**

An-Wu Xu,* Yue-Peng Cai, Hua-Xin Zhang, Li-Zhi Zhang, and Jimmy C. Yu

Since the discovery of silica mesophases,[1,2] surfactant-templated syntheses based on the hydrolysis and crosslinking of inorganic precursors (I) at the surfaces of supramolecular surfactant (S) assemblies have been used to prepare a variety of hexagonal, cubic, or lamellar mesophases through five pathways: S^+I^-, S^-I^+, $S^+X^-I^+$, $S^-M^+I^-$, and S^0I^0 (or N^0I^0) (X^- = counterion, M^+ = metal ion, N = polyethylene oxide).[3–16] Several methods are now available for the preparation of ordered structures at different length scales, such as micro-, meso-, and macroporous materials.[17,18] However, the preparation of hierarchically ordered structures in a single body, such as seen in diatoms in nature, has remained an experimental challenge.[17]

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[*] Prof. A.-W. Xu, Dr. Y.-P. Cai, H.-X. Zhang
School of Chemistry and Chemical Engineering
Zhongshan University
Guangzhou 510275 (China)
Fax: (+86) 20-84110318
E-mail: cedc17@zsu.edu.cn
Dr. L.-Z. Zhang, Prof. J. C. Yu
Department of Chemistry
The Chinese University of Hong kong
Shatin, New Territories (China)

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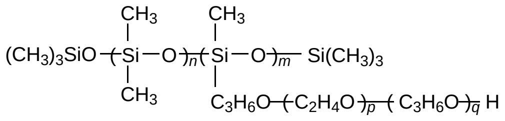
A number of models were proposed to explain the formation of the silica mesophases.[2,4] However, these models rarely consider the effect of the configuration of the supramolecular chain on the mesophase formation and are insufficient for establishing the mechanistic understanding needed for a better control of the synthetic process, which is key to improving this exciting new class of mesophases or adding to it. Stucky and co-workers presented a more detailed model to explain the formation and morphologies of surfactant/silica mesophases based on the experimental results.[19] However, formation of oxide mesophases and structure selection have not been well understood to date. On the basis of experimental data, we present here a detailed model of the oxide mesophase formation process, which explains presently known experimental data and successfully predicts conditions needed for the synthesis of desired mesostructures from the consideration of the chain configuration.

A new class of silicone-based surfactants was designed to direct the assembly of surfactant/oxide mesophases. The amphiphilic silicone surfactant is composed of a polydimethylsiloxane (PDMS) backbone and a side chain of poly(ethylene oxide)-*block*-poly(propylene oxide) (PEO-PPO) (Scheme 1). Silicone surfactants (denoted $MD_n(D'E_pP_q)_mM$, where $M = (CH_3)_3SiO_{1/2}$, $D = (CH_3)_2SiO$, $D' = CH_3(C_3H_6O)SiO$, $E_p = (C_2H_4O)_p$, and $P_q = (C_3H_6O)_qH$) are amphiphilic, cheap, nontoxic, and biodegradable, and they have lower glass transition temperatures and higher surface activities than conventional hydrocarbon surfactants.[20,21] The silicone surfactants (purity $>95\%$) were prepared by hydrosilylation addition reactions, as found elsewhere.[20]



$$(CH_3)_3SiO\!-\!\left(\underset{CH_3}{\overset{CH_3}{Si}}\!-\!O\right)_{n}\!\left(\underset{C_3H_6O-(C_2H_4O)_p-(C_3H_6O)_q H}{\overset{CH_3}{Si}}\!-\!O\right)_{m}\!-\!Si(CH_3)_3$$

Scheme 1. Primary structure of the polyether-modified polysiloxanes used in our study.

Lamellar surfactant/silica powders (denoted ZSU-L) were prepared by hydrolysis of tetraethylorthosilicate (TEOS) in the presence of pure silicone surfactants in acidic media or at neutral pH. The lamellar character of the ZSU-L products is clearly seen from the transmission electron microscopy (TEM) image of an ultrathin section of an as-prepared sample that was prepared under strong acidic conditions (Figure 1). The ZSU-L products are planar bilayers sandwiched by thick silica platelets that are arranged parallel to each other. The interlayer distance, as measured from the TEM images is 200(± 10) nm, which is much greater than those of all previously synthesized and natural layered materials.[7–16] The splitting of silica walls visible in the image is the result of ultrathin sectioning. TEM observation of the ZSU-L sample under various tilting angles did not show evidence for any framework topology other than lamellae. Even when the concentration of the silicone surfactant and HCl is substantially changed, the lamellar structure is retained, suggesting that silicone surfactants favor the formation of layered materials (see for example Figure 1 of the Supporting Information for a composite obtained at neutral pH). Lamellar silica were obtained no matter whether the silicone surfactant was of low or high molecular weight ($M(D'E_{10}OH)M$, $M(D'E_{12}H)_2M$, $MD_{28}(D'E_{12}H)_3M$, $MD_{34}(D'E_{12}P_{12})_6M$, $MD_{70}(D'E_{15}P_{15})_9M$, $MD_{103}(D'E_{18}P_{18})_{10}M$).

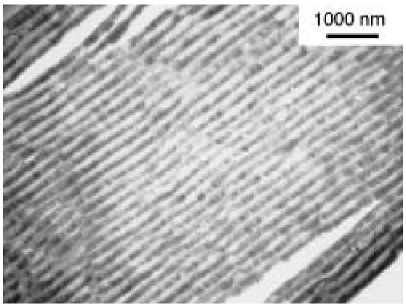


Figure 1. TEM image of an ultrathin section of an as-prepared lamellar ZSU-L product obtained using $MD_{108}(D'E_{16}P_{16})_8M$ as the template in 2 M HCl.

At low concentrations (~1 wt% for the preparation of ZSU-L powders), silicone surfactants form isotropic micelles with no long-range order.[20] Under our reaction conditions, the initial dilute solutions were completely clear and devoid of phase-segregated planar bilayer structures of the size observed for the mesostructure obtained later. No lamellar phase was observed by freeze-fracture electron microscopy analysis in the initial surfactant solution. Phase segregation and planar bilayer formation did not occur until TEOS was added to the solution of the silicone surfactant. This indicates that the formation of the ZSU-L powders is not templated by the pre-existing bilayers and vesicle templates or liquid crystal phases previously thought to be responsible for lamellar organic/inorganic adducts.[7–9,15,16]

The dimensionless effective surfactant packing parameter $g = V/a_0 l_c$ determines the mesostructure of the product;[19,22,23] V is the chain volume, l_c the chain length, and a_0 the optimal headgroup area of a surfactant molecule. The governing role of the headgroup area (a) in the selection of a particular mesostructure has already been confirmed in water–surfactant systems: the favored mesophase is that which permits a to be close to its optimum value a_0, while maintaining favorable packing of the hydrophobic surfactant chains.[19]

During freeze-dry kinetic experiments with silicone surfactant templating, we observed the lamellar mesophase after reaction times in the order of 5 min in strong acidic media; this phase remained as the reaction proceeded. We conclude that, in the early stage of the reaction, coassembly of organic and inorganic species leads to the formation of lamellar surfactant/silicate sheets. As crosslinking and condensation of the silicate species proceed, the organic–inorganic interfacial area increases and the number of silanol groups decreases, so that a_0 increases. To accommodate this change, Stucky and co-workers proposed[19] that silica condensation leads to an increase in interfacial area through corrugation of the lamellar surfactant/silicate sheets (pathway I in Scheme 2). This corrugation progresses until connection between the sheets is made at the cusps, which ultimately results in the formation of a hexagonal mesophase. In contrast, we always obtained layered silica mesophases when silicone surfactants

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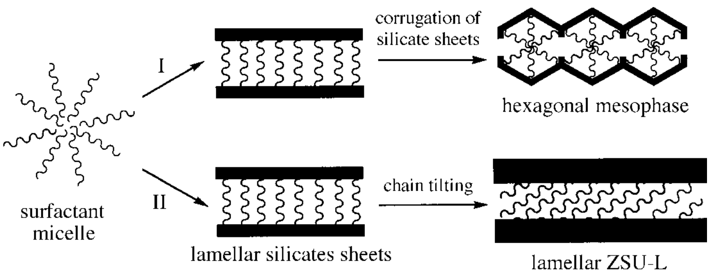

Scheme 2. Comparison of the templating pathways for conventional surfactants with a restrictive hydrocarbon chain configuration and silicone surfactants with an unrestricted siloxane chain configuration. Pathway I: transformation from lamellar surfactant/silicate sheets to a hexagonal mesophase templated by CTA$^+$, as proposed by Stucky et al.[19] Pathway II: formation of ZSU-L templated by silicone surfactants.

were used. Therefore, we suggest that the formation of lamellar ZSU-L is governed by the supramolecular chain configuration. PDMS chains are more flexible than the hydrocarbon chains in alkyltrimethylammonium ions (like CTA$^+$) or Pluronics (PEO-PPO-PEO), because the bond angle (Si-O-Si, ~143°) is significantly larger and the bond length (Si–O, 0.165 nm) significantly longer than for comparable C-C-C (109°, 0.140 nm) and C-O-C (114°, 0.142 nm) units. Thus, the obstacle to rotation is very low (rotation barrier: 0.8 kJ mol^{-1}) and the Si–O bond can freely rotate and tilt.[20,21] This is the reason why even very long PDMS chain surfactants are in the liquid state at room temperature. In contrast, hydrocarbon surfactants tend to be in the solid state at room temperature since Krafft temperatures for surfactants with long and linear hydrocarbon chains are high.[20,21]

Hill showed that the behavior of the "linear" trisiloxane surfactant MDM'E$_8$OH in the aqueous phase is essentially identical to that of the "branched" version, M(D'E$_8$OH)M. This was unexpected, as the shape of the two molecules should be quite different (see p. 30 in ref. [20]). The observation illustrates the important role of the flexibility of the Si–O chain for the behavior of silicone surfactants: the siloxane group tends to adopt a configuration that allows it to accommodate the preferred cross-sectional area of the polar group—in this case the coil of the hydrated PEO chain. This indicates that the flexible chain configuration enables a silicone surfactant to increase its a value toward a_0 through rotation or tilting of the Si-O chains, while maintaining a planar structure. In this case, the wall thickness simultaneously increases to keep the silicone surfactant/SiO$_2$ volume ratio constant. Polymerization normal to the interface substantially thickens the walls even in strong acidic media, though this was previously not expected because of the high positive charge on the silicate species in strong acidic media.[19] Thus, unrestricted supramolecular chain configurations always led to the formation of lamellar mesophases, and lamellar-to-hexagonal mesophase transformations have never been observed using silicone surfactants as the template. We suggest that silica polymerization leads to an increase in interfacial area through tilting of the siloxane chains, as indicated by pathway II in Scheme 2.

We propose that the formation of oxide mesophases is governed by the chain configuration of the supramolecular template. This enables us to predict which chain configurations favor lamellar structures and which favor other mesophases. For example, a lamellar mesophase should be formed when silicone surfactants are used as templates. To test this model, we prepared silica and TiO$_2$ films by the sol–gel method[24] in conjunction with the dip-coating process using silicone surfactants as templates. Highly ordered long-range lamellar structures of silica and TiO$_2$ films were clearly observed (see Figure 2 in the Supporting Information). Their interlayer spacing measured from TEM images was 160(±10) and 320(±20) nm, respectively. The results demonstrate that silicone surfactants with unrestricted chain configurations are responsible for the formation of lamellar mesostructures. Yang et al.[25] prepared a variety of hexagonal metal oxide mesophases using EO$_{20}$PO$_{70}$EO$_{20}$ (P123) as the template in nonaqueous solutions. However, with silicone surfactants as templates, we obtained only lamellar forms of metal oxides such as TiO$_2$ and ZrO$_2$ by the same method (see Figure 3 in the Supporting Information). Their lattice constants were 210(±10) and 160(±10) nm, respectively. These results further support our proposal that the structure of oxide mesophases is governed by the chain configuration of the supramolecular template, that is, unrestricted chain configurations (such as those of silicone surfactants) are responsible for the formation of zero-curvature (planar) lamellar silica mesophases, and restricted chain configurations (such as those of the Pluronics family, CTA$^+$) are responsible for high-curvature hexagonal mesophases.[19]

Hierarchically ordered silica (denoted ZSU-4) was prepared using a mixture of silicone surfactant and P123 as the template. Figure 2A shows that lamellar silica similar to that observed in the ZSU-L product is retained in the ZSU-4 product. Previously, in systems with a member of the Pluronics family, C$_n$EO$_m$ (polyethylene oxide), CTA$^+$, or their mixtures serving as templates, a single mesophase such as hexagonal mesoporous silica has been prepared.[26–29] Surprisingly, we find here that hexagonal pore channels were formed in the silica walls of ZSU-4 (Figure 2B). Both the lamellae and the hexagonal mesophase are assembled in a single body, representing a complex mesostructure. No X-ray diffraction (XRD) peaks are observed for the ZSU-L product (Figure 3). However, a high degree of mesoscopic order (at least three *p6mm* XRD peaks) is observed for the calcined ZSU-4 (Figure 3). It is obvious that the lamellar mesophase and the hexagonal mesoporosity in the walls were separately templated by the silicone surfactant and P123 in the mixed templating system, and thus hierarchically ordered silica formed, although both structures exist in a single system. The presented examples further supply strong evidence that the structure of oxide mesophases is governed by the chain configuration of the supramolecular template.

The N$_2$ sorption isotherm and the corresponding BJH (Barret–Joyner–Halenda) pore size distribution curve of the calcined ZSU-4 product are shown in Figure 4A and B, respectively. The N$_2$ isotherm of calcined ZSU-4 is a type IV isotherm with a large type H$_2$ hysteresis loop. This is in contrast to the isotherms of SBA-15 and MCM-41, which indicates that ZSU-4 has a three-dimensional network of mesopores.[30,31] The calcined ZSU-4 product, prepared using

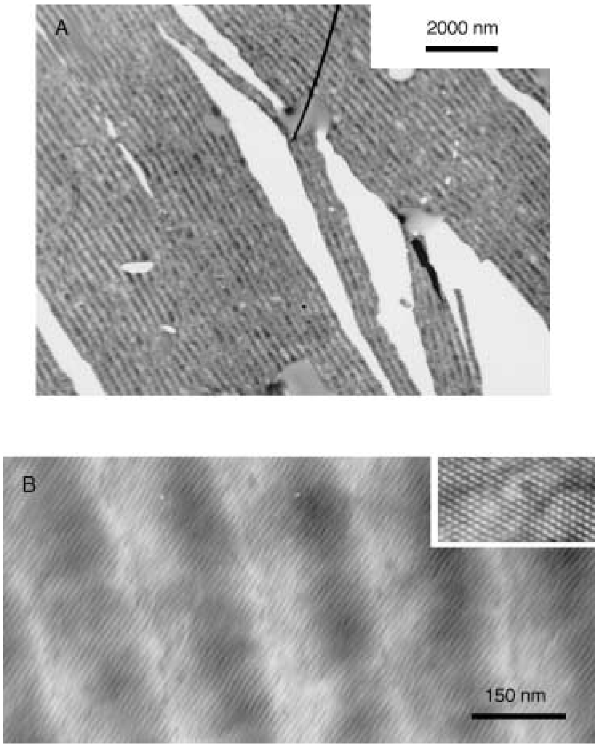

Figure 2. TEM images of an ultrathin section of the hierarchically ordered silica mesostructure ZSU-4 obtained with a mixture of silicone surfactant and P123 as the template. A) Low-magnification TEM image of the as-prepared ZSU-4; B) higher-magnification TEM image (recorded along the [110] zone axis). The inset in (B) is recorded along the [001] zone axis and shows highly ordered hexagonal mesopores.

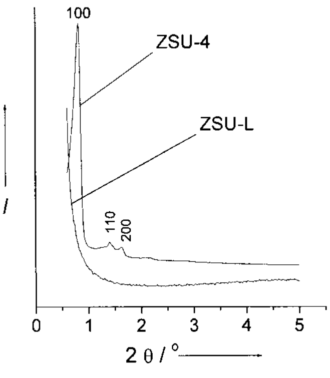

Figure 3. Powder XRD patterns of the as-prepared ZSU-L product and the ZSU-4 product (calcined at 560 °C in air for 6 h).

the mixture of silicone surfactant and P123 as the template, has a high BET surface area of 841 $m^2 g^{-1}$. The BJH analyses show that calcined ZSU-4 exhibits pore sizes of 8.1 nm (Figure 4B).

In conclusion, highly ordered lamellar hybrid oxides with large interlayer spacings were obtained using silicone surfactants as templates under a wide range of synthetic conditions. We found that silicone surfactants with unrestricted chain configuration are responsible for the formation of lamellar mesophases. The addition of copolymers can create hexagonal mesophases in the layered walls, which provides a simple route to the design of complex mesostructured materials. Coassembly of organic and inorganic species, and the fact that silicone surfactants prefer planar structures, results in the formation of highly regular lamellar structures. We believe that this novel route is universal and offers significant overall benefits for the controlled design of a wide range of materials with complex mesostructures. Oxide materials with hierarchically ordered mesostructures are of interest from the viewpoint of biomineralization, and may find wide applications in catalysis, adsorption, separation, etc. We believe that our findings provide new insights into the mechanistic issues involved in the formation of this interesting class of mesostructured materials. Further investigation, however, will be required in order to adequately elucidate the actual mechanisms of the formation of these unusual lamellar structures.

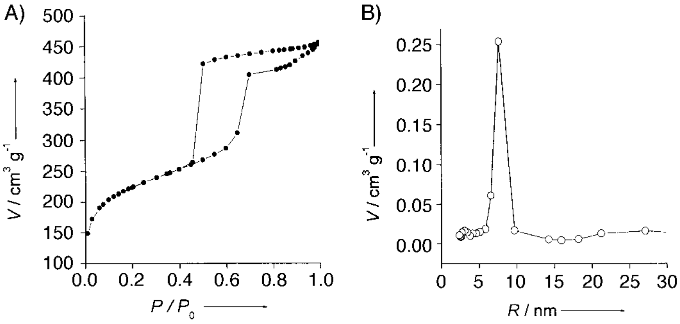

Figure 4. A) N_2 adsorption and desorption isotherms for ZSU-4 calcined at 560 °C for 6 h. B) Corresponding BJH pore size distribution curve determined from the N_2 adsorption isotherm. Prior to measurement the sample was evacuated at 523 K and 10^{-6} Torr for 16 h.

Experimental Section

Lamellar silica powders (ZSU-L) were prepared by hydrolysis of TEOS in the presence of pure silicone surfactants under a wide range of acidic conditions or at neutral pH. In a typical synthesis, silicone surfactant $MD_{108}(D'E_{16}P_{16})_8M$ (1 g) was dissolved in 2 M HCl (60 mL), then TEOS (4.16 g) was added while stirring. The reaction mixture was stirred at room temperature for 24 h to obtain the ZSU-L powder.

Complex silica mesostructures (ZSU-4) were prepared using a mixture of a silicone surfactant and P123 as the template. In a typical synthesis, $MD_{108}(D'E_{16}P_{16})_8M$ (0.8 g) and P123 (1 g) were dissolved in 2 M HCl (60 mL), then TEOS (4.16 g) was added while stirring. The reaction mixture was stirred at 35 °C for 24 h and subsequently heated for 24 h to 90 °C. The precipitate was recovered by filtration, washed with water, and air-dried. The surfactant was removed by calcination at 560 °C for 6 h in air.

XRD analysis was performed on a Rigaku Rotaflex diffractometer equipped with a rotating anode and $Cu_{K\alpha}$ radiation. TEM images were obtained with a JEOL 100CX operated at 100 kV. The samples were embedded in epoxy resin and ultramicrotomed for the TEM measurements. N_2 adsorption measurements were performed at 77 K using a Micromeritics ASAP 2010 system. The surface area was obtained by Barrett-Emmett-Teller (BET) calculations for the adsorption branch of the isotherm, the pore size distribution by BJH calculations.

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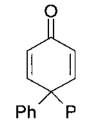
4,4-Diphenyl-2,5-cyclohexadienone: Four Polymorphs and Nineteen Crystallographically Independent Molecular Conformations**

V. S. Senthil Kumar, Anthony Addlagatta,
Ashwini Nangia,* Ward T. Robinson,*
Charlotte K. Broder, Raju Mondal, Ivana R. Evans,
Judith A. K. Howard,* and Frank H. Allen*

Polymorphism is the existence of the same chemical substance in at least two different crystalline arrangements of molecules.[1] The existence of polymorphism implies that free energy differences between different crystalline forms are small (1–2 kcal mol^{-1}) and that kinetic factors are important during crystal nucleation and growth.[2] Molecular conformations, packing arrangements, hydrogen bond synthons, and lattice energies of the same molecule in different crystalline environments can be compared in polymorphic structures. Polymorphs represent special situations for the study of structure–property relationships with a minimum number of variables, since differences arise from crystal packing effects and not because of the presence of a different chemical species. A proper understanding of polymorphism is important in crystal engineering[3] because the unexpected occurrence of a new polymorph can well demolish the best of crystal design strategies. Getting the correct polymorph[4] is of the utmost importance in the synthesis of drugs, pharmaceuticals, explosives, dyes, pigments, flavors, and confectionery products.



1

We describe here four X-ray crystal structures of 4,4-diphenyl-2,5-cyclohexadienone (**1**) that exhibit conformational polymorphism,[5] conformational isomorphism,[5] and concomitant polymorphism[6]

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[*] Prof. A. Nangia, V. S. S. Kumar, A. Addlagatta
School of Chemistry, University of Hyderabad
Hyderabad 500046 (India)
Fax: (+91)40-301-1338
E-mail: ansc@uohyd.ernet.in

Prof. W. T. Robinson
Department of Chemistry, University of Canterbury
Christchurch (New Zealand)
Fax: (+64)3-364-2110
E-mail: w.robinson@chem.canterbury.ac.nz

Prof. J. A. K. Howard, C. K. Broder, R. Mondal, I. R. Evans
Department of Chemistry, University of Durham
South Road, Durham DH1 3LE (UK)
Fax: (+44)1913743-745
E-mail: J.A.K.Howard@durham.ac.uk

Dr. F. H. Allen
Cambridge Crystallographic Data Centre
12 Union Road, Cambridge CB2 1EZ (UK)
Fax: (+44)1223-336-013
E-mail: Frank.Allen@ccdc.cam.ac.uk

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