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Liquid-crystalline glycolipids: towards understanding the roles of liquid crystals in biological and life processes

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Liquid-crystalline glycolipids: towards understanding the roles of liquid crystals in biological and life processes

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A Commentary on the paper "Liquid-crystalline behaviour in the *n*-alkyl gluconamides and other related carbohydrates", by B. Pfannemüller, W. Welte, E. Chin and J.W. Goodby. First published in *Liquid Crystals*, **1**, 357-370 (1986).

The paper 'Liquid-Crystalline Behaviour in the n-Alkyl Gluconamides and Other Related Carbohydrates' by B. Pfannemüller, W. Welte, E. Chin and J.W. Goodby had interesting origins. It was written by me, John Goodby, while I was employed at Bell Laboratories, New Jersey, USA. I had always had an interest in biologically related research and the first opportunity I had to study carbohydrate liquid crystals was while I was working with George Gray at Hull University. In 1978 we studied the liquid crystal properties of fully substituted penta-alkoxy D-glucopyranosides, which were provided to Hull by the Ministry of Defence (MoD) at Porton Down. Sadly these materials did not appear to be liquid crystals, however they could be substantially supercooled, and indeed many of the materials remained in a glassy state to temperatures below −50°C. Then in July 1983 I attended the Gordon Research Conference on Liquid Crystals at Brewster Academy, New Hampshire, USA, (see figure 1), and I listened to a fascinating talk by Professor George Jeffrey of the University of Pittsburgh on the liquid crystal properties of carbohydrates. 'Jeff', as he was known, reported that octyl 1-*O*-*β*-D-glucopyranoside was liquid crystalline, but he did not know which mesophase he was studying. After discussions with Jeff it became fairly apparent to me that it was a smectic A phase. Upon returning to Bell Laboratories, I purchased as many glycolipids from Sigma that I could find, and set about studying them. This resulted in the classification of octyl 1-*O*-*β*-D-glucopyranoside, the results for which were published in a heavily cited paper in *Molecular Crystals Liquid Crystals* in 1984 [1]. After publication Jeff visited Bell Laboratories and we began our collaboration on liquid-crystalline carbohydrates which lasted until he retired.

Substituted carbohydrates are not often the easiest of materials to synthesise because they are multifunctionalized with hydroxy groups. Knowing, at the time, I was heavily involved in the synthesis of ferroelectric liquid crystals, Jeff acquired materials for me to examine from his colleagues in Europe, most notably from Bette Pfannemüller's laboratory. One set of materials that I was given were the n-alkyl gluconamides, see figure 2(a), which Evelyn Chin and I set out investigating by differential scanning calorimetry and optical microscopy. The results are given, of course, in the paper, however, the data set was the first of its kind which detailed the effect of changing aliphatic chain length on the thermotropic liquid-crystalline properties of open chain sugars [2]. This work followed on from the study made with Jeff on the single compound, octyl D-gluconate [3].

The overall results of these two pieces of work showed that it was possible to sustain liquid crystal properties for aliphatic substituted carbohydrates, where the carbohydrate units were in their open chain forms. Thus, as the materials have no pyranose or furanose rings, they are flexible with no rigidity associated with their chemical structures, which was not the case at the time with conventional liquid crystals. From the classification of the mesophases formed by the gluconamides as smectic A, it was clear that the structure of the mesophase was composed of alternating hydrophobic and hydrophilic slabs, (see figure 2(b)). Consequently, this work was really the first to demonstrate that microphase segregation could be used to support thermotropic mesophase formation.

A subsequent paper [4] was written two years later with Bette Pfannemüller on the glucitols **I** and glucanamides **II** and **III** shown in figure 3. These materials were mostly non-mesogenic, but those that exhibited liquid-crystalline behaviour showed the same phase types as the *n*-alkyl gluconamides, i.e. the mesophases were smectic A.

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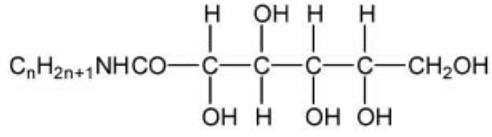
Figure 1. Gordon Research Conference 1983, G. Jeffrey (front) and J. Goodby (back) circled

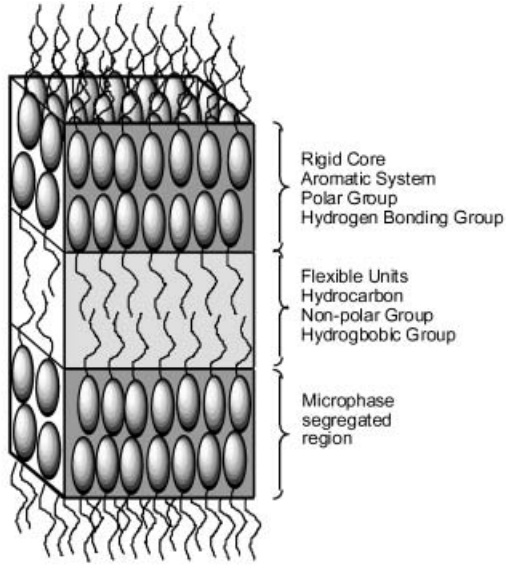
There was a break in my research on carbohydrate liquid crystals until a new collaboration was started with Dr Grahame Mackenzie at Hull University, who was part of an informal network with French Professors Villa (Amiens), Plusquellec (Rennes), Boullanger (Lyons) and Queneau (Béghin Say and Lyons). Our investigation of the thermotropic properties of open chain polyols continued in collaboration with Professor Villa's Research Group at Amiens. We investigated the effects that the number of hydroxyl groups had on the melting and clearing points of the dodecyl substituted sugars shown in figure 4 (**A** to **F**) [5a–e]. It was clear from these studies that the clearing points were essentially linearly dependent on the number of hydroxyl moieties in each individual material, whereas the melting points were not. Similarly the clearing points were independent of chiral structure, whereas the crystal phases were very much dependent on stereochemistry [5b,e]. These observations are now regarded as standard for most material systems of this nature and chemical design.

The systematic investigations of open chain ring systems were further developed to generate structure/property activities between molecular structure and mesophase incidence and transition temperature. In another study the position of substitution of the aliphatic chain was investigated for the dodecyl xylitols, (see figure 5). It can be seen for positions of the dodecyl chain where the molecular flexibility is lowered, as at position 3, the clearing and melting points are higher than for the other positions of substitution. This reflected the fact that for the 3-substitution the molecules have a more rigid structure [5b,e] and the highest melting and clearing points. In addition to substitution patterns and hydroxyl content, a variety of linking groups located between the aliphatic chain and



n-Alkyl Gluconamides

(*a*)



(*b*)

Figure 2. Structure of the *n*-alkyl gluconamides, and the structure of the microsegregated thermotropic smectic A phase

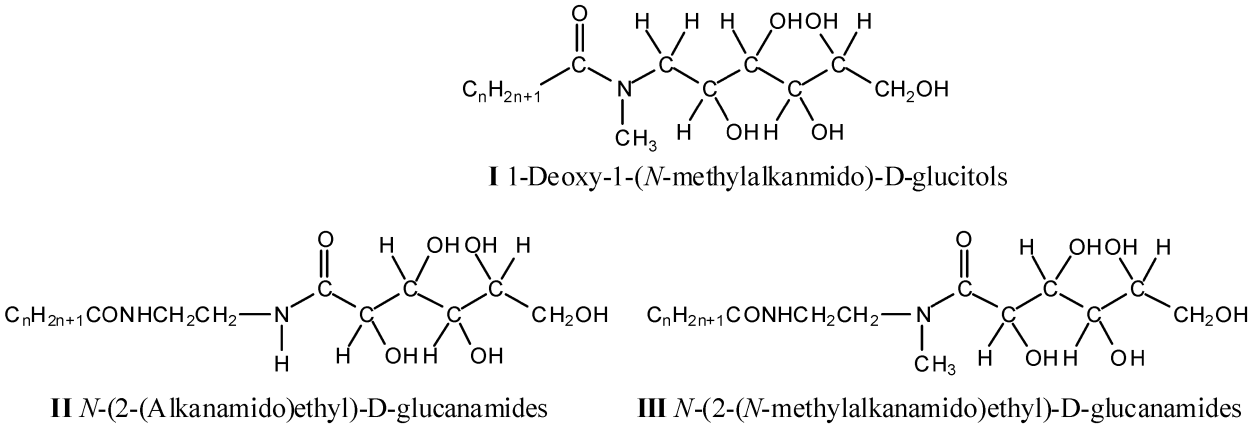


Figure 3.

the sugar unit were investigated as a function of transition temperature and aliphatic chain length. Thioethers, were found to have higher clearing points, relative to esters, relative to ethers [5c,e].

In all of these studies the liquid crystal phase that was exhibited was smectic A, which was easily identified from its focal-conic and homeotropic textures. Upon addition of water many of the materials exhibited lyotropic lamellar Lα phases. Interestingly, the range of materials, as a function of aliphatic chain length, that exhibited thermotropic phases was greater than the range that exhibited lyotropic phases. The classification of the thermotropic phase as a smectic A phase can be extended further to smectic A* for those materials that are chiral. The symmetry of the achiral smectic A phase is, of course, $D_{\infty h}$ whereas for the chiral version it is D_{∞}. Thus the chiral materials should be capable of exhibiting electroclinic behaviour. Whether or not this has any relevance to layered, bilayer or membrane structures and their properties is not known.

After these systematic studies we attempted to increase the size of the head group to see if we could

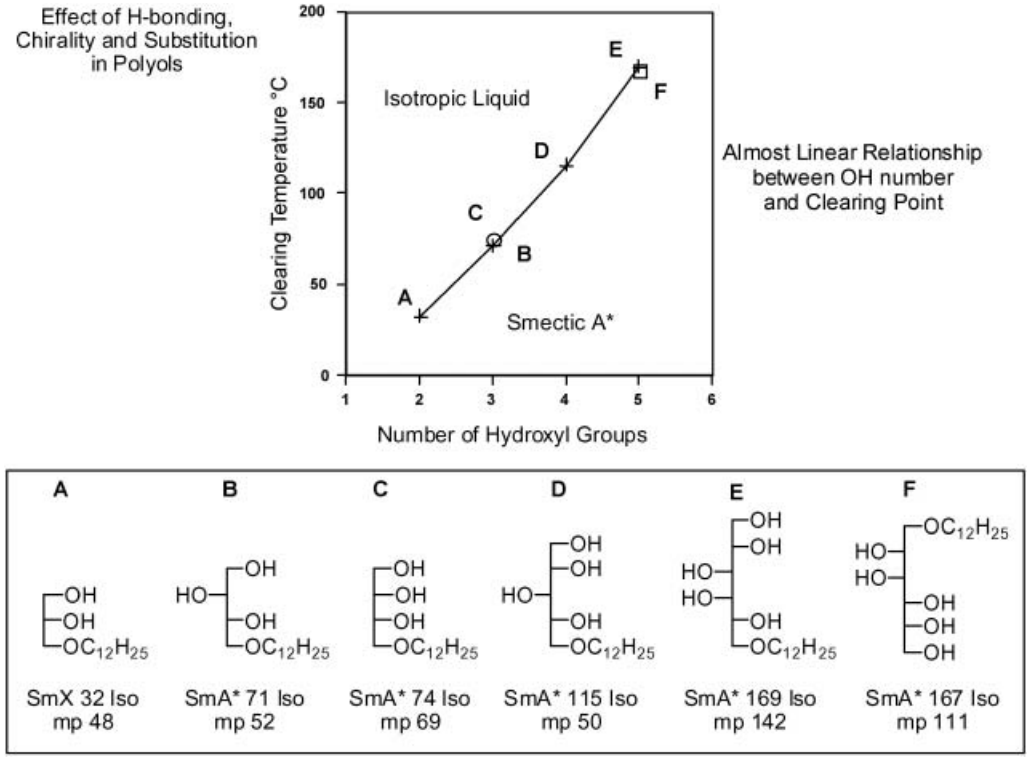


Figure 4. Effect of the number of hydroxyl groups on the clearing point and melting temperatures

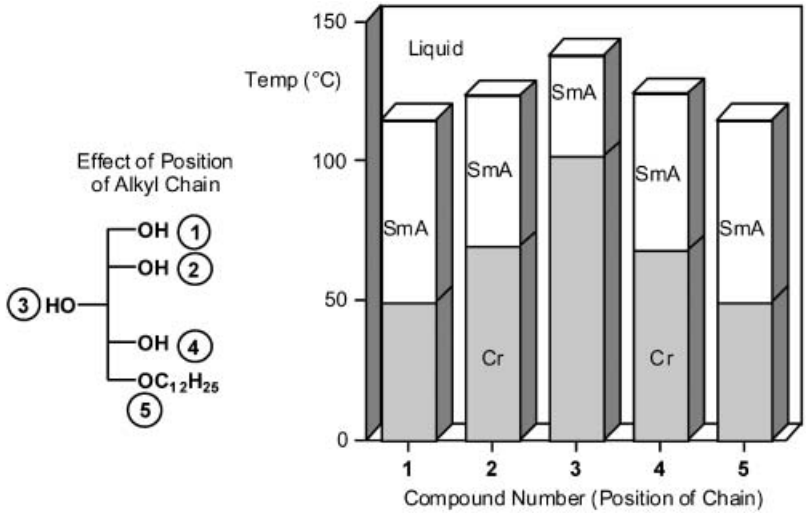
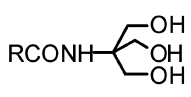


Figure 5. Effect of aliphatic chain substitution on the melting and clearing points for the dodecyl xylitols

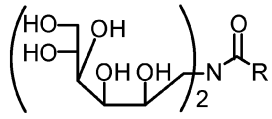
induce the formation of columnar phases. The simple derivatives of tris, the *N*-[2-hydroxy-1,1-*bis*-hydroxymethyl]ethylalkanamide, were still found to exhibit smectic A phases [4e], whereas the *N,N-bis*-(D-mannitolyl)alkylamides which have larger head groups, (see figure 6), exhibited columnar phases. Thus the indications were that the type of thermotropic phase formed by these materials was dependent on the curvature of packing of the molecules, in a similar way to how curvature effects mesophase formation in lyotropic phases. By mixing materials with three head groups and one aliphatic tail with materials with one head group and three tails we expected to be able to recreate the lyotropic phase diagram, as function of the curvature of packing, but with thermotropic liquid crystal phases, as shown in figure 7. A good portion of the phase diagram was replicated by experiment, thereby demonstrating that the formation of smectic, columnar and cubic phases is by-and-large dependent on the curvature of packing for thermotropic phases, which is dependent to a large degree on molecular shape.

All of the materials described, which were a direct result of the early work with Jeff and Bette, possessed open chain hydroxylated segments. Thus, the primary use of the materials was as surfactants and detergents. Ring closed systems on the other hand were far more interesting from the point of view of living systems. In 1977 Small [6] had linked various liquid-crystalline glycolipids to diseases, (see figure 8), however, he did not link liquid crystal properties with disease or with the treatment of disease. Therein lies the challenge in this area of liquid crystal research. This challenge is possibly the most important faced by liquid crystals, and potentially the most lucrative. The question becomes:- "Can some biological functions, certain diseases and infections, and drug treatments be linked to liquid crystallinity and liquid crystal properties?" The indications are to answer this question with a qualified yes [7].

Many glycolipids that are involved in biological processes possess cyclic ring structures. Typically for mammalians six-membered pyranose rings are found as opposed to five membered furanose rings. Thus, applying similar analytical techniques learned through the study of the gluconamides, we investigated naturally occurring galactocerebrosides that were isolated from bovine brain, and compared the results obtained with those prepared by synthetic methods [8]. Both sets of materials exhibited thermotropic columnar mesophases with the fatty chains located on the exteriors of the columns with the galactosyl head-groups located



N-[2-hydroxy-1,1-*bis*-hydroxymethyl]ethylalkanamides



N,N-bis-(D-mannitolyl)alkylamides

Figure 6.

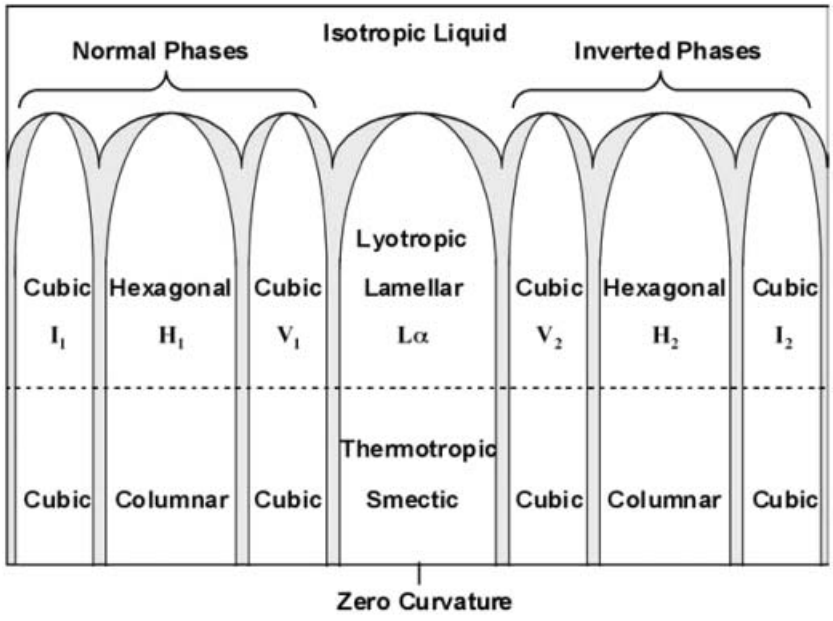


Figure 7. Phase diagram for lyotropic and thermotropic liquid crystals as a function of the curvature induced from the packing of molecules

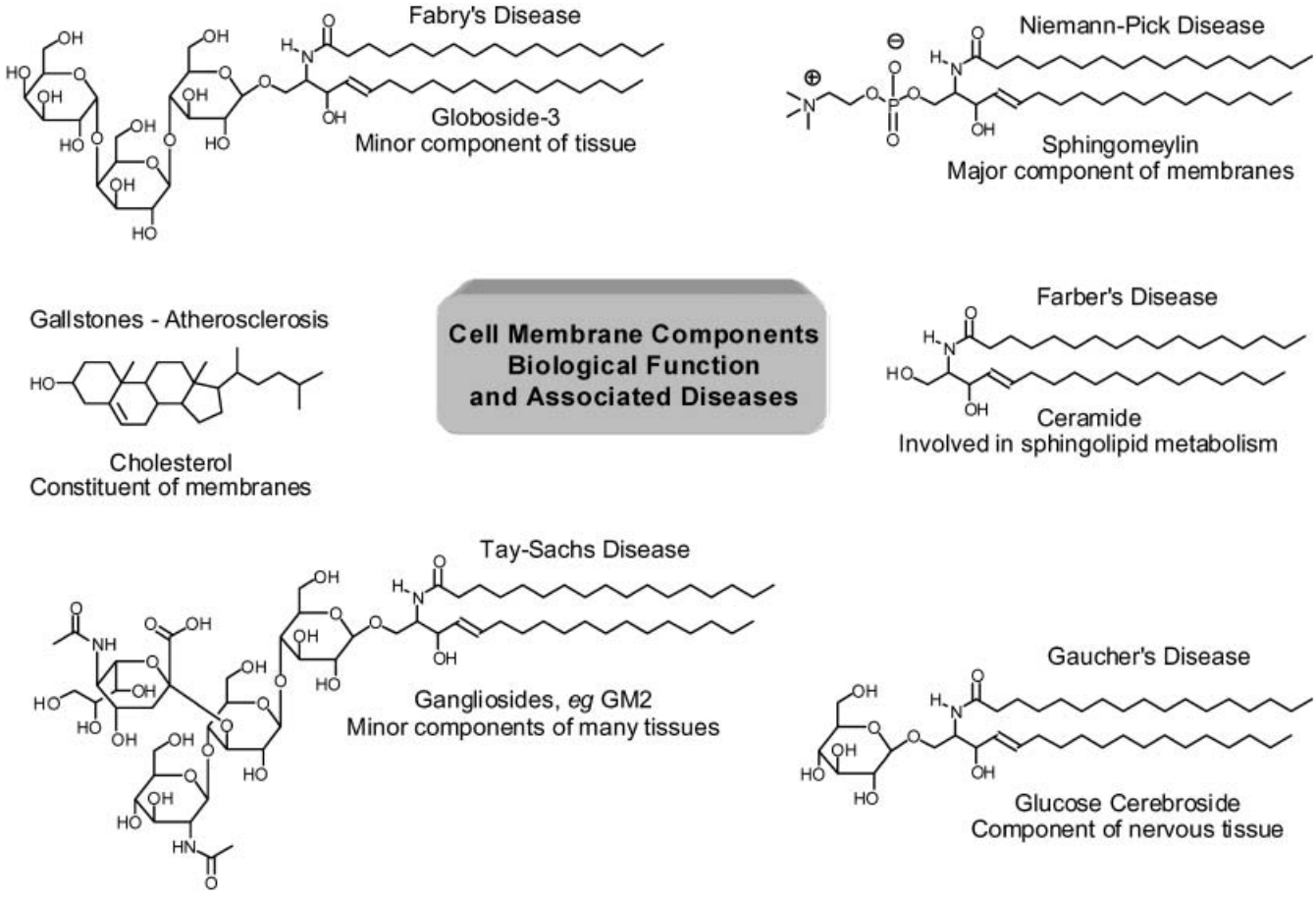


Figure 8. Naturally occurring glycolipids and the diseases that they are associated with

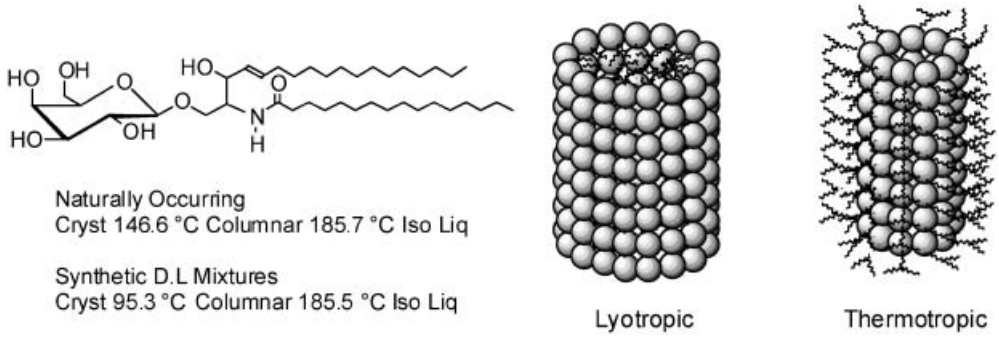


Figure 9. Liquid-crystalline galactocerebrosides and columnar structures of the lyotropic and thermotropic phases that they form

towards the interiors of the columns. Addition of water inverted the structures so that now the head groups were located on the exteriors of the columns (see figure 9).

The transition temperatures for the synthetic versus the naturally occurring materials showed that the clearing points were almost identical but that the melting points of the natural (chiral) materials were much higher, as shown in figure 9. These results demonstrate two points; (i) that the glycolipids found in the brains of cattle are liquid crystal, and (ii) the melting points are quite high, thus the materials need to be modified in order to reduce these values; this is achieved through the incorporation of *cis* double bonds which are found in many galactocerebrosides.

In collaboration with Daniel Plusquellec and Thierry Benvegnu we realised that biological membranes were a great resource for the isolation of novel lipids, which could be mimicked [9]. The membrane lipids of ancient bacteria served as fascinating and inspirational templates for the synthesis of novel glycolipids. Many of the lipids were composed of isoprenic groups, and a number were found to possess giant macrocycles which spanned the bilayers of membranes, (see the top of figure 10). Another interesting feature of the natural glycolipids was their propensity to possess furanose

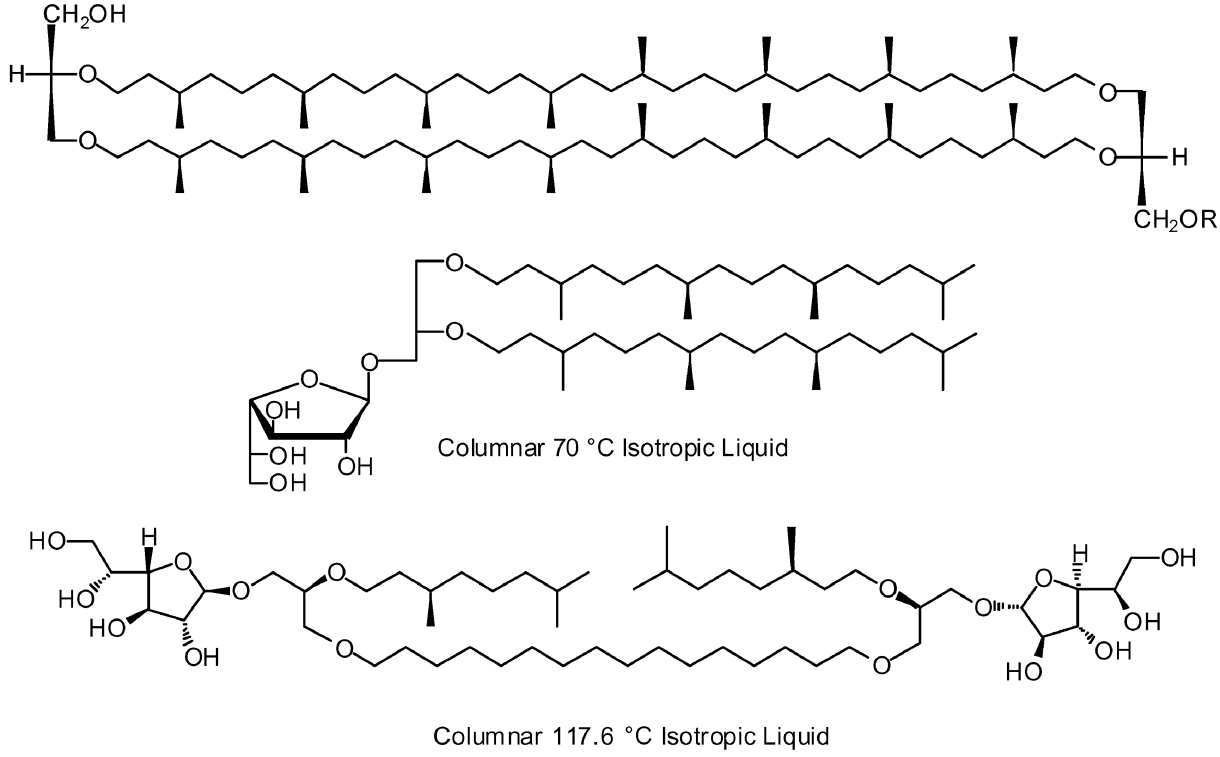


Figure 10. Lipids formed by archaebacteria (top), liquid-crystalline mimics prepared at Rennes [9] bottom two materials

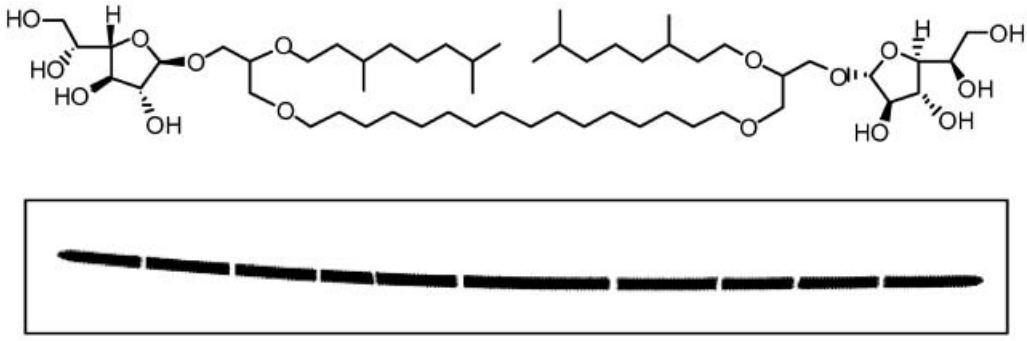


Figure 11. TEM of vesicles formed by the quasi-macrocyclic archaeal mimic shown above

rings. Mimicking these materials resulted in families of novel glycolipids being prepared which exhibited two interesting properties; (i) very low melting points, often with no crystal forms being observed but instead liquid crystal glassy phases were found at temperatures as low as -70°C, secondly, the bolaamphiphiles shown in the lower part of the figure exhibited thermotropic columnar phases indicating that the molecules had folded structures. These materials also formed very unusual vesicles, (see the TEM in figure 11). There are indications, from the breaks in the vesicle, that its structure may be related to lyotropic TGB phases.

More complex sugar based systems were also investigated because of their abundance in nature [10]. In particular it was interesting for us to combine pyranose and furanose ring systems and to understand how the liquid crystal properties would vary. Derivatives of sucrose were a suitable vehicle for study and many derivatives were investigated in collaboration with Yves Queneau at Lyons. Novel mesophase structures were found for both mono-alkylated and di-alkylated sugars, and one family of materials in particular, the 6,6′-di-*O*-alkanoylsucroses, showed unusual changes in the lamellar spacing as a function of chain length. The stearoyl member, see figure 12, showed a layer expansion of over 30% on cooling, coupled with a change in the X-ray line-shape, indicating the possibility that two smectic A phases might be present [11]. Interestingly these materials were also found to exhibit immunostimulant and anti-tumour properties.

Most liquid-crystalline carbohydrates up until this point were designed to have the head group and the aliphatic chains essentially separated, however, for these classes of compounds, the chains appear to be located at opposing ends of the carbohydrate cores, in a similar way to the chemical structures of conventional thermotropic liquid crystals. This is not strictly true as the head groups for disaccharides are often bent giving the resulting glycolipid the possibility of forming folded structures. Folding is, of course, important in biological function, *cf.* proteins and DNA. Interestingly, disaccharides possessing four aliphatic chains have some fascinating biological functions and many have been mimicked. For example, maltose tetrapalmitate mimics Lipid A, (see figure 13) shows promising immunostimulation responses to tumour transplants in animals. Similarly, Cord Factor, which is the 6,6′-dimycolic ester of α,α-trehalose, is another interesting material. This material induces virulent *tuberculosis bacilli* to form cords in solution. Moreover, it is usually present in virulent (active) forms of TB. Cord Factor has also been shown to possess immunostimulatory and antitumour properties. If one examines the surfaces of TB bacteria, the complexity of bacterium becomes immediately apparent, (see figure 14). Apart from the plasma

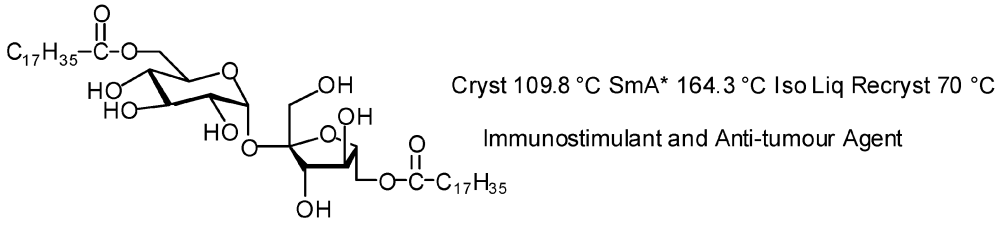


Figure 12.

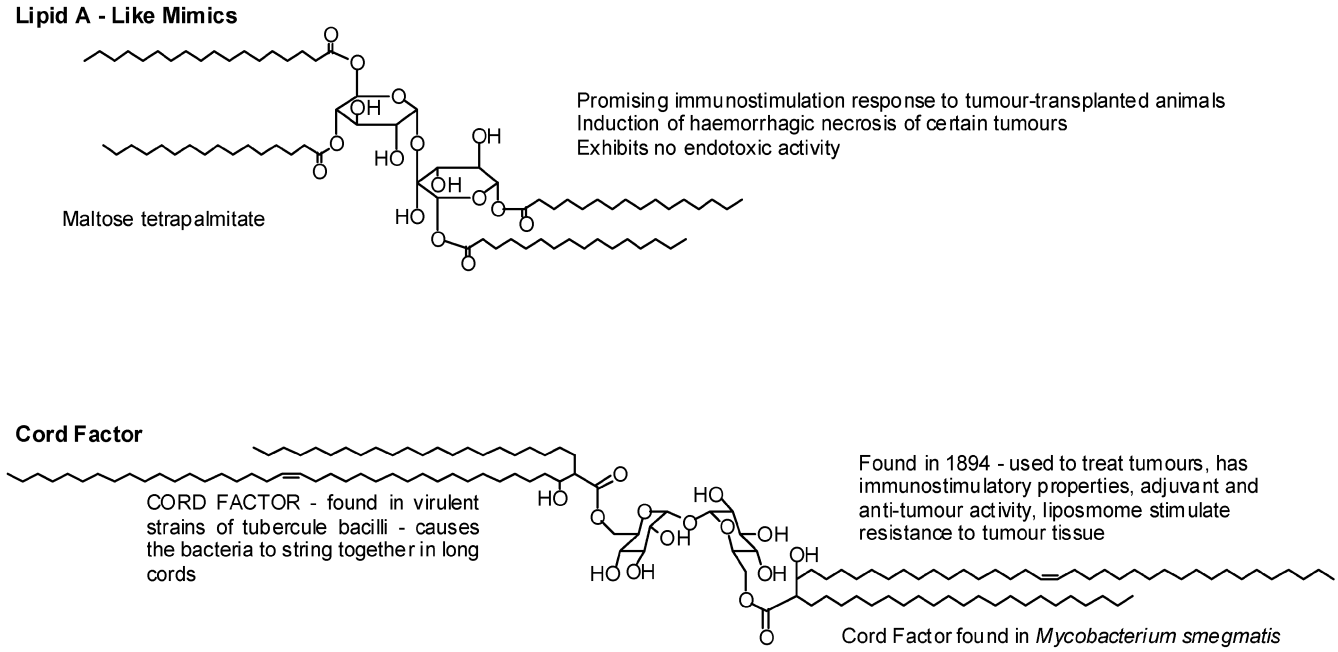


Figure 13. Structures of maltose tetrapalmitate and 6,6′-dimycolic ester of α,α-trehalose (Cord Factor)

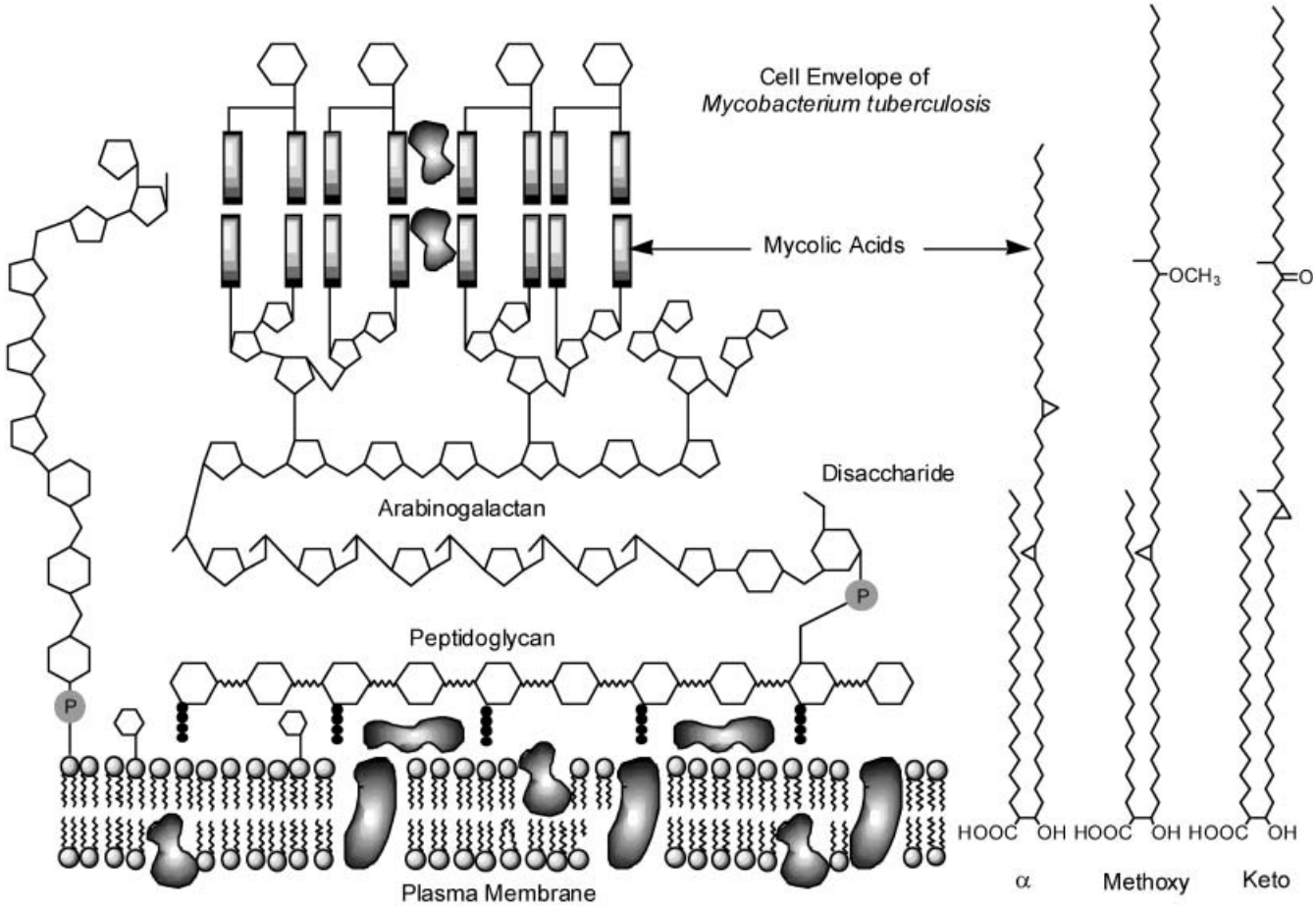


Figure 14. Proposed model of the surface of *mycobacterium tuberculosis*

membrane, there is a complicated polysaccharide and lipid coating, culminating with sugar derivatives of mycolic acid at or near to the surface. The mycollic acid derivatives are, of course, also associated with virulent strains of *tuberculosis*.

Thus, through rewarding friendships and collaborations, which are often so apparent in the field of liquid crystals, our studies of glyco- and phospho-lipids have resulted in over 35 publications since the report of n-alkyl gluconamides. Moreover our research in this area continues, with ever closer studies to real living systems. Indeed, in the last few years we have also studied living cells which were coated with thermotropic liquid crystals in order to see if liquid crystals might amplify cell functions, such as cascade effects [12]. The links between liquid crystal chemistry to biology are thus becoming closer [6, 7, 13], in a similar way to how liquid crystal chemistry has intimate connections to liquid crystal physics and engineering. In my view this connection represents a new and challenging frontier in liquid crystal science.

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Liquid-crystalline behaviour in the *n*-alkyl gluconamides and other related carbohydrates

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Many alkyl derivatives of carbohydrates are used as detergents for cell wall membranes. This study describes the liquid-crystalline properties of a number of these systems. The combination of a hydrophilic carbohydrate moiety and a hydrophobic aliphatic substituent leads to the formation of both thermotropic and lyotropic liquid-crystal mesophases. Materials with this structural combination are suspected to form interdigitated bilayer smectic A phases. The central core region of the layer is held together by dynamic hydrogen-bonding between the neighbouring carbohydrate moieties, whereas the terminal aliphatic chains create fluidity between layers.

1. Introduction

Thermotropic liquid-crystal mesophases were recently discovered and classified in carbohydrate systems [1–4]. Generally, materials which exhibit these properties are alkyl derivatives of carbohydrates in their cyclic pyranose forms. However, it was recently shown that *n*-octyl gluconate, which has an open chain structure, also exhibits liquid-crystalline properties [5].

The formation of liquid-crystalline phases in carbohydrate systems appears to be promoted by the different interactions of the two chemically dissimilar portions of the molecular structures of these compounds. The carbohydrate moieties interact strongly through hydrogen-bonding, whereas the alkyl chains interact only weakly through van der Waals forces. This produces a bilayer structure similar to that for interdigitated smectic A (A_d) phases [2], except that the bilayer in this case is held together by hydrogen-bonding within the layer planes rather than by strong dipolar interactions, as in for example the 4-*n*-alkyl-4′-cyanobiphenyls [6]. Consequently, the hydrogen-bonded form of the phase is more viscous than the dipolar variation. The two modifications also appear to be immiscible because of the breakdown of the hydrogen-bonding of the carbohydrate containing species caused by mixing with non-hydrogen-bonding dipolar aromatic molecules [2].

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In this study the liquid-crystalline properties of the *n*-alkyl gluconamides, an open chain carbohydrate system, are described. The results obtained are compared with those for cyclic derivatives and mixed (open chain and cyclic ring) structures.

2. Experimental

The synthesis of the materials was reported previously [7]. Their structures and purities were determined by infra-red spectroscopy and elemental analysis. The sample of *n*-octyl-α-D-glucopyranoside was kindly provided by Dr. M. Garavito, Biozentrum, Basel (Switzerland). The liquid-crystalline behaviour of the carbohydrates was in vestigated by thermal, polarized-light microscopy employing a Zeiss Universal microscope in conjunction with a Mettler FP52 microfurance and FP5 control unit, and by differential scanning calorimetry using a Perkin–Elmer DSC-4-TADS instrument. Homogeneously aligned specimens of the liquid-crystal phases were obtained in cells constructed of nylon 6–10 coated glass plates separated by 10 µm spacers [8].

3. Results

The results obtained for the melting behaviour of the materials investigated are given in tables 1 and 2. Table 1 gives the transition temperatures and enthalpies for the *n*-alkyl gluconamides. Table 2 lists the transition temperatures for a number of related materials. The transition

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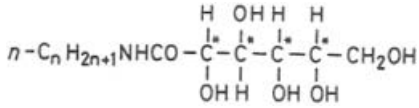
Table 1. Transition temperatures† determined for the *n*-alkyl gluconamides



n	K_1		K_2		K_3		S		Iso
6 ΔH‡	•	119.7 (1.08)	•		—		—	155.6 (33.64)	•
7 ΔH	•	79.2 (2.15)	•	96 (7.49)	•	(150.4)	•	156.4† (36.76)	•
8 ΔH	•	72§	•	87.4 (9.79)	•	158.2 (33.5)	•	159.1† (0.51)	•
9 ΔH	•	83.5§	•	99.36 (9.46)	•	159.5 (33.75)	•	174.9†	•
10 ΔH	•	74.6 (4.54)	•	91.15 (7.58)	•	156.9 (31.09)	•	182†	•
11 ΔH	•	77.2 (3.18)	•	99.4 (7.72)	•	156.7 (35.21)	•	190.2†	•
12 ΔH	•	80.5 (2.31)	•	94.4 (8.18)	•	155 (28.61)	•	189†	•
18 ΔH	•	111 (1.92)	•	151 (32.7)	—		•	196.7†	•

†The clearing points were determined by thermal optical microscopy, the other temperatures were obtained from D.S.C. ‡Values obtained in cal/g; 1 cal is equivalent to 4.184 J. §Too small to measure. Decomposition in the liquid-crystal phase, therefore the enthalpy could not be measured.

temperatures obtained for the *n*-alkyl gluconamides are shown as a function of increasing terminal alkyl chain length in figure 1. The results obtained for the various properties of these compounds are summarized as follows.

3.1. *Melting behaviour*

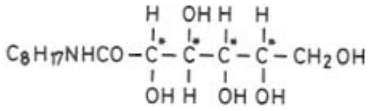
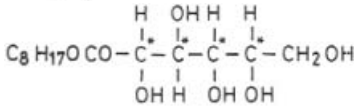
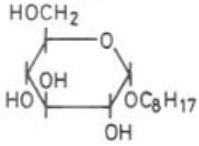
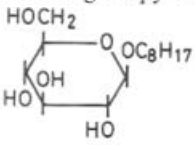
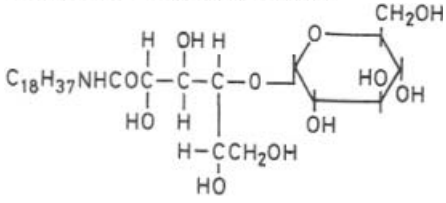
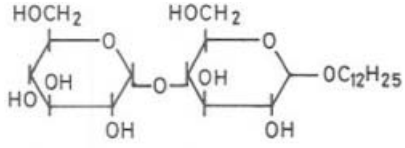
Generally the *n*-alkyl gluconamides studied melted in a complex manner through two or three crystal phases into a liquid crystal and then to the liquid, or alternatively directly to the liquid. The first crystal phase (K_1) usually appears highly birefringent between crossed-polarizers, however the subsequent crystal phases (K_2) and (K_3) lose most of the coloured birefringence on heating, producing a monotone crystalline texture. Melting into the liquid-crystal phase produces an oily-streak texture (figure 2) accompanied by homeotropic areas bounded by the streaks. Differential scanning calorimetry confirmed the optical studies and showed that enthalpy values for the crystal-crystal phase changes were in the region of 2 to 7 cal/g, whereas the melting points were normally greater than 30 cal/g. The enthalpy values for the liquid crystal–isotropic liquid clearing points could not be obtained because of excessive decomposition (caramelization). A number of heating and cooling cycles obtained by differential scanning calorimetry are shown in figures 3 to 9 inclusive. It is interesting to note that the transition temperatures, enthalpy peak size, and peak shape for *n*-octyl gluconamide (figure 5) are very similar to those reported previously for *n*-octyl gluconate [5].

3.2. *Thermal decomposition processes*

Thermal decomposition through caramelization showed some interesting comparisons between material classes. First, within an homologous series, for example the *n*-alkyl gluconamides or the *n*-alkyl-1-*O*-β-D-glucopyranosides, decomposition was more rapid in materials that exhibited liquid-crystal phases than in those that did not (figure 10). Comparison between figures 3 to 9 for *n*-hexyl, *n*-octyl, and *n*-undecyl gluconamides exemplifies this process. In figure 3 for the *n*-hexyl member, a normal melting point is obtained, recrystallization (figure 4) occurs fairly readily on cooling and no liquid-crystal phase is observed. The *n*-octyl homologue (figure 5) exhibits a short temperature-range liquid-crystal phase. The heating cycle clearly shows a peak for the liquid-crystal-isotropic liquid phase change occurring just after the melting point on heating. The cooling cycle (figure 6) however is erratic due to decomposition. Finally the *n*-undecyl member exhibits a wider temperature-range liquid-crystal phase than the other two homologues, but in this case decomposition is initiated in the heating cycle at the phase change to the liquid crystal. At this point the trace (figure 7) becomes erratic and meaningless. Cooling of this sample produces no enthalpy peaks (figure 8) because the specimen had completely decomposed after being heated to the isotropic liquid. Decomposition through caramelization is more rapid in the liquid-crystal phase than either the crystal or the amorphous liquid. The upper clearing point temperatures were obtained from thermal optical microscopy by rapidly heating the specimen and observing an appropriate area that had not undergone much decomposition.

Second, decomposition occurs much more rapidly in the open chain sugars than it does in the cyclic pyranoside analogues. For example, *n*-octyl 1-*O*-α-D-glucopyrano can be cycled up and down in temperature by differential scanning calorimetry with little decomposition. Figure 9 shows the heating cycle for this

Table 2.

Compound	m.p./°C	cl. pt./°C
	158.2	159.1
n-octyl gluconamide		
	160.1	160.0
n-octyl gluconate		
	72.3	116.3
n-octyl 1-*O*-α-D-glucopyranoside		
	67.1	106.4
n-octyl 1-*O*-β-D-glucopyranoside		
	109.5	>207 (Decomp)
n-octadecyl maltobionamide		
	102	>245
n-dodecyl maltoside		

compound, the trace through the wide temperature range of the liquid-crystal phase is normal unlike those obtained for the gluconamides. Similarly in a study of the maltoside and maltobionamide, the maltoside was relatively stable whereas the maltobionamide rapidly degraded once it was heated to the liquid-crystal phase.

3.3. *Liquid-crystalline behaviour*

The transition temperatures of the *n*-alkyl gluconamides are depicted in figure 1 as a function of increasing alkyl chain length. The liquid-crystal phase, which is common to certain members of this homologous series, is injected at the *n*-heptyl homologue where it is observed as a monotropic phase. Injection at the *n*-heptyl homologue is typical for carbohydrate systems. The liquid crystal to isotropic liquid transition temperatures rise rapidly with increasing chain length, whereas the melting points of the individual members remain at a relatively constant value of between 150 and 160°C. The recrystallization temperatures, however, start to fall at the point of injection of the liquid-crystal phase. This may be due to increased decomposition of the samples that exhibit liquid-crystal phases.

The isotropic liquid-liquid-crystal phase transition temperatures alternate along the series with the odd members lying on the upper temperature curve shown in

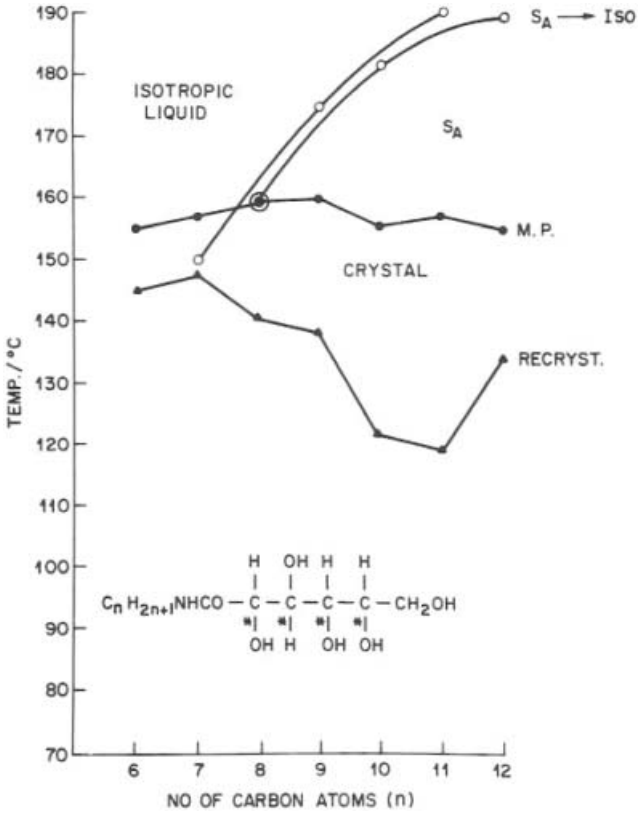


Figure 1. Plot of the transition temperatures versus increasing *n*-alkyl chain length for the *n*-alkyl gluconamides. Key: •, crystal to isotropic liquid or smectic A; ○, smectic A to isotropic liquid; △, isotropic liquid or smectic A to crystal on cooling.

figure 1. The alternation is in the same sense as the N to I, or S_A to N or I sequencing pattern commonly observed for liquid-crystalline systems [9].

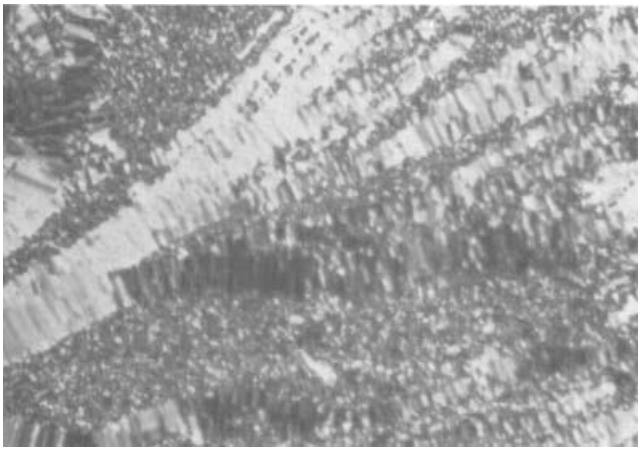


Figure 2. The oily-streak texture of *n*-undecyl gluconamide formed on melting from the crystalline state.

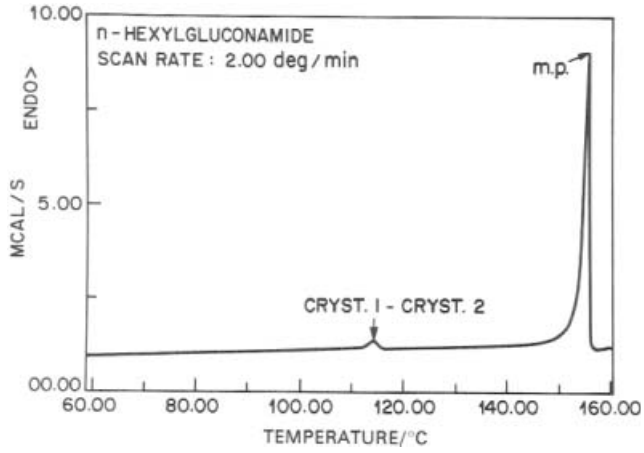


Figure 3. D.S.C. trace for the first heating cycle of *n*-hexyl gluconamide; 1 cal is equivalent to 4.184 J.

The identification of the liquid-crystal phase exhibited by the compounds shown in both tables 1 and 2 was made from textural observations. The phase was initially shown by miscibility studies to be the same as the one exhibited by the *n*-alkyl 1-*O*-*β*-D-glucopyranosides (see figure 11). Textural investigations were then made on selected members of the two groups. The results obtained were found to be common to those materials studied. When observed between clean glass slides and crossed polarizers the materials melted to give an oily-streak texture (figure 2). The streaks appeared to be composed of focal-conic domains oriented laterally to the long axis of the streak. In most cases the oily-streaks bounded areas that were essentially homeotropic. Unfortunately a conoscopic figure for these regions could not be obtained, possibly because of the weak birefringent nature of the materials. Classical

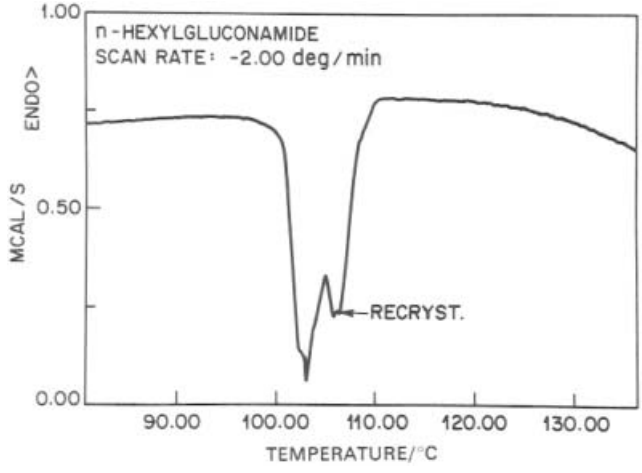


Figure 4. D.S.C. trace for the cooling cycle of *n*-hexyl gluconamide.

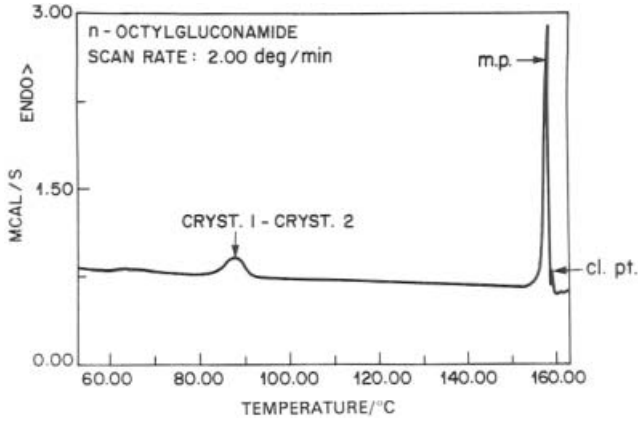


Figure 5. D.S.C. trace for the first heating cycle of *n*-octyl gluconamide.

textures of the mesophase suitable for phase identification were obtained in glass cells, where the plate separation was 10 µm and the internal surfaces had been coated with a nylon 6–10 surfactant [8]. The liquid-crystal mesophase nucleated in the form of bâtonnets (figure 12). These coalesced (figure 13) to produce a classical focal-conic domain texture with clearly defined confocal elliptical-hyperbolic defects typical of the smectic A phase [10] (figure 14).

The cholesteric, S_A and S_C phases form focal-conic defects on cooling from the isotropic liquid, however, the S_A phase is the only one to form a corresponding homeotropic texture. The combination of these two observations classifies the mesophase as smectic S_A, but of an unknown subgroup. Attempts were made through miscibility studies to categorize the S_A subgroup. Initially the mesophases of the *n*-alkyl 1-*O*-*β*-D-glucopyranosides, the *n*-alkyl-1-O-α-D-glucopyranosides, the *n*-alkyl gluconates, the *n*-alkyl gluconamides, the *n*-alkyl

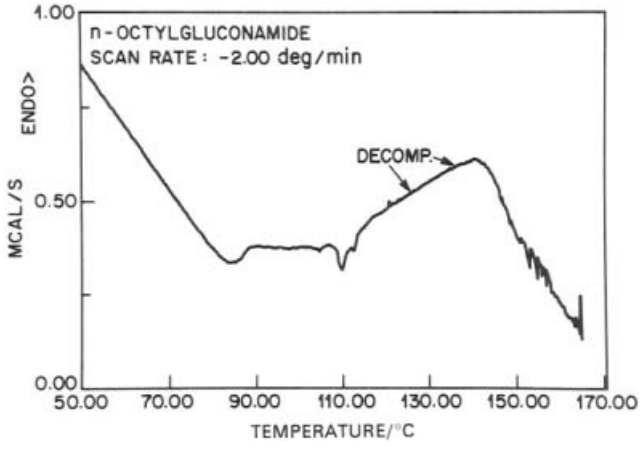


Figure 6. D.S.C. trace for the cooling cycle of *n*-octyl gluconamide.

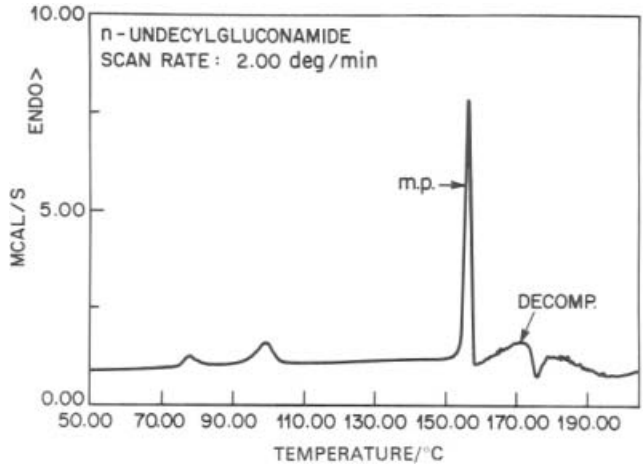


Figure 7. D.S.C. trace for the first heating cycle of *n*-undecyl gluconamide.

maltosides, and the *n*-alkyl malto-bionamides were shown to be of the same miscibility group. Attempts to classify the subgroup with known, previously classified material outside of carbohydrate systems failed. Structural studies on the *n*-alkyl 1-*O*-*β*-D-glucopyranosides suggest that the mesophase is composed of an interdigitated bilayer [1, 2], which is an S_{Ad} classification. Consequently it is expected, because of the miscibility between the carbohydrates studied, that the mesophase exhibited is of the S_{Ad} type for the other homologous series.

4. Discussion

The results show that the several carbohydrate systems studied exhibit a single mesophase of the smectic A type. The subgroup classification is probably S_{Ad} which

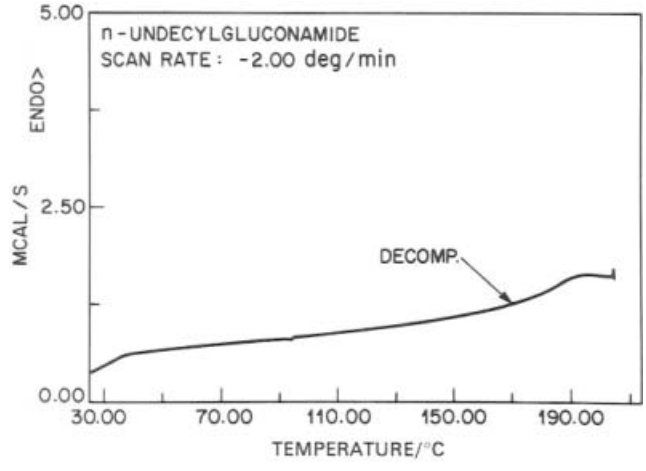


Figure 8. D.S.C. trace for the cooling cycle of *n*-undecyl gluconamide.

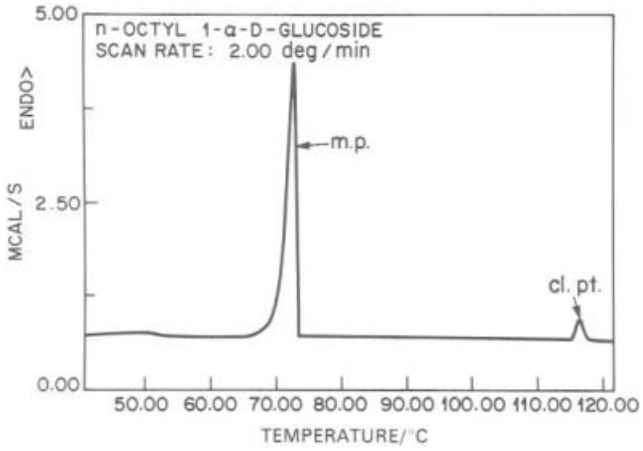


Figure 9. D.S.C. trace for the first heating cycle of *n*-octyl 1-*O*-α-D-glucopyranoside.

has an interdigitated bilayer structure. This result appears to be irrespective of whether the carbohydrate molecules have the cyclic pyranose or open chain configuration. Consequently, the drive to form a liquid-crystalline structure is probably derived from a desire for the hydrophilic parts of the molecules to pack strongly together to give a disordered hydrogen-bonded structure. The weaker interacting hydrophobic aliphatic regions probably form a liquid-like barrier between the layers of hydrogen-bonded cores as shown in figure 15 for the *n*-alkyl gluconamides. This would give a lamellar spacing which on average would be equal to twice the hydrophobic aliphatic chain length plus the length of the carbohydrate moiety, i.e. a lamellar spacing between one and two times the molecular length. This is a proposed model for the mesophases of monoalkyl

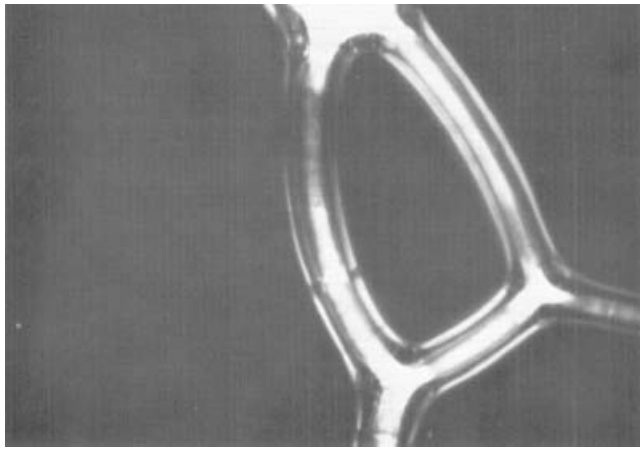


Figure 10. Decomposition of *n*-undecyl gluconamide by caramelization; the liquid-crystalline phase forms a webbing pattern of focal-conic-like defects bounding areas of decomposed gaseous material and air.

Figure 11. Contact preparation between *n*-nonyl gluconamide (left-hand side) and *n*-dodecyl 1-*O*-β-D-glucopyranoside (right-hand side), showing that the two materials are continuously miscible in their liquid-crystal phases.

carbohydrates. However, it should be remembered that in this smectic phase the molecules are in a dynamic state. The aliphatic chains are relatively fluid, and the hydrogen-bonding that holds the cores together often breaks and reforms as the molecules undergo reorientational motion.

Table 2 lists a number of interesting comparisons; first the *n*-octyl gluconamide and *n*-octyl gluconate have similar phase sequences and transition temperatures. In liquid-crystal systems where the cores are not hydrogen-bonded the progression from an ester linkage to a hydrogen-bonding amide would produce great differences in transition temperatures and phase type. In this case, however, the amide inter and intra-molecular hydrogen-bonding is only a small fraction of the total hydrogen-bonding in the system. Therefore, the effect of

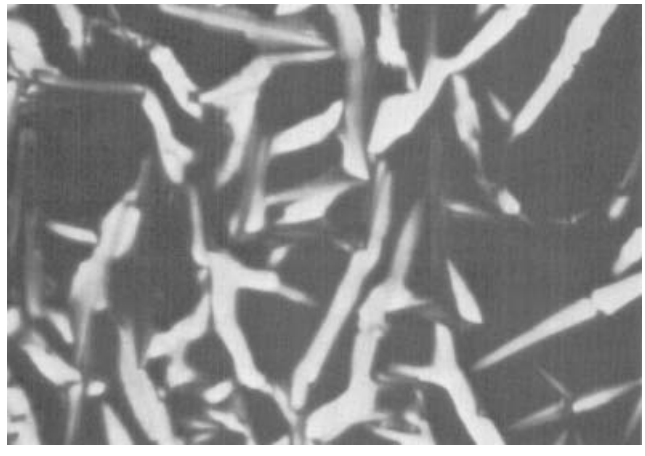


Figure 12. The smectic phase of *n*-undecyl gluconamide separating in the form of bâtonnets on cooling the isotropic liquid.

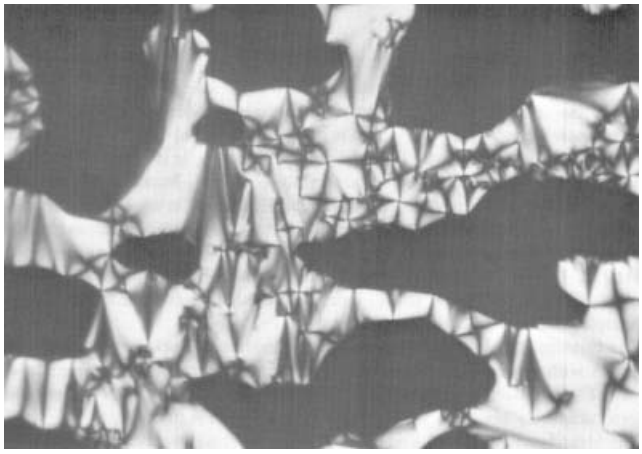


Figure 13. Coalescence of the bâtonnets of *n*-undecyl gluconamide to form a smectic A focal-conic texture. The formation of hyberbolic and elliptical lines of optical discontinuity can be seen clearly as black crosses in the texture.

the extra hydrogen-bonding due to the amide linkage is minimal, thus the two molecules become almost isostructural and consequently have similar phase behaviour.

Second, the 1-*O*-β and the 1-*O*-α pyranosides have similar phase transition temperatures [11]. The alkylated axial α position has a slightly higher transition temperature than the equatorial β position. In non-hydrogen-bonded liquid-crystal systems this would produce great differences in phase behaviour with the axial analogue being more likely to have a poorer tendency to form mesophases. In carbohydrate systems, however, it does not appear to matter greatly if the hydrophobic terminal chain is axial or not with respect to the hydrogen-bonded core. This may be due to the

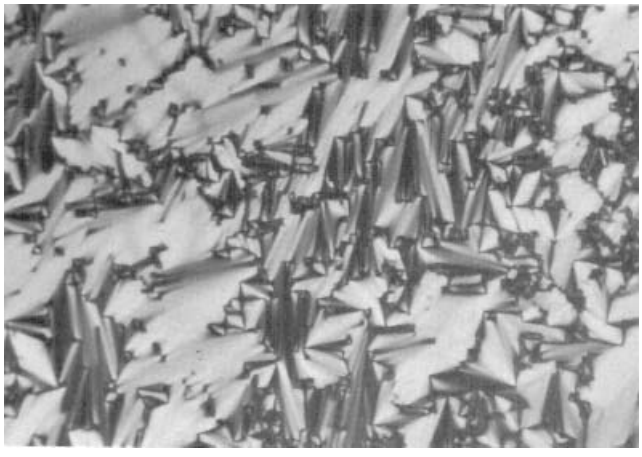


Figure 14. The focal-conic texture of the smectic A phase of *n*-undecyl gluconamide.

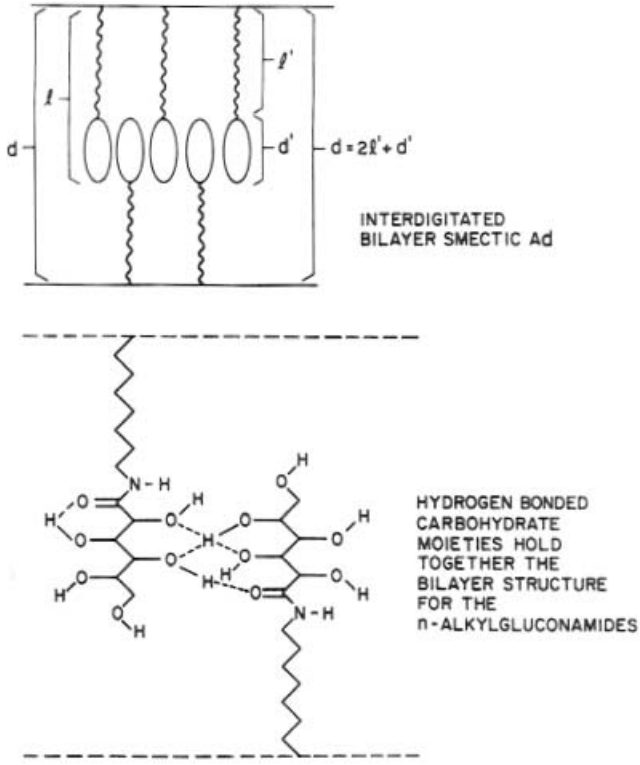


Figure 15. A hypothetical model for the layer structure of the *n*-alkyl derivatives of carbohydrates. The hydrogen-bonded ordering within the layers is shown for *n*-octyl gluconamide. Note, this is only one of the many possible orientations and conformations of the molecules in this dynamic smectic state.

carbohydrate cores packing at a slight angle to one another so that each position is equally favoured, or that the hydrogen-bonding is so strong and the aliphatic interaction so weak that the transitions are dependent first on a melting of aliphatic chains (crystal to liquid crystal), and then on a melting of the carbohydrate cores (liquid crystal to isotropic liquid).

Third, the transition temperatures of materials with open chain carbohydrate cores are often higher than those with closed ring structures, except when decomposition occurs rapidly.

Fourth, monosaccharide and disaccharide systems have similar relationships to transition temperature behaviour as di- and tri-aromatic ring systems in non-carbohydrate liquid crystals. For example, *n*-dodecyl 1-*O*-β-D-glucopyranoside has a clearing point of 144°C, but for *n*-dodecyl maltoside it is greater than 245°C. However, the transition temperatures appear to be only slightly affected if one carbohydrate moiety has an open chain structure. For example, the clearing points for *n*-octadecyl gluconamide and *n*-octadecyl maltobionamide are only 10°C apart. The lack of a great difference

in clearing point values for these two materials may be due to the fact that the maltobionamide degrades at a faster rate, and thus the true clearing point temperature was never obtained. Additionally, the maltobionamide has a closed carbohydrate ring attached to the fourth carbon atom and not to the terminal carbon atom of the open chain carbohydrate. Hence the overall structure is broader and shorter than the linear structure. This in turn lowers the clearing point in comparison to a fully extended structure. Thus it is possible in the light of the above considerations that a mixed system (open chain and closed ring glucose) can also act as a double ring core structure.

Lastly the decomposition process (caramelization) occurs more rapidly in the liquid-crystalline mesophase than in either the solid or the liquid, and for carbohydrates in their open chain structure rather than a pyranose structure. The structural format for the crystalline state of a number of these materials is a head-to-tail interlayer packing [1, 5, 12] with the molecules overlapping with each other and the same way up. In the liquid the molecules are randomly ordered, but in the liquid crystal they have a head-to-tail overlap of the carbohydrate residues. This antiparallel arrangement of the carbohydrate residues (as shown in figure 15) (unlike that in the crystal where they are parallel) may be instrumental in the decomposition process. Thus it is possible that caramelization is initiated by an intermolecular process where the carbohydrate residues are in an antiparallel open chain format.

5. Conclusions

The *n*-alkyl gluconamides were found to exhibit liquid-crystalline phases which are miscible with those of the *n*-alkyl 1-*O*-*β*-D-glucopyranosides. The phases are classified as smectic S_A, tentatively as S_{Ad} where the carbohydrate cores overlap to produce a bilayer structure.

Comparative studies show that the liquid-crystal phase transitions are relatively insensitive to changes in central linkages, position of hydrophobic terminal chains, and to mixing open carbohydrate structures with closed ring pyranose structures.

Acknowledgements

The authors are grateful to Professor G. Jeffrey for many useful discussions.

Note added in proof.—Concurrent to our investigations on the *n*-alkyl gluconamides an X-ray study has been carried out by Drs. D. Bayens-Volant and C. David on the smectic phases of some of these materials. In a personal communication they indicated that the S_A phase is composed of layers where the lamellar spacing is approximately equal to the molecular length, thus classifying the system as smectic A_1. Consequently, in mixtures of these materials with the glucopyranosides there must be an S_{Ad}–S_{A1} phase transition in the phase diagram.

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