The Induction of Chirality in Sol–Gel Materials

SHARON MARX† AND DAVID AVNIR*,‡

Department of Physical Chemistry, Israel Institute for Biological Research, Ness Ziona, 74100 Israel, and Institute of Chemistry, The Hebrew University of Jerusalem, Jerusalem, 91904 Israel

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ABSTRACT

We review the different approaches that lead to chiral sol–gel materials. These methods include the use of silanes bearing a chiral group for silylating the surface of the porous sol–gel (SG) material, the use of such silanes as monomers or co-monomers in SG polycondensations, the physical entrapment of chiral molecules by SG procedures, the imprinting of SG materials with chiral templates and the creation of chiral pores, and the induction of chirality in the matrix skeleton itself. Analytical methods for detecting chirality are reviewed, including fluorescence methods, electrochemical methods, NMR, and induced CD. Applications are reviewed as well, including sensing, catalysis, chromatography, and optics. While most of the examples are focused on silicas and derivatized silicas, the methods and the analytical tools are generally applicable to other oxides and to preparation procedures other than sol–gel processes.

Introduction

Chirality is a well-developed research field particularly in the domain of small organic molecules, where practically all of the basic concepts and practices have been developed. Adaptation of these concepts to materials science has become an increasingly important issue, and while the more elementary definitions associated with chirality, such as chirality itself, handedness, diastereomerism, etc. hold, regardless of the object analyzed, materials science, as we shall see below, calls for specifically tailored solutions and approaches. We have been addressing them for quite some time in practice with SiO_2-based, sol–gel (SG)-derived materials, which will therefore be at the focus of this Account. We do emphasize however that the content is conceptually applicable to most other families of materials. A key issue in the study of chirality is the analytical methods used to detect the existence of this structural property, and so the specific examples detailed herein were also selected in order to provide a useful library of analytical methods.

Because an Account requires a focus on the activity of the authors, the examples detailed below originate from our laboratories and span from early work to recent unpublished results; yet we do wish to point out that the study of chiral silicates is a lively field, and therefore we did lace this report with references to other laboratory activities as well.

One can divide the methods for inducing chirality in silicas and SG materials into four major domains: the use of silanes bearing a chiral group for silylating the surface of the pores of given materials; the use of such silanes as monomers or co-monomers in SG polycondensations; the physical entrapment of chiral molecules by SG procedures; and the imprinting with chiral templates. Here is how it is done.

The Silylation of Silica Surfaces

The classical method for inducing chirality is composed of two stages/phases: first the synthesis of the (porous) material and subsequently covalently anchoring on its surface a chiral molecule. This anchoring is quite often done by a silylation reaction with monomers such as $(OR)_3$–SiR*, where R* is a chiral residue, and the approach is well-known and well-studied. One of its main applications has been in the preparation of chromatographic materials for separation of enantiomers, and we mention here the pioneering study of Gil-Av and co-workers,[1] who were the first to prepare chiral HPLC columns by anchoring to the surface of aminopropyl-silica a chiral tetranitrofluorenyl compound (which is capable of donor–acceptor π-system interactions); the authors used these interactions successfully to separate the enantiomers of a series of helicenes. The example we have selected for this part from our labs is from a completely different domain, namely, the photophysical recognition of a chiral surface. The idea behind the experiment was to anchor to the surface excitable chiral ligands, and then to quench the excited surface with a chiral quencher.[2] Specifically, silica was derivatized with either *S*- or (*R*)-(–)-1,1′-binaphthyl-2,2′-dihydrogen phosphate through an aminopropyl chain (Figure 1). We recall that the chirality of binaphthyls, often used in chirality studies, is due to the inability of the two naphthyl groups to freely rotate around the bond that links them, thus creating a left-handed or a right-handed twist option. This derivatization therefore resulted in left-handed and right-handed surfaces (L-Sur and R-Sur). Once excited by UV irradiation, the excited surfaces can be quenched, and here again, a pair of enantiomeric quenchers was used, namely, (*R*)-(+)- and

Dr. Sharon Marx was born in 1968 in Jerusalem. In 1991, she finished her B.Sc. in chemistry at the Hebrew University of Jerusalem, Israel, and in 1996 her Ph.D. in organic chemistry of supramolecular systems at the same university. Since 1996 she has been a staff research scientist in the point detection group, a part of the physical chemistry department, at the Israel Institute for Biological Research, Ness Ziona, Israel. Her research interests include molecularly imprinted polymers, thin film sensors, biosensors, and nanofibers.

David Avnir is a chemistry Professor at the Institute of Chemistry, The Hebrew University of Jerusalem, where he received all his academic education. His current scientific activities include experimental studies in sol–gel materials, experimental studies in organically doped metals, and theoretical/computational studies in symmetry and chirality. Earlier major interests included fractal theory and far-from-equilibrium phenomena. He has coauthored 300 scientific papers on these topics, which have been cited over 10000 times in total. He holds a number of key patents on doped sol–gel materials and is a cofounder of Sol-Gel Technologies, Ltd. He serves as the Chairman of the Board of the International Sol–Gel Society. More can be found at http://chem.ch.huji.ac.il/employee/avnir/index.html.

* Corresponding author.
† Israel Institute for Biological Research.
‡ The Hebrew University of Jerusalem.

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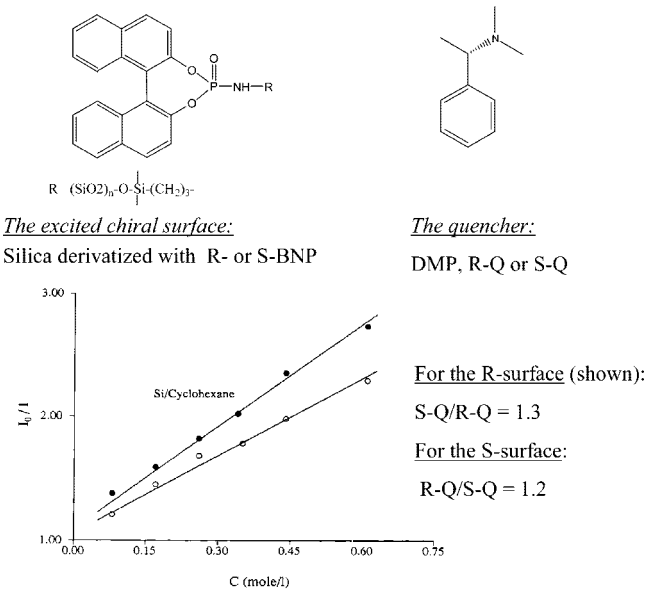

FIGURE 1. Enantioselectivity in fluorescence quenching of a chirally modified silica surface. Silica was derivatized by a binaphthyl (*R*- or *S*-BNP) group and stereoselective quenching by DMP was demonstrated; see the Stern–Volmer graph.

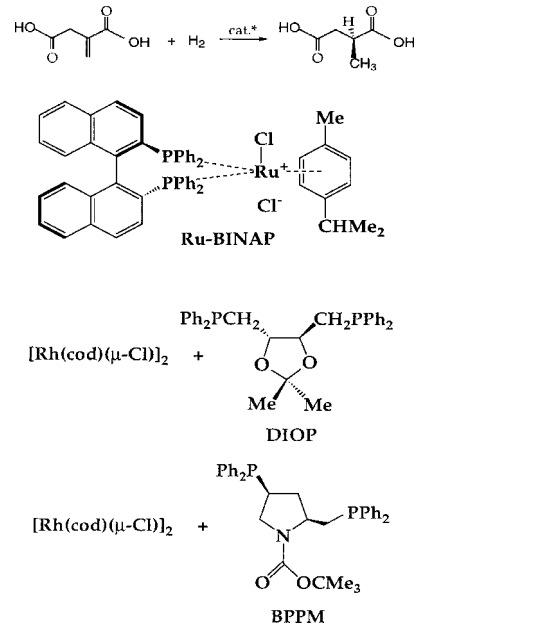

FIGURE 2. Three chiral catalysts entrapped in a sol–gel matrix (bottom) and used for the enantioselective reduction of itaconic acid (top).

(*S*)-(–)-*N*,*N*-dimethyl-1-phenethylamine, R-Q and L-Q. Chiral recognition would mean that L-Sur be quenched differently by R-Q and L-Q. The quenching efficiency was determined by the well-known Stern–Volmer analysis, in which the decrease in emission intensity is determined as a function of increase in the concentration of the quencher, and it was found (Figure 1) that L-Q quenches the right-handed surface, R-Sur, more efficiently than R-Q by a factor of 1.3 (which in chiral recognition studies is considered to be a significant value); that is, the left-handed quencher recognizes the right-handed surface better than the right-handed quencher. An important additional experiment, which serves in studies of chirality as a test for the authenticity of observations, was carried out: A similar enantioselectivity ratio should be obtained with the "mirror" experiment, which was indeed the case. When the left-handed surface, L-Sur, was used, it was the right-handed quencher, R-Q, that showed better quenching efficiency over L-Q, by a similar factor of 1.2. Is it surprising that a right-handed object recognizes better a left-handed object? Not at all! A recurrent theme here and in chirality studies in general is that left-handedness and right-handedness are just labels with no inherent value beyond it; we return to this issue below.

As mentioned in the Introduction, chiral silanes can be used not only for silylation of surfaces but also as monomers, which are polycondensed to obtain chiral organic–inorganic hybrids. Much work in this direction was done mainly by Moreau and his colleagues in the context of chiral catalysis, and the interested reader is referred to refs ,3 and 4.

Entrapment of Chiral Molecules

Whereas the method described above allows surface modification only and requires covalent bonding, a completely different approach to induce chirality has been opened by the SG methodology. The ability to obtain silica by low-temperature polycondensation reactions opened the possibility to physically entrap molecules within the bulk material.[5,6] Numerous applications covering practically all domains of modern materials chemistry have been demonstrated and amongst them, of course, the possibility to entrap chiral molecules. Many chiral molecules and biomolecules were entrapped successfully, including sugars,[7] amino acids,[8] enzymes,[9–11] antibodies,[12] inorganic complexes,[13] surfactants,[14] and chiral polymers.[15]

Perhaps the most obvious optical property of chiral materials is their ability to rotate circularly polarized light, and indeed, the detection of optical rotation in SG silicas doped with the chiral molecules has been reported.[7] A related optical property is circular dichroism (CD), and in the context of SG silicas, one should mention the good CD spectra that were obtained by Shinkai and co-workers from SG entrapped chiral gelators;[16] we return to CD in detail below.

A unique, and at first unexpected, property of doped SG materials is that the dopant is accessible to external molecules, diffusing to it through the pore network.[17,18] That property has enabled one to construct *reactive* SG materials wherein the entrapped molecule is a sensing molecule,[19] a chemical reagent,[20] an enzyme,[10] or a catalyst;[21] numerous other examples exist. Of much practical relevance is the entrapment of a chiral catalyst. If successful, such a catalyst should provide a product with an appreciable enantiomeric excess (ee). One such case has been the entrapment of a series of catalytic organometallic complexes shown in Figure 2, which were used for the enantioselective reduction of the double bond of itaconic acid.[13] The resulting ee was 78%, similar to what is obtained under homogeneous conditions, yet this example helps in demonstrating the advantages of het-

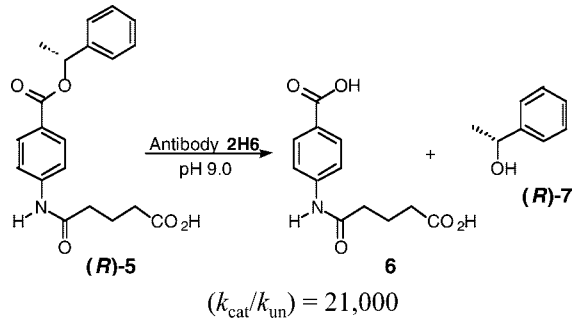

FIGURE 3. Chirality-retaining hydrolysis of the chiral ester (*R*)-**5** by a sol–gel entrapped 2H6 antibody.

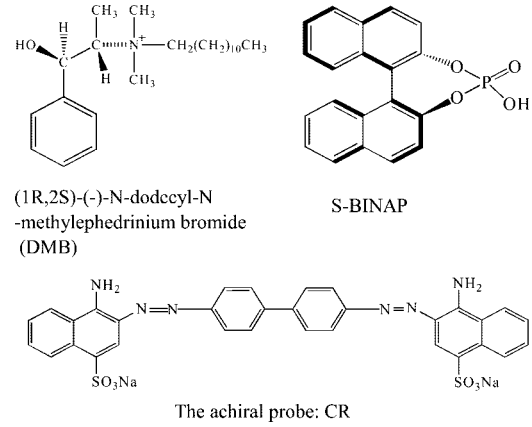

FIGURE 4. The chemical structure of the chiral surfactant, DMB, of the chiral probe BINAP used for the NMR studies, and of the achiral probe Congo Red (CR) used for the induced CD studies.

erogenizing the reaction by the SG approach. First, covalent bonding chemistry is not needed for anchoring the catalyst, and thus no interference with its structure occurs. Second, although all three catalysts (Figure 2) are hydrophobic, the reaction was carried out in water; and third, easy recyclability is possible.

The entrapment of any protein imparts chirality to the composite material, by virtue of the chirality of their building blocks (the amino acids) and by virtue of the folding of the polypeptide chain into chiral 3D structures such as helices. The intensive research into the properties of SG materials doped with proteins has been extensively reviewed[10,22,23] (see also this special issue). Proteins impart chirality also by virtue of their chiral catalytic activity, much as the entrapped chiral catalysts described above do, again because most active sites of enzymes are chiral, and if a prochiral substrate reacts with them, then a high ee product is formed. The specific example that we selected for demonstration this point is the chiral catalytic activity of a reactor based on SG entrapped antibodies (Figure 3).[24] Here, the monoclonal catalytic antibody 14D9, which catalyzes various hydrolytic reactions, and antibody 2H6, which catalyzes the basic hydrolysis of inactivated esters, were entrapped directly in tetramethoxysilane-derived silica SG matrixes, retaining their catalytic activity. Thus, 2H6 effected the hydrolysis of the chiral ester **5** with an impressive $k_{cat}/k_{un} = \sim 21\,000$, retaining the chirality of the product **7**. The catalytic reactions were carried out either in batchwise operations or in a continuous flow apparatus.

Entrapment of Chiral Surfactants

We devote a separate section for the entrapment of chiral surfactants, because of the emerging importance and versatility of the use of these dopants (as is evident also in the next section). In this section, we shall concentrate on a recent study,[25] namely, the doping of sols, gels, and xerogels of silicas with the chiral surfactant (–)-*N*-dodecyl-*N*-methylephedrinium bromide (DMB, Figure 4). We use this example, because it has utilized two analytical tools for the detection of chiral interactions, which are novel in the context of chiral SG materials. In the first method, diastereomeric interactions between DMB and each of the pure enantiomers of co-doped 1,1′-binaphthyl-2,2′-diyl hydrogen phosphate (Figure 4) were detected using ^{31}P NMR spectroscopy. In the second method, *induced* circular dichroism (ICD) signal was obtained from the *achiral* dye Congo Red (Figure 4) codoped with DMB. NMR and ICD were complementary in understanding the way in which the chiral surfactant creates chiral environments inside the SG materials and, in particular, in providing evidence that *the silica network itself becomes chiral* due to the entrapment of the chiral surfactant.

We begin with the NMR detection of diastereomeric interactions between DMB and BINAP within silica sols and gels. We recall that two such interactions are possible in principle: DMB/(*S*)-BINAP and DMB/(*R*)-BINAP. Of the various nuclei, ^{31}P NMR spectrum proved successful in detecting these different diastereomeric environments for the two enantiomers of BINAP. Figure 5 shows the observations: First, one can see in the ^{31}P NMR measurement of (*rac*)-BINAP in D_2O/methanol solution two distinctly different peaks (Figure 5a) that appear at 5.94 and 5.99 ppm. These differently located peaks attest to the different diastereomeric interactions between DMB and each of the BINAP enantiomers and to the association between the two, which is presented schematically in Figure 6. And indeed, when (*rac*)-BINAP was dissolved in a D_2O/methanol solution without DMB, only one ^{31}P peak was observed at 6.03 ppm (Figure 5b). In order to assign handedness to each of the two peaks, each of the two pure enantiomers was subjected to the same experiment separately, and the assignment was found to be δ (*R*)-BINAP = 5.94 ppm and δ (*S*)-BINAP = 5.99 ppm. When entrapped within a sol of pure silica, the two peaks are still seen (5.98 and 6.00 ppm, Figure 5c), indicating that the different enantioselective environments for the two enantiomers of BINAP are maintained. The peak separation ($\Delta\delta$) is smaller in comparison to the one observed in solution ($\Delta\delta$ values of 0.05 and 0.02 ppm for solution and PSG, respectively). This decrease is probably because the DMB molecules are also attracted to the silica surface silanols and, as a result, some of these molecules are entrapped elsewhere within the sol particle matrix and not near the BINAP molecules. In other words, there is a decrease in the effective surfactant concentration in

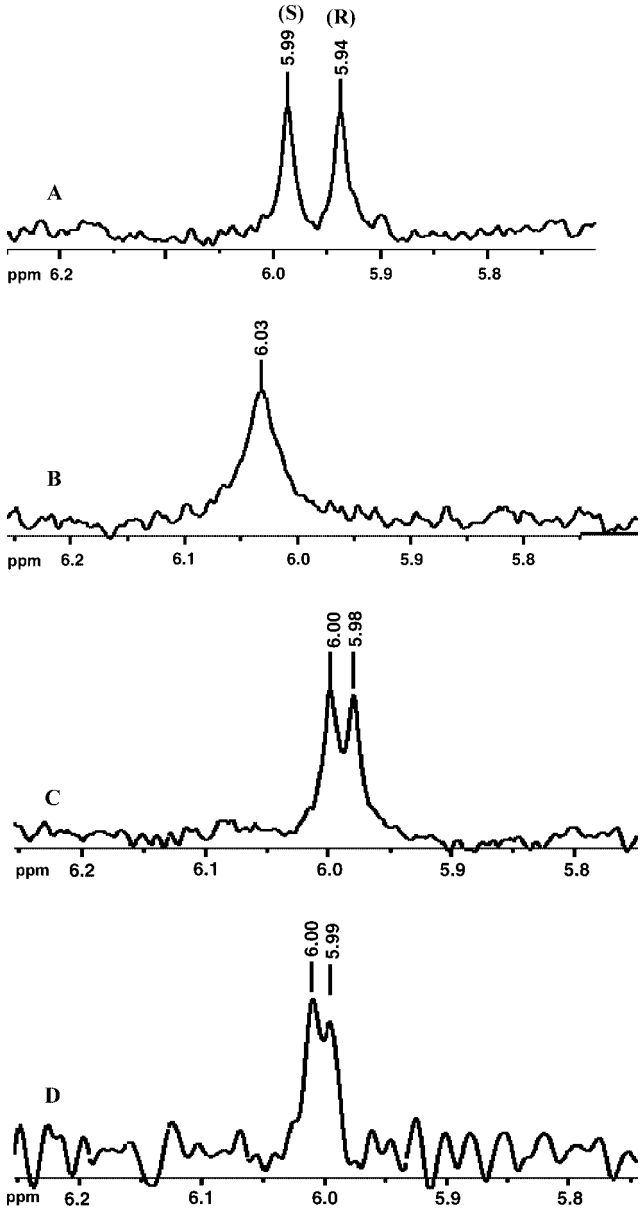

FIGURE 5. ^{31}P NMR spectrum of racemic BINAP in (a) D_2O–methanol solution of DMB and (b) without DMB and ^{31}P NMR spectrum of DMB–BINAP@SG at the sol stage (c) and at the gel stage (d).

comparison to the solution. After gelation within the NMR tube, the ^{31}P NMR of DMB–BINAP@SG was measured (at the wet-gel stage) under identical conditions, and the results are shown in Figure 5d. Clearly, upon gelation, the peaks shifted to a lower field by about 0.15 ppm, accompanied with further slight reduction in $\Delta\delta$ (0.02 and 0.014 ppm before and after gelation, respectively). The fact that diastereomeric interactions are observed in the entrapped form shows that micellar-like aggregates of DMB molecules, which solubilize BINAP, are maintained; that is, the silica environment acts as the water–methanol solution with the polar groups of the surfactant pointing to the surface and the alkyl and aryl chain pointing away, solubilizing the BINAP. Indeed, in an early study on the entrapment of molecules in SG matrixes, it was shown that the polarity of the surface of silica is between that of water and methanol;[6] and in other relevant studies it was

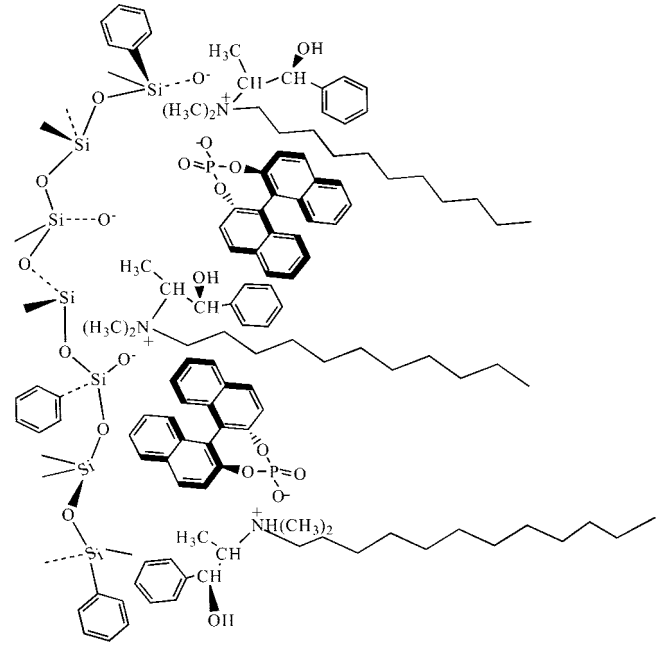

FIGURE 6. Schematic illustration of the proposed DMB aggregation and BINAP solubilization within it, in aqueous methanolic solution.

shown that the geometric convolution of the silica is so high that it resembles a 3D (fractal) surface,[26–28] which is capable of providing silanols in a 3D manner, as in a solvent.

Inducing circular dichroism (induced CD, ICD) in an achiral dopant within DMB@silica proved to be yet another novel method for the study of chiral interaction in SG silicas. We first recall that CD spectroscopy is based on the difference between the interactions of either left-handed circularly polarized light (L-CPL) or right-handed light (R-CPL) with a chiral molecule, for example, of (*S*)-chirality: "diastereomer 1" is L-CPL/S and "diastereomer 2" is R-CPL/S. The absorption spectra are slightly different, and that difference spectrum is the principle behind obtaining a CD spectrum. We recall that the ICD phenomenon allows one to extract a CD signal from an achiral probe, which in our case is Congo Red (CR). Being achiral, CR should not show a CD signal; this is indeed the case as seen in Figure 7A: Only a baseline curve is obtained. However, an achiral molecule can be "converted" to a chiral one, if its surroundings are made chiral and if there is strong enough interaction between the achiral probe and the chiral surroundings. In that case, the chiral entity that gives rise to the CD signal is the complex between the achiral probe and the molecules that comprise the environment. A CD signal indeed forms when DMB is added to the CR solution, as seen in Figure 7A. Having in mind the solution behavior, CR was then used as an optical probe for the chiral environment created by DMB within two different sols, namely, purely hydrophilic silica (CR–DMB@SG) and a 10% octadecylated TMOS-derived silica (CR–DMB@OSG). As seen in Figure 7B, an ICD signal is evident, and is obtained from within the two sols. Compared with solution, a number of changes are seen, reflecting the changes in the environment: Thus while the

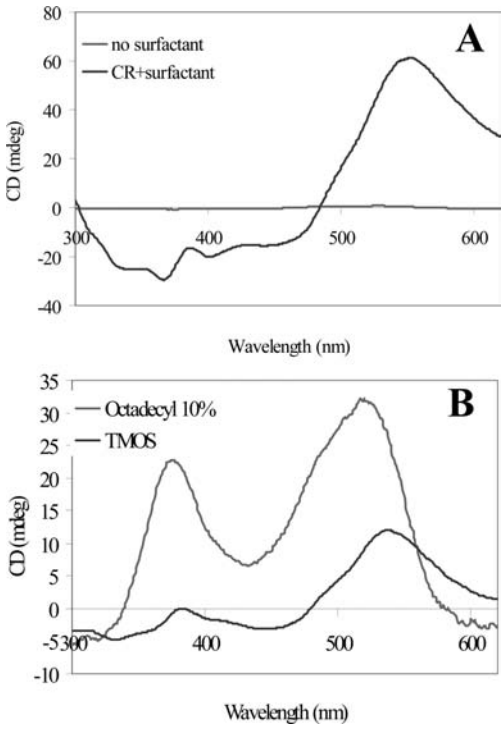

FIGURE 7. The induced CD spectra of (A) CR in the presence of DMB in an aqueous methanol solution and the same measurement performed without DMB (flat baseline) and (B) co-entrapped CD–DMB in hydrophilic (bottom line) and hydrophobic (top line) sols.

main peak at λ_{max} = 543 nm observed in solution is retained upon entrapment with the sol, although shifted (λ_{max} = 540 and 525 nm for SG and OSG, respectively), the lower wavelength region shows reversal in the sign of the signal. The aqueous–methanolic solution and the hydrophilic sol resemble each other in their polarities and in their potential interactions with the DMB–CR, and therefore, $\Delta\lambda_{max}$ is small (3 nm). On the other hand, the OSG sol has a more hydrophobic nature, which is evident not only in the much larger value of $\Delta\lambda_{max}$ (18 nm) but also in the direction of the shift. It is a blue shift, which reflects the destabilization of the polar form in a less polar environment.

We conclude this section with two comments (each deserving a full expansion, impossible here for space limitations): First, a central question is whether it is possible to induce *molecular level structural* chirality in a material; namely, is it possible to obtain a siloxane network that is chiral? Reference 29 provides ICD proof of such chiral induction by the DMB on the silica structure itself. Second, on the supramolecular microscopy level, it was shown, mainly by the intensive work of Shinkai et al.,[30] that helical silica structures can be obtained by the use of organogels as templates.

Chiral Imprinting of Silicas

Our next general approach for the induction of chirality is imprinting, namely, the preparation of porosity with predetermined geometry, chiral in our case. The idea of imprinting silica was first introduced by Dickey[31] (a student of Linus Pauling) in 1949, who discovered that it is possible to prepare a "tailor made" adsorbent for chromatography by premixing an azo dye derivative to be resolved with sodium silicate and later to extract the analyte from the formed silica. He found that this process leaves structural information in the silica, which is later translated to favorable binding of the initial bound analyte. This idea was largely developed into what is termed today "molecular imprinting". The basic idea is to imprint the three-dimensional structure during the polymerization process, which is carried out in the presence of the imprinting molecule. In the case of chiral sol–gel materials, this would be done by mixing the chiral template molecule with alkoxysilane monomers. After the polymerization is complete, the template is extracted from the material, leaving behind its three-dimensional "negative" chiral pore (Figure 8). The monomers are chosen so that there will be complementary interactions with the template; that is, if the template has an aromatic moiety, then phenylalkoxysilane will be used, and if the template is also acidic, than a monomer such as aminopropyl-trialoxysilane will be added to the mixture, and so on. It was indeed found that a synergistic effect between several functional monomers enhances the effectiveness of the recognition between the templating molecule and the imprinted silica.[32]

Molecular imprinting is of course not limited to chiral templates, but chirality adds yet another degree of complexity to the system. The three dimensional cavity formed in the silica is now required to recognize not only the right size and general shape but also the specific handedness; that is, the formed hole should be able to distinguish left from right (Figure 8). We have demonstrated how it is possible to tailor the silica to discriminate between the imprinted enantiomer and its counterpart, and we have shown how to obtain general enantioselective chiral recognition, namely, the formation of imprinted silica that is capable of discriminating between enantiomers of several molecules, none of which was used for the templating procedure. We would like to point out an interesting feature of the chiral imprinting: While the template used is chiral, the silane monomers are achiral; yet the polymerization yields the chiral silicate polymer, at least in the vicinity of the template.

It is worth mentioning that there is a variant of the imprinting technique in which the template is *covalently* bound to one of the monomers prior to the polymerization. This covalent bond is cleaved after the polymerization is complete. This method is known as the "covalent method" contrary to the above described "noncovalent" method. The covalent approach was greatly developed by the group of Wulff.[33] A disadvantage of this method is the extra, often nontrivial, synthetic step needed to bridge the template to the monomer in a labile bond. Another example comes from the lab of Katz who reported a method for imprinting silica using a proline-functionalized silane.[34]

The first example of chiral molecular imprinting in silica was reported by Curti in 1951.[35] In the reported

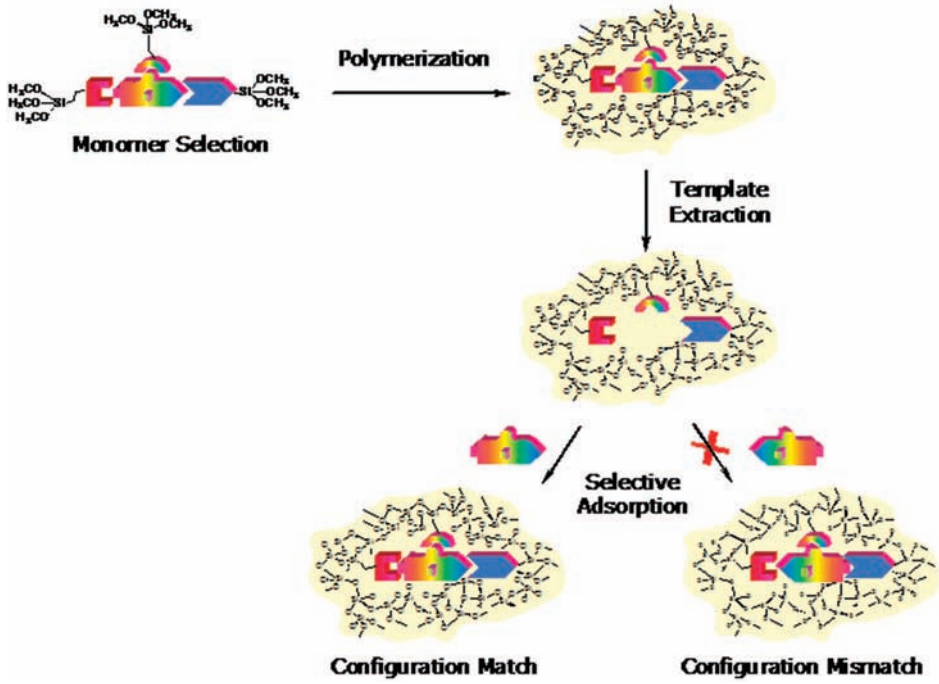

FIGURE 8. Schematic representation of the strategy of molecular chiral imprinting of a sol–gel matrix using a chiral template and achiral suitable silanes.

experiment, camphorsulphonic acid and mandelic acid were mixed with sodium silicate to achieve partial chromatographic resolution (after the templates were extracted from the adsorbent) with the resulting extracted silica. A recent example is from the group of McLoughlin, who used a chiral template to prepare a solid-phase extraction (SPE) cartridge for the drug lisinopril. However, the authors did not use the imprinted medium for enantiomer separation.[36] Finally, we mention that imprinted silicas are very attractive for enantioselective catalysis. Thus, Markowitz et al. reported the surface imprinting of silica with a template that was an amino acid derivatized with a surfactant. Catalytic sites were created on the surface of the particles, and the particles were able to catalyze hydrolysis of one enantiomer of an amino acid 43 times faster than that of the other enantiomer.[37]

Once imprinted, a thin SG film can be used for sensing purposes. The fabrication of sensors requires fast diffusion rates of the analyte from the tested medium to the sensor surface. The sensor surface is comprised from the transducer and the sensing layer, the imprinted film. In order to achieve fast diffusion rates, it is desirable to coat the transducer with a very thin layer of the imprinted silica, while forming enough binding sites that will produce a measurable signal. Film thickness from several nanometers to tens of micrometers has been reported. In various studies by us and by other groups, systems have been coupled to either chiral or achiral binding measurements which included fluorescence,[38] radiolabeling,[38] electrochemical detections,[39] the use of quartz crystal microbalance (QCM),[40] and transistors.[41] An example using fluorescence is the imprinting of SG films with the enantiomers of propranolol. The film was prepared from TMOS, methyltrimethoxysilane, and phenyltrimethoxysilane to

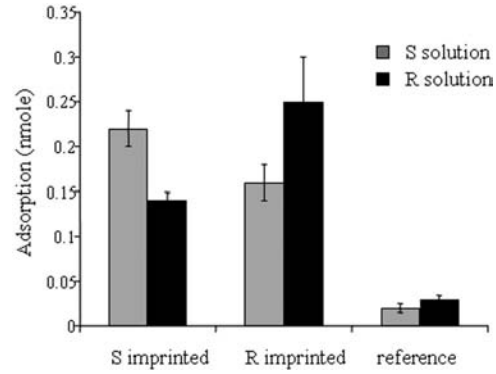

FIGURE 9. Fluorescent assay of enantioselective binding of the enantiomers of propranolol to sol–gel imprinted with either of the two enantiomers. The (*S*)-imprinted film recognizes better the (*S*) enantiomer, and the (*R*)-imprinted film shows the expected "mirror" behavior. Also shown is adsorption on reference nonimprinted films.

introduce several points of noncovalent interaction between the matrix and the template. The films were 700 nm thick. For the evaluation of the enantioselectivity we used either radioligand labeling or fluorescence methods. Results of the latter are shown in Figure 9, where one can see that a film imprinted for (*S*)-propranolol recognized that enantiomer much better than the counter-enantiomer and the film imprinted for (*R*)-propranolol recognized better this enantiomer.

Electrochemical detection methods prove to be yet another powerful transduction scheme. An electrode surface is coated with a film of imprinted SG composite silica material; the template is extracted after the polymerization is complete, and then the electrode is challenged with a solution of the analyte at low concentrations. We have developed such films that were imprinted towards

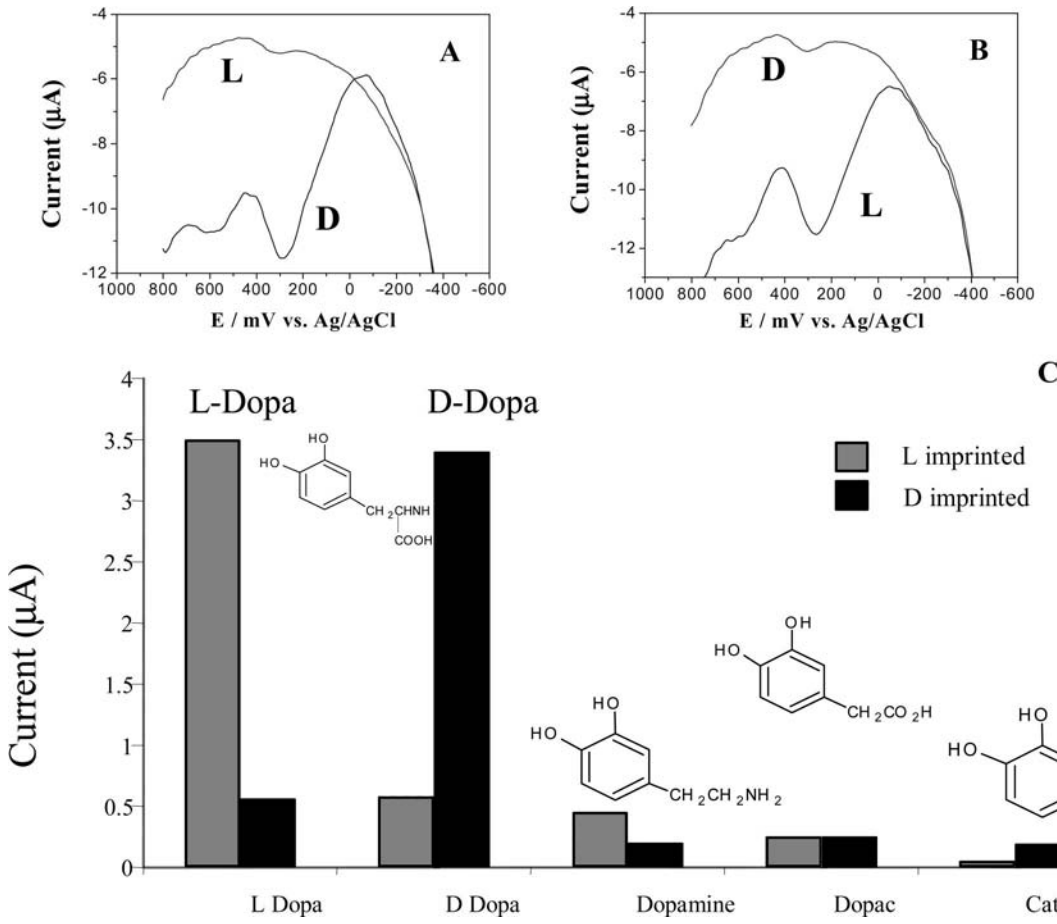

FIGURE 10. Electrochemical detection of D- and L-dopa binding to a 70 nm thick molecularly imprinted sol–gel film by square-wave voltammetry: (A) D-dopa signal in a D-dopa-imprinted film compared with L-dopa binding to the same film; (B) the "mirror" behavior, L-dopa binding to an L-dopa-imprinted film compared with D-dopa binding to the same film; (C) chemical selectivity of the molecularly imprinted film; three chemically and structurally related compounds, dopamine, di-hydroxyphenyl acetic acid (dopac), and catechol, are barely adsorbed. The selectivity is viewed as the current measured using the dopa-imprinted film with dopa vs the current measured with the selected compound.

L- and D-dopa (dihydroxyphenylalanine) and towards *N*,*N*′-dimethylferrocenyl ethylamine (Fc*). The coated electrodes were indium tin oxide (ITO), which was chosen because this material provides an excellent substrate for SG film adhesion and is easy to spin-coat, as well as being conductive. The films were 70 nm thick, and we found that compared with films 10 times thicker, the diffusion (and detected signals, as a result) were at least 20 times higher. The detection limit of dopa was in the nanomolar range, while for Fc*, we could detect micromolar concentrations in water. Excellent enantioselectivities and chemical selectivity were found in both cases: in the case of the dopa imprinted films, films that were imprinted for D-dopa detected D-dopa and only a small amount of L-dopa (Figure 10A). The exact mirror image behavior was achieved when L-dopa was the imprinted template (Figure 10B).[42] Another desired feature is the ability of the film to specifically bind the imprinted molecule and not a structurally related one. In the case of the dopa imprinting, the resulting films did not bind dopamine, dihydroxyphenyl acetic acid (dopac), or catechol (Figure 10C). The second example, as mentioned above, for the successful electrochemical detection of enantioselectivity was obtained by the imprinting with a chiral ferrocene derivative, *N*,*N*′-dimethyl ferrocenylethylamine, Fc*. It is worth mentioning that this is, to the best of our knowledge, the first example of metallocene imprinting. It is of relevance here to mention that electrochemical chiral detection methods were also used for titania thick films by Willner[41] and by Kunitake.[43]

The question that arises from reading the literature is: what is better, to tailor a chromatographic material for each specific target molecule or to have a general chiral adsorbent that can be used to separate a variety of chiral molecules? The tailored adsorbent was developed by several groups, but we believe that this approach is limited (unless an industrial process requires extremely high selectivity and specificity for a unique template). The "general user" will rather have a "generally chiral" adsorbent, similar to the commercial chiral columns, which are based on chiral derivatization of the silica surface, described above. To this end, we have looked into the preparation of a general chiral SG material that can be used for chiral separations.[44] In this study, a SG thin film was imprinted with the above-mentioned chiral surfactant, DMB. The surfactant was used in a concentration higher than the cmc, so it created regions of chiral hemimicelles in the material, similar to other surfactant-templated silicas.[45] After the preparation of the film, the surfactant was removed

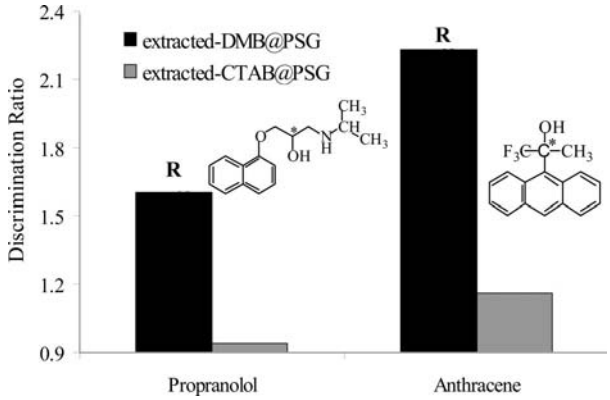

FIGURE 11. A 20% phenylated silica, 270 nm thick, imprinted with the chiral surfactant DMB, enantioselects enantiomer pairs of two different molecules, propranolol and trifluoroanthryl ethanol (black bars). Shown also (gray bars) is the blank of imprinting with an achiral surfactant.

by solvent extraction. The resulting material showed enantioselectivity towards pure enantiomers of small chiral molecules different than DMB, such as propranolol and 2,2,2-trifluoro-1-(9-anthryl)ethanol) (Figure 11).

Conclusions and Outlook

Although rare and by-and-large uncontrollable, silicates can form spontaneously chiral structures (such as in quartz). However, as a routine working and design tool, the use of an auxiliary chiral molecule is needed. With such a molecule, several approaches are available for rendering a material chiral. These include covalent attachment of chiral moieties, silylation with chiral silanes, copolymerization of standard silane precursors with chiral precursors, doping of the matrix with a chiral molecule (small or polymeric, synthetic or of biological origin), and the extraction of such dopants, leaving behind chirally imprinted cavities. The chirality of the material can then manifest itself in several ways. The most elementary one is chirality, which is associated only and directly with the chiral silane or the chiral dopant. Then there is the chirality of the imprinted cage (in the presence or absence of the dopant), and finally, the relatively unexplored possibility is of chirality of the Si–O–Si skeleton itself beyond the immediate cage, which is induced by the auxiliary molecule. This last option is associated with chiral pores that do not have the shape of that auxiliary molecule. More research in that last direction is desired, because chiral sol–gel materials, the chirality of which is due to their porosity and due to the silicate backbone structure (and not due to covalent attachment or doping of a chiral molecules), are potentially more versatile, more stable, and more general in their use.

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