

2D Ising Model for Adsorption-induced Enantiopurification of Racemates

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Mechanisms for the spontaneous transformation of achiral chemical systems into states of enantiomeric purity have important ramifications in modern pharmacology and potential relevance to the origins of homochirality in life on Earth. Such mechanisms for enantiopurification are needed for production of chiral pharmaceuticals and other bioactive compounds. Previously proposed chemical mechanisms leading from achiral systems to near homochirality are initiated by a symmetry-breaking step resulting in a minor excess of one enantiomer via statistical fluctuations in enantiomer concentrations. Subsequent irreversible processes then amplify the majority enan-

tiomer concentration while simultaneously suppressing minority enantiomer production. Herein, equilibrium adsorption of amino acid enantiomer mixtures onto chiral and achiral surfaces reveals amplification of surface enantiomeric excess relative to the gas phase; i.e. enantiopurification of chiral adsorbates by adsorption. This adsorption-induced amplification of enantiomeric excess is shown to be well-described by the 2D Ising model. More importantly, the 2D-Ising model predicts formation of homochiral monolayers from adsorption of racemic mixtures or prochiral molecules on achiral surfaces; i.e. enantiopurification with no apparent chiral driving force.

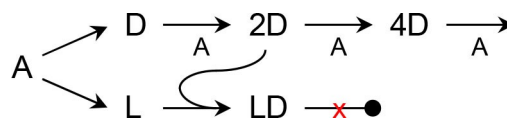
1. Introduction

Chemical and physical processes that yield enantiomerically pure chiral products from achiral or racemic reactants are critical to the production of chiral pharmaceuticals and also provide insight into the processes that may have led to the homochirality of life.^[1–5] A variety of abiotic processes spontaneously yield enantiomerically enriched chiral compounds from achiral starting materials or racemic mixtures of chiral compounds.^[6–10] The first model for such a process was proposed in 1953 by Frank who described a two-step mechanism (Scheme 1 below) in which prochiral molecules, *A*, react to form enantiomers, *D* and *L*, of a chiral product.^[11] Initially, statistical fluctuations lead to a slight excess of one enantiomer; the symmetry breaking step. Subsequently, chiral amplification occurs, if the chiral products, *D* and *L*, replicate themselves via homochiral autocatalytic conversion of *A*. This alone is insufficient to yield dominance of one enantiomer over the other. However, if the majority enantiomer sequesters the

minority enantiomer such that it cannot replicate, then the concentration of the majority enantiomer increases autocatalytically, at the expense of the minority enantiomer, until the product yield is almost exclusively homochiral. Common features of mechanisms proposed for the spontaneous origination of homochirality are the symmetry breaking step followed by the irreversible chiral amplification of one enantiomer accompanied by suppression of the minority enantiomer replication path.^[2,9]

At the end of his seminal paper, Frank suggested that ‘it may not be impossible’ to identify a chemical system that would replicate the features of his model.^[11] He was correct, but it took almost 40 years before such a chemical system was demonstrated by Soai.^[12,13] Furthermore, 30 years after its discovery, the Soai reaction remains the only example of a homogeneous autocatalytic reaction yielding enantiomeric excess from achiral reagents.^[14]

Heterogeneous crystallization can also yield spontaneous symmetry breaking. Kondepudi and Viedma demonstrated independently that stirring of supersaturated solutions of NaClO₃ or slurries of racemic NaClO₃ crystals, respectively, leads to spontaneous symmetry breaking and homochiral crystal formation.^[7,10] Subsequently, the Viedma process was adapted to achieve enantiomeric purification of a racemic mixture of conglomerate forming chiral molecular crystals.^[8] Stirring re-



Scheme 1. Two-step mechanism for chiral symmetry breaking proposed by Frank.^[11] Symmetry breaking during initial conversion of *A* into *D* (or *L*) followed by amplification of *D* via homochiral autocatalytic conversion of *A*. Simultaneously, *D* suppresses autocatalysis by *L*.

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cycles chiral molecules from the crystals through the solution phase where they can racemize. In the process, statistical fluctuations lead to an excess of larger crystals of one enantiomer than of the other. Subsequent chiral amplification occurs by Ostwald ripening of the larger majority enantiomer crystals at the expense of the smaller minority enantiomer crystals. As in the case of the Frank model, this leads to high enantiomer purity. When initiating these processes with racemic or achiral mixtures, the resulting chirality is unpredictable, however, seeding the initial solution with crystals of one enantiomer biases the result towards the chirality of the seed. Monte Carlo simulations of these processes reveal that they also have characteristics consistent with those set forth by Frank.^[9,11, 15]

Complementing the mechanistic models of processes that lead to enantiomeric excess are processes leading to thermodynamic control of asymmetric amplification.^[16,17] In saturated slurries with some enantiomeric excess, one can find a eutectic solution phase in equilibrium with both a racemic solid and a conglomerate solid of the enriched enantiomer. Under these conditions, the enantiomeric excess of the eutectic solution phase is virtually independent of and potentially much higher than the enantiomeric excess of the overall slurry. As a consequence, chemical reactions occurring in the eutectic solution phase can have an enantioselectivity that is much higher than the overall enantiomeric excess of the slurry. Lattice Monte Carlo simulations have been used to understand the requisite ternary phase diagrams yielding this thermodynamic control of enantiomeric excess in slurries of saturated solutions in equilibrium with crystalline phases.^[18]

Herein, we apply a thermodynamic view of competitive enantiomer adsorption on surfaces that is based on the 2D-Ising model. This predicts our experimentally observed amplification of surface enantiomeric excess, ee_s , relative to gas phase enantiomeric excess, ee_g , for species that are conglomerate formers in 2D. More importantly, the 2D Ising model predicts that even in the presence of a racemic gas phase, $ee_g = 0$, thermodynamic fluctuations on the surface can lead to arbitrarily high $ee_s \approx \pm 1$. This leads to the conjecture that adsorption of a prochiral molecule onto an achiral surface can lead to the formation of an enantiomerically pure chiral monolayer.

Experimental Section

Equilibrium Co-Adsorption of Asp Enantiomers on Cu(*hkl*) Surfaces

The observations on which this work is based come from measurements of the equilibrium adsorption of *D*- and *L*-aspartic acid (Asp, $\text{HO}_2\text{CCH}(\text{NH}_2)\text{CH}_2\text{CO}_2\text{H}$) mixtures on achiral Cu(111) and chiral Cu(3,1,17)^{R&S} surfaces. The methods have been described in prior publications;^[19,20] however, we summarize here. Under ultrahigh vacuum conditions, the clean Cu(*hkl*) surfaces were exposed to fluxes of *D*- and *L*-Asp simultaneously emanating from two independently controlled Knudsen cells. The temperatures of the cells were used to control the enantiomeric excess of the gas phase mixture, ee_g . After reaching equilibrium, the relative coverages of

the two adsorbed enantiomers were determined by heating the surface to induce decomposition and by using mass spectrometry to measure the amounts of CO_2 desorbing. The key to the experiment is the differentiation of enantiomers by using isotopically labelled 1,4- $^{13}\text{C}_2$ -*L*-Asp in conjunction with non-labelled *D*-Asp. During decomposition, the *D*-Asp yields $^{12}\text{CO}_2$ (44 amu) while the labelled *L*-Asp yields $^{13}\text{CO}_2$ (45 amu), thereby quantifying the surface enantiomeric excess, ee_s , at a given value of ee_g .

2. Results

Chiral surfaces can be used as adsorbents for enantiomer purification, separation and as catalysts for enantioselective production of chiral compounds. It has also been suggested that surfaces and interfaces played a role in prebiotic chemistry by virtue of their ability to spatially concentrate molecular species by adsorption from solution.^[5,21,22] Here, we demonstrate that the role of surfaces can include symmetry breaking during adsorption of chiral or prochiral molecules, even if the surface is achiral. To do so, we have modeled (sect. S11 in the Supporting Information) the competitive adsorption equilibria measured for *D*- and *L*-Asp adsorbing from gas phase mixtures of arbitrary enantiomeric excess, $ee_g = (P_D - P_L)/(P_D + P_L)$, onto the achiral Cu(111) surface and the chiral Cu(3,1,17)^{R&S} surfaces (Figures 1a and 1b). These equilibrium adsorption isotherms have been measured under conditions where the total coverage is close to saturation, $\theta = \theta_D + \theta_L \approx 1$, (see refs^[19,20] for experimental detail). The equilibrium adsorption isotherms measured for these Asp mixtures at 460 K are presented in Figures 1c and 1d (solid and open blue circles) in the form $ee_s = (\theta_D - \theta_L)/(\theta_D + \theta_L)$ versus ee_g . On the chiral Cu(3,1,17)^{R&S} surfaces the isotherms reveal enantiospecific adsorption, $ee_s \neq 0$ when $ee_g = 0$.^[19] On the Cu(111) surface, the adsorption isotherm reveals adsorption-induced auto-amplification of enantiomeric excess, $|ee_s| > |ee_g|$, in spite of the fact that the surface is achiral.^[19,20] Diastereomerism, $ee_s^{\text{Cu}(hkl)-R}(ee_g) = -ee_s^{\text{Cu}(hkl)-S}(-ee_g)$, is demonstrated in both cases. Similar adsorption-induced auto-amplification of chirality has also been observed during equilibrium adsorption on other chiral surfaces and using other adsorbates: Asp/Cu(643)^{R&S},^[23] Asp/Cu(653)^{R&S},^[24] and Pro/Cu(643)^{R&S} (sections S12 and S13).^[25] Interestingly, in all of those systems the driving force for auto-amplification of chirality appears to dominate over enantiospecific adsorption on the chiral surfaces.

Adsorption on surfaces has been simulated using a variety of lattice gas models to describe single-component adsorption, competitive two-component adsorption, etc. Prior applications to chiral systems include simulations of the Frank model,^[26,27] Viedma ripening during crystallization,^[9,15,28] and packing of chiral adsorbates on surfaces with chiral lattice structures.^[29–31] Our prior attempt to model enantiomer co-adsorption used a Langmuir-like model that incorporated interactions between adsorbates and thus, homochiral or heterochiral cluster formation.^[24] Unfortunately, the approximations made therein are correct in the limit of low coverage, whereas the measurements (Figure 1) are all made in the limit of saturation coverage where the Ising model is much more appropriate.

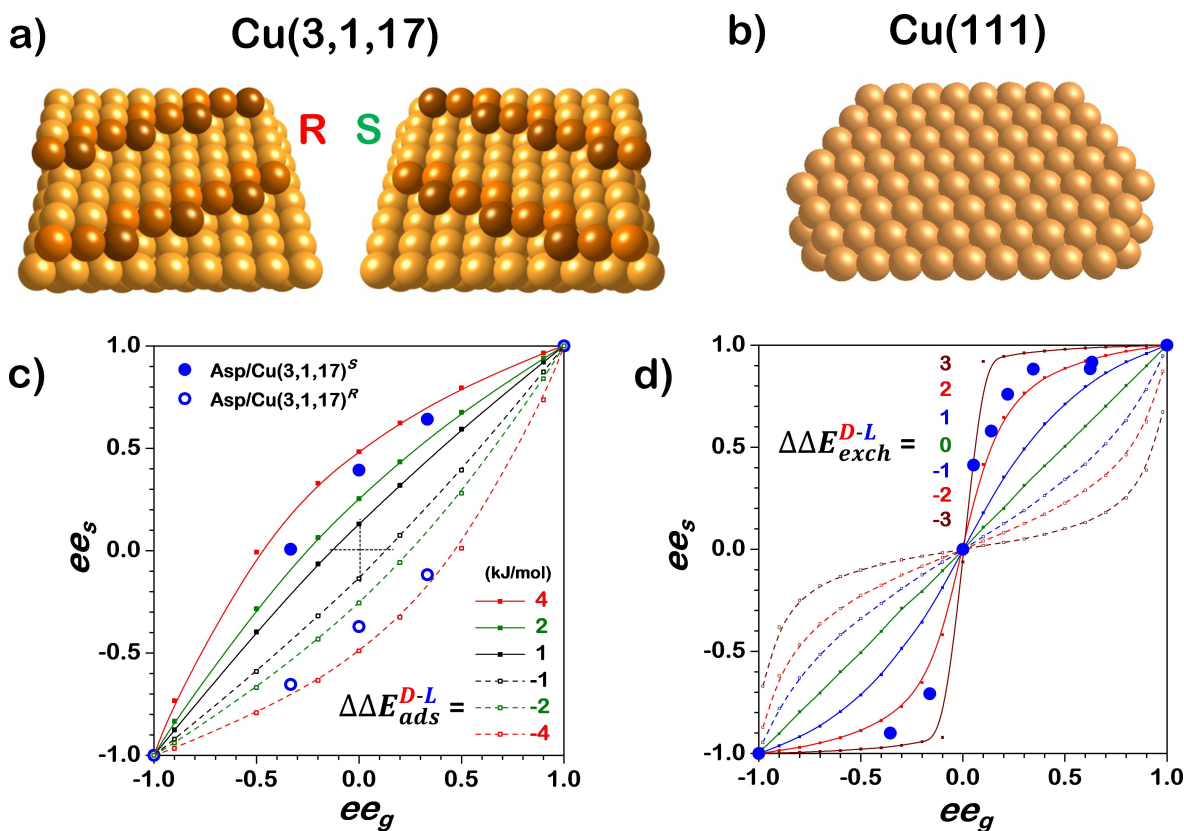


Figure 1. Ideal atomistic structures of a) the chiral Cu(3, 1, 17)^{R&S} surfaces and b) the achiral Cu(111) surfaces. The chirality of the Cu(3, 1, 17)^{R&S} arises from the sense of rotational orientation of the (111), (100) and (110) microfacets forming the kinks. c) The ee_s versus ee_g isotherms (solid and open blue circles) measured for equilibrium exposure of D- and L-Asp mixtures to the Cu(3, 1, 17)^{R&S} surface at 460 K.^[21] Also shown are the isotherms predicted by Monte Carlo simulations of the 2D Ising model using enantiospecific adsorption energy differences in the range $\Delta\Delta E_{ads}^{D-L} = -4$ to 4 kJ/mole. d) The ee_s versus ee_g isotherms (solid blue circles) for equilibrium exposure of D- and L-Asp mixtures to the Cu(111) surface at 460 K.^[22] Also shown are the ee_s versus ee_g isotherms predicted by Monte Carlo simulations of the 2D Ising model using enantiomer interaction energies in the range $\Delta\Delta E_{exch}^{D-L} = -3$ to 3 kJ/mole.

Herein, we have considered enantiomer co-adsorption using a simple lattice gas model to yield ee_s versus ee_g isotherms at saturation coverage. The experimental data (solid and open blue circles in Figures 1c and 1d) have been modeled using a simple Monte Carlo simulation on a square lattice with $N = 100 \times 100$ sites (Figure 2b). Each site is occupied by either a D- or L-enantiomer and the state of each site is defined as $\chi_i = 1$, if occupied by a D-enantiomer and $\chi_i = -1$, if occupied by an L-enantiomer. The state of the lattice is described by a vector enumerating the chirality of the adsorbate at each site, $\bar{\chi} = \{\chi_i\}_{i=1 \dots N}$. In each simulation step the enantiomer at a randomly chosen site is exchanged with one from the gas phase using the energy function [Eq. (1)] to determine the probability of exchange occurring.

$$E(\bar{\chi}) = -\left(\Delta\Delta E_{ads}^{D-L} + RT \cdot \Delta\mu_g^{D-L}\right) \sum_i \chi_i - \frac{1}{2} \Delta\Delta E_{exch}^{D-L} \sum_i \left(\chi_i \sum_{nn_i} \chi_{nn_i}\right) \quad (1)$$

The term $\Delta\Delta E_{ads}^{D-L} = (\Delta E_{ads}^D - \Delta E_{ads}^L)$ quantifies the difference in the adsorption energies of the two enantiomers on a chiral surface. $\Delta\Delta E_{ads}^{D-L} = 0$ on an achiral surface. The term $\Delta\mu_g^{D-L} = (\mu_g^D - \mu_g^L)$ quantifies the difference in the chemical potentials of the two enantiomers in the gas phase and is given by $\Delta\mu_g^{D-L} = \ln(P_D/P_L)$ for ideal gases. For a racemic mixture, the difference in enantiomer chemical potentials in the gas phase is $\Delta\mu_g^{D-L} = 0$. The term $\Delta\Delta E_{exch}^{D-L}$ represents the difference between the interaction energies of homochiral and heterochiral nearest neighbor pairs of adsorbed enantiomers. Finally, the sum over nn_i is the sum over the four nearest neighbor sites of site i . Physically, the first summation in eq. 1 quantifies the difference between the numbers of D- and L-enantiomers on the surface. The second summation quantifies the difference between the numbers of homochiral and heterochiral nearest neighbor pairs.

Enantiomer adsorption on the achiral Cu(111) surface (Figure 1d) was simulated using $\Delta\Delta E_{ads}^{D-L} = 0$. Values of ee_s were determined using adsorbate interaction energies in the range $-3 \leq \Delta\Delta E_{exch}^{D-L} \leq 3$ kJ/mol. Values of $\Delta\Delta E_{exch}^{D-L} < 0$ indicate attraction that is stronger for heterochiral pairs than for homochiral pairs and results in suppression of the gas phase enantiomeric excess, $|ee_s| < |ee_g|$, clearly inconsistent with the data (solid

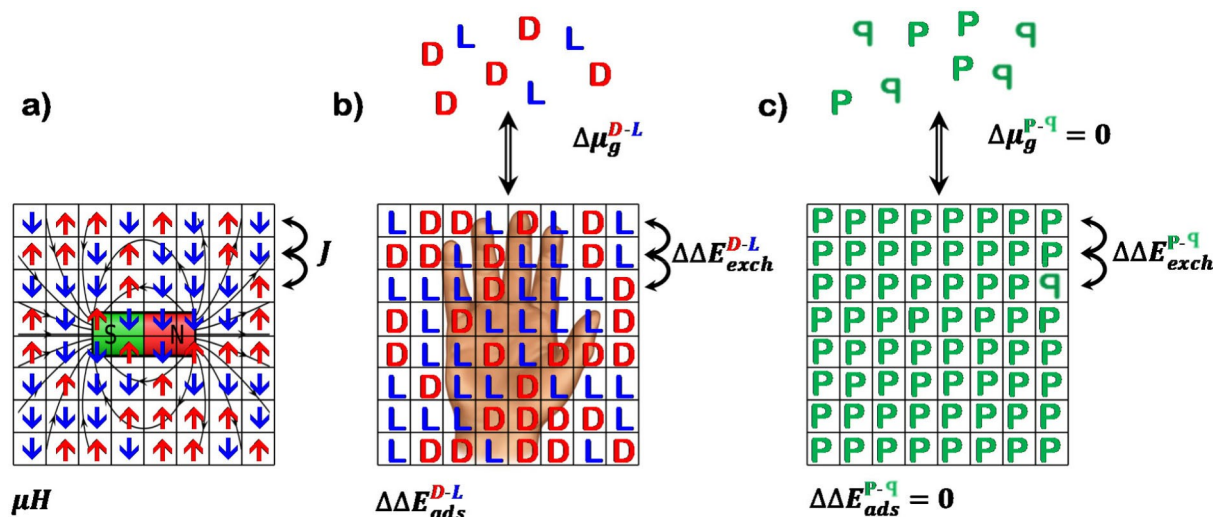


Figure 2. Pictorial representations of square 2D Monte Carlo lattices. a) The Ising model for 2D ferromagnetism considers atomic spins, $\uparrow$ or $\downarrow$, represented by $s_i = \pm 1$ and interacting with both an external magnetic field, μH , and with each of their four nearest neighbors with energies $\pm J$ for aligned or unaligned spins. b) Adsorbed enantiomers, D and L , in equilibrium with a gas phase mixture having a chemical potential difference of $\Delta\mu_g^{D-L}$. On a chiral surface the enantiospecific adsorption energies differ by $\Delta\Delta E_{ads}^{D-L}$. Enantiomers interact with their four nearest neighbors with energies $\pm\Delta\Delta E_{exch}^{D-L}$ for homochiral versus heterochiral pairs. c) Prochiral adsorbates are achiral in the gas phase and once adsorbed on an achiral surface their two adsorption-induced enantiomers have identical adsorption energies, $\Delta\Delta E_{ads}^{P-Q} = 0$. The adsorption-induced enantiomers interact with their four nearest neighbors with energies $\pm\Delta\Delta E_{exch}^{P-Q}$ for homochiral versus heterochiral pairs.

blue circles in Figure 1d) collected on Cu(111). Homochiral attraction, $\Delta\Delta E_{exch}^{D-L} > 0$, results in amplification of enantiomeric excess, $|ee_s| > |ee_g|$; consistent with our observations for Asp adsorption on Cu(111) (Figure 1d),^[20] and also on Cu(643)^{R&S},^[23] Cu(653)^{R&S},^[24] and for Pro adsorption on Cu(643)^{R&S} (sect. S13).^[25] This behavior is that of a conglomerate former and the data suggest that $\Delta\Delta E_{exch}^{D-L} \approx 2.5$ kJ/mol for Asp on Cu(111). Note that neither Asp nor Pro are conglomerate formers in 3D crystallization, indicating that there is a disconnect between enantiomer aggregation behavior in 2D and 3D, as has been suggested elsewhere.^[32,33] Asp adsorption on the chiral Cu(3, 1, 17)^{R&S} surfaces (Figure 1c) was simulated using $\Delta\Delta E_{exch}^{D-L} = 0$ and values of the enantiospecific adsorption energy in the range $-4 \leq \Delta\Delta E_{ads}^{D-L} \leq 4$ kJ/mole. These simulations replicate the observed behavior and indicate that $\Delta\Delta E_{ads}^{D-L} \approx 3$ kJ/mol favoring adsorption of D -Asp on the Cu(3, 1, 17)^S surface.

3. Discussion

3.1. 2D Ising Model for Competitive Enantiomer Adsorption

The Hamiltonian [Eq. (1)] used to evaluate the energies for enantiomer co-adsorption on chiral and achiral surfaces is identical to that of the 2D Ising model for ferromagnetism (Figures 2a and 2b). The Ising model was originally formulated to describe the behavior of atomic spins, $\uparrow$ or $\downarrow$, in an applied magnetic field and predicts much of the observed behavior of such ferromagnetic systems in 2D and 3D.^[34] Analogous to our model for enantiomer adsorption, the Ising lattice is fully occupied by atomic spins that can be labeled $s_i = \pm 1$ depend-

ing on the alignment of the spin with respect to an applied magnetic field. Such lattice models have been used to describe single- and two-component adsorption isotherms with various types of adsorbate-adsorbate interactions^[35,36] and to simulate properties of systems of enantiomers.^[29,30] As defined by Ising, the model is ideally suited to describing the competitive adsorption of enantiomers at saturation coverage and to predicting the ee_s versus ee_g isotherms as measured in our work.^[19,20,23–25] The term $\Delta\Delta E_{ads}^{D-L} + RT \cdot \Delta\mu_g^{D-L}$ in Equation (1) accounts for the enantiospecific adsorption energy on chiral surfaces and for the difference in the chemical potential of the enantiomers in the gas phase and is exactly equivalent to the applied magnetic field, μH , in the Ising model. The term $\Delta\Delta E_{exch}^{D-L}$ for enantiomer interactions in eq. 1 is analogous to the interaction, J , between nearest neighbor spins in the Ising model. This phenomenological link between chirality and ferromagnetism has been suggested in the past, even to the point of coining the term ‘ferrochirality’ to describe dynamical phenomena in helical polymers.^[37,38] Here we have established a link between the 2D Ising model and competitive co-adsorption of enantiomers at saturation coverage on chiral and achiral surfaces.

The 2D Ising model is particularly interesting because it was solved by Onsager to yield an analytic expression for the magnetism, M , in the absence of an applied magnetic field, $H = 0$.^[34,39] In the case of enantiomer adsorption, the condition equivalent to having $H = 0$ is the exposure of an achiral surface to a gas phase with no net chirality; i.e. either a racemic mixture or prochiral molecules that have no chirality in 3D but are rendered chiral by adsorption. The 2D Ising model with $H = 0$ predicts the spontaneous onset of magnetism as the temperature of the system drops below a critical value, T_c , that is

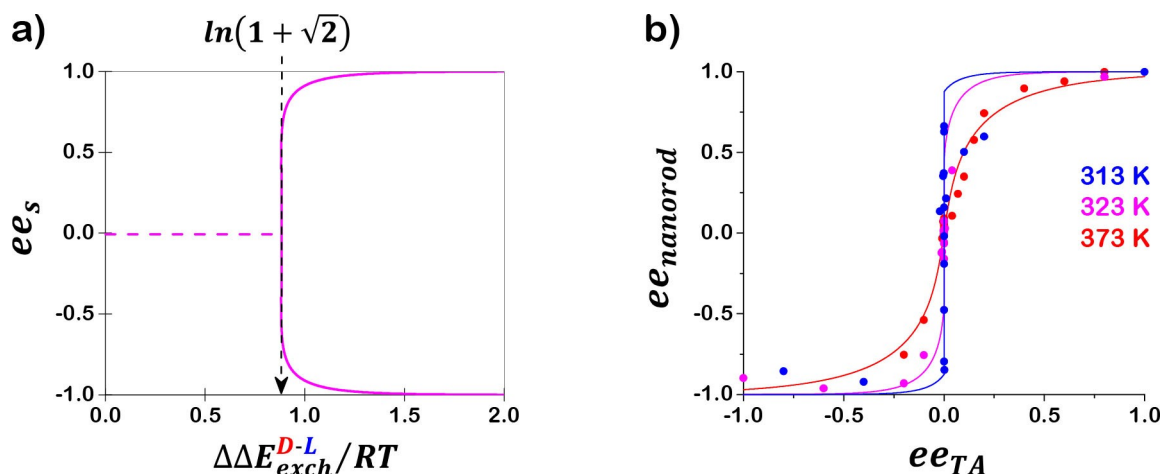


Figure 3. a) Plot of ee_s versus $\Delta\Delta E_{\text{exch}}^{D-L}/RT$ predicted by the 2D Ising model for adsorption of a racemic mixture, $\Delta\mu_g^{D-L} = 0$, of conglomerate forming chiral molecules exposed to an achiral surface, $\Delta\Delta E_{\text{ads}}^{D-L} = 0$. For $\Delta\Delta E_{\text{exch}}^{D-L}/RT < \ln(1 + \sqrt{2})$ the composition of the surface is racemic. For $\Delta\Delta E_{\text{exch}}^{D-L}/RT > \ln(1 + \sqrt{2})$ the composition of the adsorbed phase bifurcates towards $ee_s \approx \pm 1$. b) Synthesis of chiral $\text{TbPO}_4 \cdot \text{H}_2\text{O}$ nanorods from solutions containing mixtures of *D*- and *L*-TA with differing ee_{TA} yields nanorod mixtures with varying ee_{nanorod} .^[41] At $T = 373$ K, ee_{nanorod} versus ee_{TA} exhibits the behavior of the Ising model for $T > T_c$; similar to *D*- and *L*-Asp adsorption on Cu(111) (Figure 1d). At $T = 313$ K, the behavior of $\text{TbPO}_4 \cdot \text{H}_2\text{O}$ nanorod synthesis is that of an Ising-like system with $T < T_c$. At $ee_{\text{TA}} = 0$ and even in the absence of TA, $ee_{\text{nanorod}} \gg 0$.

determined by the spin-spin interaction energy, J , which is analogous to $\Delta\Delta E_{\text{exch}}^{D-L}$ in the case of enantiomer exchange.

$$RT_c = \Delta\Delta E_{\text{exch}}^{D-L} / \ln(1 + \sqrt{2}) \quad (2)$$

The Onsager solution for magnetism in a 2D system with $H = 0$ translates into the following expression [Eq. (3)] for the equilibrium surface enantiomeric excess in the presence of a racemic mixture:

$$ee_s = \left[1 - \sinh^{-4} \left(\frac{\Delta\Delta E_{\text{exch}}^{D-L}}{RT} \right) \right]^{1/8} \quad (3)$$

This predicts (Figure 3a) that in the presence of a racemic mixture in the gas phase, the adsorbed monolayer at $T > T_c$ should also be racemic, $ee_s = 0$, as we observe for racemic *DL*-Asp adsorption on Cu(111) (Figure 1d). Figure 3a reveals that as the temperature drops, a phase transition occurs at T_c and the enantiomeric excess of the adsorbed monolayer spontaneously evolves from $ee_s = 0$ towards $ee_s \approx \pm 1$. In other words, at $T < T_c$ a racemic or prochiral gas phase adsorbs onto an achiral surface to yield an adsorbed monolayer of arbitrarily high enantiopurity. By analogy with the 2D Ising model in an applied magnetic field, $H \neq 0$, the presence of a non-racemic gas phase biases the chirality of the resultant monolayer towards that of the dominant gas phase enantiomer.

Our estimate of $\Delta\Delta E_{\text{exch}}^{D-L} \cong 2.5$ kJ/mole for Asp on Cu(111) corresponds to a value of $T_c \cong 340$ K, significantly lower than the temperature of 460 K used for our measurements of equilibrium adsorption of *D*- and *L*-Asp.^[19,20] Unfortunately, the exchange rates between gas phase and adsorbed Asp on Cu(111) are too low at 340 K to achieve equilibrium on a feasible timescale, thereby precluding our observing the phase

transition in this system. There is, however, recent evidence of such a phase transition during growth of chiral, crystalline $\text{TbPO}_4 \cdot \text{H}_2\text{O}$ nanorods from solutions containing *D*- and *L*-tartaric acid (TA) with variable ee_{TA} .^[40] Examination of the net chirality of the product nanorods reveals a temperature dependent relationship between ee_{nanorod} and ee_{TA} (Figure 3b). At 373 K, the data are very similar to those for equilibrium adsorption of *D*- and *L*-Asp mixtures on Cu(111) (Figure 1d), exhibiting amplification of the enantiomeric excess of the nanorods with respect to the TA, $|ee_{\text{nanorod}}| > |ee_{\text{TA}}|$. At $ee_{\text{TA}} = 0$ and $T = 373$ K, $ee_{\text{nanorod}} = 0$ suggesting that in the Ising framework $T_c < 373$ K. However, $\text{TbPO}_4 \cdot \text{H}_2\text{O}$ nanorod synthesis at $T = 313$ K exhibits behavior characteristic of an Ising-like phase transition. At $ee_{\text{TA}} = 0$ or in the absence of TA, $\text{TbPO}_4 \cdot \text{H}_2\text{O}$ nanorods are produced with large fluctuations in their net enantiomeric excess, suggesting that $T_c > 313$ K. The large values of ee_{nanorod} in the absence of a chiral bias are manifestations of the phase transition predicted by the Ising model.

It is important to note that, the phase transition that we describe in terms of the 2D Ising model is quite generic, and is not affected by details of the lattice or the interparticle interactions.^[34] It can be observed in simulations on lattices other than fourfold and for adsorbate-adsorbate interactions that are longer range than just nearest neighbor distance. The phase transition occurs in 2D and in higher dimensions, although the exact solution used here applies only to the 2D square lattice with nearest neighbor interactions.

One of the key points to note about the Ising model for enantiomer adsorption on surfaces or interfaces is that it is a purely thermodynamic model. The transition from $ee_s = 0$ to $ee_s \approx \pm 1$ is the result of reversible statistical fluctuations in the system. As compared to the spontaneous symmetry breaking described by Frank, the Ising model obviates the need to postulate some irreversible mechanism by which small fluctua-

tions in enantiomer concentration are amplified and the need to consider mechanisms by which the dominant enantiomer inhibits amplification of the other.^[2,9,11,26] In systems that conform to the phenomenology of the Ising model, statistical fluctuations are sufficient to lead directly to arbitrarily high enantiomeric purity at $T < T_c$.

3.2. Early Molecular Symmetry Breaking

It is interesting to speculate on how homochirality might have occurred in primordial times. As we have shown, reversible adsorption of racemic chiral mixtures on solid surfaces can be described by the 2D Ising model which, for values of $\Delta\Delta E_{\text{exch}}^{D-L}/RT$ high enough that $T < T_c$, predicts spontaneous formation of an enantiomerically pure adsorbed monolayer by adsorption from a racemic reservoir onto a solid surface or a liquid-gas interface. One of the complications in thinking about the Ising model to describe such systems is that, if the system has a limited, finite reservoir of chiral molecules available for adsorption, enantiomer enrichment of the adsorbed monolayer would lead to depletion of that enantiomer from the reservoir such that the reservoir is no longer racemic. The resulting chemical potential difference between enantiomers in the reservoir would limit the maximum achievable ee_e . Perhaps a more likely scenario for reaching enantiopurity and one that would have been achievable before the appearance of chiral molecules in the early evolution of the pre-biosphere is the adsorption of prochiral species that are rendered chiral on adsorption (Figure 2c). Such a process is well-described by eq. 3 because the reservoir would remain achiral throughout the adsorption and enantiomer enrichment of the interface. One of the important features of this possibility is that prochiral molecules need not desorb or exchange with the reservoir in order to achieve enantiopurity. They can simply flip their conformational chirality on the surface without ever detaching from the surface or recycling through the reservoir.^[41,42] What remains unaddressed in this discussion is the process by which the enantiomeric purity generated by Ising-like adsorption was then translated into homochirality in the pool of molecules on which life is based.

One of the necessary conditions for the formation of an enantiomerically pure monolayer during adsorption is that the adsorbate be a conglomerate former in 2D, $\Delta\Delta E_{\text{exch}}^{D-L} > 0$. While racemate formation is more common than conglomerate formation in 3D,^[43] racemate and conglomerate formation are equally likely in 2D adsorbed systems. This is relevant as we consider the relative likelihood of adsorption in 2D versus crystallization in 3D as a route to early spontaneous symmetry breaking.^[32,33] It has been suggested that surfaces played an important role because of their ability to concentrate organic compounds from an otherwise dilute environment.^[5,21,22] Within the framework of an Ising-like model, the 2D system is expected to reach enantiopurity more rapidly than the 3D system because the 2D system has all adsorbates in direct contact with the reservoir whereas, in the 3D system most molecules are sequestered in the interiors of crystals and relatively inacces-

sible to the achiral reservoir. Also favoring the argument for a surface process in early spontaneous symmetry breaking is the observation that conglomerate formation, which is a prerequisite for achieving enantiopurity, is more common in 2D than in 3D.^[32,33]

4. Conclusions

As demonstrated herein, adsorption of enantiomer mixtures on chiral and achiral surfaces exhibits a number of features predicted by the 2D Ising model; principally, enantiospecific adsorption on chiral surfaces and amplification of enantiomeric excess on achiral surfaces. One of the key predictions of the 2D Ising model is that exposure of an achiral surface to a racemic mixture or to a prochiral adsorbate can result in the formation of an adsorbed monolayer of arbitrarily high enantiomeric excess and physical extent. This represents a simplification over previously proposed chemical mechanisms for spontaneous molecular symmetry breaking and amplification. It also suggests that for synthesis of enantiomerically pure chiral compounds, simple adsorption processes might be developed for purification of enantiomers from racemic mixtures.

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Conflict of Interest

The authors declare no conflict of interest.

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