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### Progress in Physics (54)

#### Exploring enantioselective processes on intrinsically chiral metal surfaces

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# Progress in Physics (54)

The Swiss Nobelprize laureate Heinrich Rohrer from IBM Rüslikon always pushed the vision that the physical research field of Nanoscience will once prosper as reliable tool in fields like material science. Thus he would have enjoyed the following exciting article of our colleagues from Empa and EPFL, describing the adsorption of organic molecules on complex metallic surfaces like PdGa.

Bernhard Braunecker

## Exploring enantioselective processes on intrinsically chiral metal surfaces

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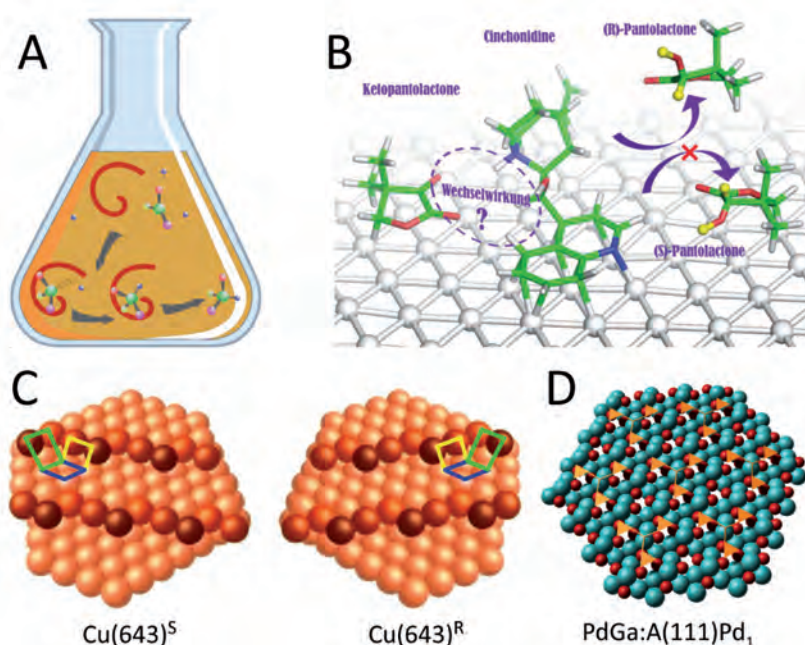
### 1. Introduction

One remarkable feature of biochemical and physiological processes is their often dramatic dependence on the handedness or more technically chirality of the involved molecular components. A rather harmless example is the odor of the two mirror symmetric forms of Carvone (C<sub>10</sub>H<sub>14</sub>O), where the right-handed R-enantiomer tastes of spearmint and the left-handed S-Carvone of caraway. As a consequence, the synthesis of stereopure chemicals is of tremendous importance for the production of pharmaceuticals, synthetic flavors and agrochemicals but also for materials for non-linear optics. In this respect the tragic example of the chiral pharmaceutical agent Thalidomide, which has caused severe birth defects in several thousand children in the early 1960's, is often cited. The detailed relation of the handedness of Thalidomide and its physiological effects, being a sedative on one hand and a mutagen on the other, is still not fully resolved and complicated by the racemization of the molecule in the physiological environment [1].

The synthesis of a specific enantiomer, i.e. a stereoisomer with a specific stereogenic or chiral center, can be accomplished by purification of the racemic mixture or by means of homochiral catalysis. In the latter case, as the physiochemical properties of two enantiomers are exactly the same, an enantioselective reaction step in catalysis requires chiral binding centers. In homogeneous catalysis (Figure 1A), these binding centers may be provided by enantiopure molecules, which bind achiral reactants in a chiral configuration, leaving a specific site of the reactant exposed for the attack of a second reactant. This directs the reaction into a predefined chiral pathway which leads to enantioselective synthesis. In heterogeneous catalysis, enantioselectivity is commonly achieved by using surface modifiers or auxiliaries. Typically, those are chiral molecules that are adsorbed on an achiral support. In the example shown in Figure 1B, the adsorbate complex and the surface form a chiral binding center for the achiral reactant. Also "naturally" chiral surfaces, i.e. surfaces that exhibit chiral features in the pristine, adsorbent-free state, have been investigated with respect to chiral adsorption and enantioselective

separation of racemic mixtures [2,3]. In the case of achiral crystals, chirality can be induced by vicinal cutting of single crystals at low symmetry crystal planes. The resulting high-Miller index surfaces can exhibit chiral binding centers at atomic kink sites (Figure 2C), and in consequence might offer an energetically favorable binding for one of the enantiomers of the adsorbed racemat.

A different approach is based on the intrinsic chirality of materials, as present for example in minerals [4]. In contrast to the heterogeneous methods discussed above, where the chirality is imparted by chiral modifiers or precise cutting of achiral single crystals, these materials are chiral in their bulk crystal structure, which might be projected to their surface (Figure 1D). In principle, the chirality is conserved also af-



**Figure 1:** Different approaches to chiral synthesis of molecules. **A)** Homogeneous enantioselective catalysis is based on chiral molecules (red spirals) binding the non-chiral reactant (3-atomic molecule). A fourth atom (blue) connects on a well-defined site, defining the handedness of the product (4-atomic molecule). **B)** In heterogeneous catalysis, an adsorbed chiral auxiliary (Cinchonidine) binds an achiral reactant (Ketopantolactone), which is subsequently hydrogenated from the side of the substrate (figure adapted from Ref. [5]). **C)** Kinks of single crystal surfaces offer chiral binding sites (figure adapted from Ref. [2]). **D)** Clean surface of a chiral intermetallic compound exhibiting chirality in every surface unit cell (structure indicated by orange triangles). The handedness is defined by the bulk enantiomer form of the compound.

ter grinding of these materials into powders, or after surface etching, which makes them prospectively interesting materials as industrial catalysts. We show that on the Pd<sub>1</sub> terminated PdGa(111) surface room temperature adsorption of a small prochiral molecule (9-Ethynylphenanthrene) leads to exceptionally high enantiomeric excess ratios of up to 98%. Our findings highlight the great potential of intrinsically chiral intermetallic compounds for the development of novel, enantioselective catalysts which can be operated at high temperatures and potentially also in harsh chemical environments.

## 2. Results and Discussion

In the investigation of stereochemical processes at surfaces the use of chiral metal substrates has been extremely scarce and mainly limited to self-assembled chiral molecular layers [3,6-7] and vicinal surfaces exhibiting chiral kink sites at the step edges of atomic terraces [2,8-9]. Due to its non-centrosymmetric bulk structure of the space group P2<sub>1</sub>3, the intermetallic compound PdGa exists in two enantiomeric forms A and B, which are denoted as PdGa:A and PdGa:B respectively [10-12]. Large PdGa single crystals can be grown by the Czochralski method and all the low index surfaces (111), (-1-1-1), (100) and (110) can be prepared to show large single atomic terraces by standard ultra-high vacuum (UHV) preparation using sputtering and annealing cycles [11-13]. As no significant surfaces reconstructions occur [11,12], the bulk chirality is preserved at all these surfaces. This means that a high density of chiral bonding centers is present on the bare surfaces, potentially leading to higher enantioselective catalytic activity compared to approaches based on the handedness of terrace step kink sites [2,8-9].

PdGa:A(111) is terminated by an atomic layer containing one isolated Pd atom per surface unit cell [11] and is denoted as Pd<sub>1</sub> (Figure 2A). These single Pd atoms form a hexagonal lattice with 0.69 nm lattice constant and the chiral nature of the surface can only be appreciated when considering the structure of the 2<sup>nd</sup> and 3<sup>rd</sup> outermost surface layers, consisting of Ga and Pd trimers respectively. As can be seen in Figure 2A the subsurface Pd (blue) and Ga (red) atoms form equilateral trimers rotated to the right and

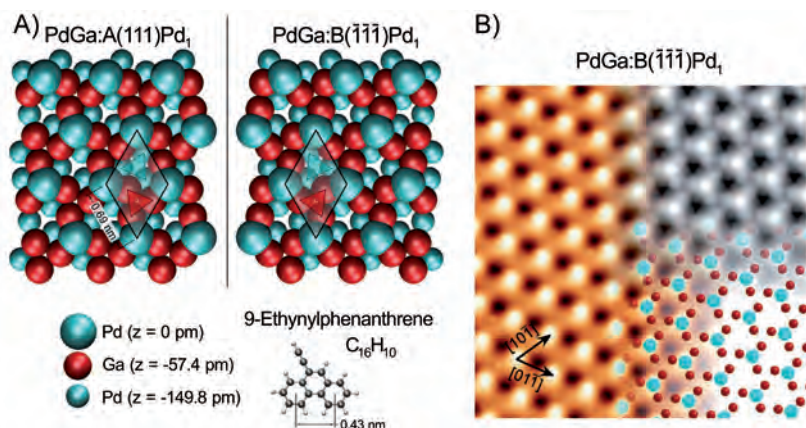
the left respectively. The enantiomorph of the PdGa:A(111) (abbreviated A:Pd<sub>1</sub>) is the PdGa:B(-1-1-1) surface (B:Pd<sub>1</sub>), where the rotation of the subsurface trimers is mirrored with respect to the A:Pd<sub>1</sub> surface.

The effect of the intrinsic chirality of the A:Pd<sub>1</sub> and B:Pd<sub>1</sub> surfaces on enantioselective adsorption is investigated by deposition of the prochiral molecule 9-Ethynylphenanthrene (9-EP, see Figure 2A). Prochirality is a property of planar molecules which possess in-plane but not out-of-plane mirror symmetry and are thus achiral. However, when deposited on a surface the molecule forms a chiral adsorbate complex by lying either “face-up” or “face-down”, forming either enantiomer R or S. For achiral substrates, energetically equivalent adsorption sites for the R and S enantiomers are available, and thus they appear in equal abundance [14]. To achieve an excess of one of the two enantiomeric forms, i.e., enantioselectivity, the substrate must exhibit chiral binding sites that promote the preferred adsorption into either R or S configuration.

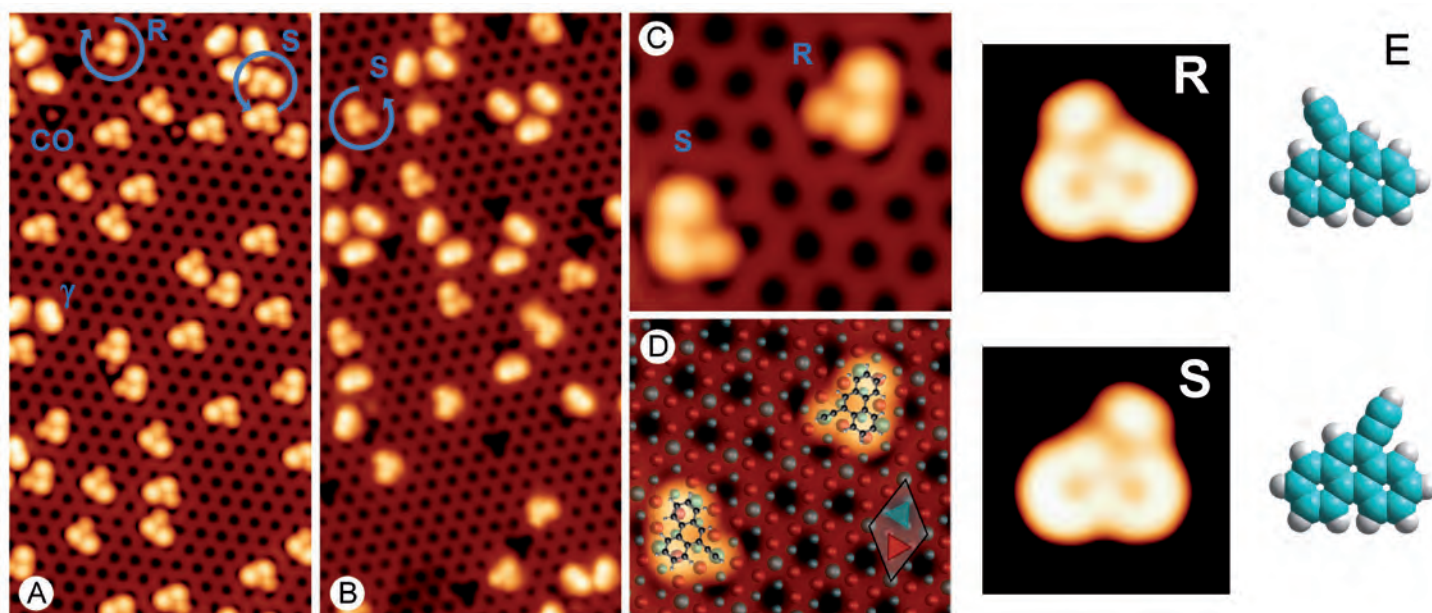
Figure 3 shows high resolution STM images of 9-EP deposited at room temperature (RT) with submonolayer coverage, imaged at 5 K on A:Pd<sub>1</sub> and B:Pd<sub>1</sub> respectively. Single 9-EP molecules can easily be distinguished and appear in two predominant morphologies. The most relevant ones regarding enantioselectivity consist of three differently sized lobes in the STM topography (see Figure 3C). The handedness of these types can be inferred from the sense of rotation going from the largest to the smallest lobe [15], where the clockwise rotation from the large, over medium, to small protrusion is defined as R-, and the counterclockwise sequence as S- enantiomer, as labelled in Figure 3A and B. For adsorption on A:Pd<sub>1</sub>, shown in Figure 3A, the excess of the R- enantiomer is evident (R:S = 215:7, evaluated over a series of STM images), while S is predominant on B:Pd<sub>1</sub> (Figure 3B) (R:S = 2:196). Due to the threefold symmetry of the substrate, each enantiomer appears with equal probability in three orientations which are rotated by 120° to each other. The 0°:120°:240° rotated orientations for the R and S enantiomers, are observed in quantities of 69:68:78, and 69:77:50, on the A:Pd<sub>1</sub> and B:Pd<sub>1</sub> surfaces, respectively.

Alternatively, 60° rotated configurations with the centered phenanthrene ring atop a Ga trimer of the 2<sup>nd</sup> layer are observed. As the clockwise or anticlockwise rotations of these alternative adsorbates can still be identified, they are considered a sub group of the R and S enantiomers in this study. For deposition at RT, the statistical analysis of molecules in R and S configuration yields an enantiomeric excess *ee* ( $ee = |R-S| / (R+S)$ ) of 0.94 and 0.98 on A:Pd<sub>1</sub> and B:Pd<sub>1</sub>, respectively. A third group of adsorbed 9-EP molecules is observed as brighter protrusions, which are molecules bound to surface vacancies(γ) [12].

Evaporating the 9-EP molecule with the surfaces kept at low temperature of 100 K results in a roughly 50:50 (i.e.  $ee \approx 0$ ) racemic mixture of the R and S configurations. Upon annealing of the racemic mixture to temperatures close to 300 K results in the development of the enantiomeric excess. To quantify the temperature dependence of



**Figure 2:** **A)** Surface structure of PdGa:A(111)Pd<sub>1</sub> and its enantiomorph B(-1-1-1)Pd<sub>1</sub>. The chiral arrangement within the hexagonal surface unit cell (black lozenge) is highlighted by the cyan and red triangle, representing the Pd and Ga trimers of the subsurface layers, respectively. Upon adsorption on a surface, the prochiral molecule 9-Ethynylphenanthrene forms a chiral adsorption complex. **B)** STM image (left) and superimposed DFT based STM simulation (top right) of the B:Pd<sub>1</sub> surface together with a ball structure representation (lower right). Figure adapted from [16] and [17].



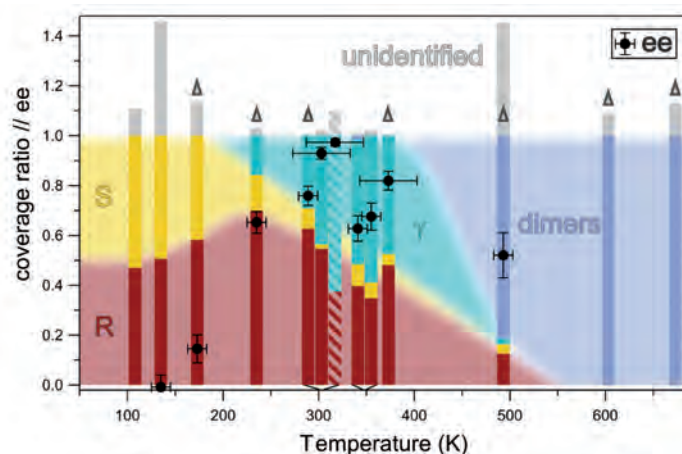
**Figure 3:** STM images ( $10 \times 20$  nm, 0.02 V, 2 nA,  $T = 5$  K) of 9-EP adsorbed at room temperature on **A)** the PdGa:A(111)Pd<sub>1</sub> surface and **B)** the PdGa:B(-1-1-1)Pd<sub>1</sub> surface. The different adsorbates are identified as clockwise (R) and counterclockwise (S) adsorption conformation, vacancy pinned molecules ( $\gamma$ ) and CO molecules. Some unoccupied vacancy defects (dark features) are visible in B. **C)** Zoom ( $3.8 \times 3.5$  nm) showing R and S enantiomers on A:Pd<sub>1</sub>. **D)** The structure overlay allows to identify the adsorption position within the surface unit cell. (cf. Figure 2). **E)** Extended Hückel Theory based STM simulations of the R- and S-9-EP with the corresponding chemical structure models. Figure adapted from [16].

the enantioselectivity of the Pd<sub>1</sub> surface towards the adsorption of 9-EP, we evaluated and assigned a large number of adsorbates ( $N \approx 400$ ) for each of the experiments performed at different adsorption and annealing temperatures. In every case all the absorbed molecules have been classified in the categories; R, S,  $\gamma$  and dimers, which start forming at annealing temperatures of 400 K. 9-EP molecules whose adsorbate configuration cannot be unambiguously determined from their topographic appearance in STM, are classified as unidentified. The result is shown as vertical colored bars in Figure 4, representing the normalized fraction of adsorbate configurations R, S,  $\gamma$  and molecules that have formed dimers. Atop the bars, the amount of unidentifiable adsorbates is given for each experiment. Based on the temperature dependent quantities, a tentative phase diagram was constructed for the 9-EP species on A:Pd<sub>1</sub> (see background in Figure 4). The graph shows the transition from the racemic mixture of R and S enantiomers at low temperatures, over a region yielding high enantioselectivity situated around 300 - 350 K, to the formation of dimers for  $T \approx 450$  K. The appearance of  $\gamma$  type molecules, i.e. molecules pinned at vacancies, at higher substrate temperature is linked to the increase in mobility. *ee* is shown for each experiment as black marker with estimated errors for temperature and statistically computed errors for *ee*.

### 3. Conclusion and Outlook

We have demonstrated remarkably high enantioselective adsorption of a prochiral molecule on the bare, chiral surface of an intermetallic compound at room temperature. The adsorption of 9-Etynylphenanthrene on the A(111) surface and its mirror symmetric equivalent the B(-1-1-1) surface of PdGa has shown enantiomeric excess of 0.94 and 0.98 for the R and the S enantiomorphs, respectively. By studying the temperature dependence of the process we showed that the racemic molecule mixture, formed by adsorption of the

9-EP at temperatures below 120 K, is efficiently transformed to an almost enantiopure ensemble at room temperature. This observation shows that the bulk chirality of PdGa can be expressed sufficiently strong at its surfaces to yield highly enantioselective processes. After having showed highly selective adsorption the next step in line is the demonstration of the on-surface synthesis of homochiral molecules. We are currently pursuing this goal within the SNF project “Chiral Intermetallic Surfaces For Enantioselective Reactions”. In a first stage to achieve this goal we have observed the formation of prochiral 9-EP trim-



**Figure 4:** Phase diagram based on statistical evaluation of 9-EP molecules on Pd<sub>1</sub>. Normalized abundances for the R and S enantiomers, as well as molecules pinned to surface vacancies ( $\gamma$ ), and dimers. Annealed samples are marked by gray triangles. A phase diagram, based on the data of the different adsorbate configuration ratios, is presented as background. All bars represent the A:Pd<sub>1</sub> surface apart from the striped one representing B:Pd<sub>1</sub> (colors for R and S are inverted for clarity). The enantiomeric excess (*ee*) is given for each experiment as black circles. Error propagation of the counting errors in the number of R and S enantiomers was used to compute the error for *ee*. Figure from [16]. Reprinted by permission of John Wiley & Sons, Inc.

ers with a large enantiomeric excess on the A(-1-1-1) and B(111) PdGa surfaces, which in contrast to the Pd<sub>1</sub> surfaces (i.e. PdGa:A(111) and PdGa:B(-1-1-1)) terminate in Palladium trimers [17]. The 9-EP trimers form at 490 K starting from a racemic mixture at room temperature. At the moment the bonding motive in the trimer (covalent or metal coordination) is not clear and under investigation. However, these preliminary results are very encouraging for the prospect of achieving chiral heterogeneous catalysis under operation conditions beyond the ones allowed by catalyst surfaces based on functionalization with organic, chiral modifiers.

### Acknowledgements

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