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Training and Promotion of Innovative Thought in Condensed Matter Physics Experiments

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Abstract

In order to cultivate students' innovative consciousness and ability, the changing their way of thinking is primarily important. By introducing condensed matter physics experiments into undergraduate teaching in advance, which can train students in innovative thinking at the academic frontier. This paper selects a typical example of case in the field of surface physics, i.e. mercaptan molecular self-assembly structure, combined with the ultra-high vacuum and low temperature scanning tunneling microscope technique, uses the experimental exploration method of controlling variables, and introduces a set of independently designed experimental teaching scheme based on the knowledge learned in quantum mechanics and solid physics, as well as the method of how to change students' thinking mode in this experimental teaching. In addition to training innovative thinking in the experiment, we also integrate the curriculum thought and politics into the experimental teaching, thereby guide students to establish the learning concept of analyzing the essence of physics based on physical phenomena, the awareness of independent problem-solving, reverse thinking and engineering thinking, and help students establish a practical and realistic dialectical materialist world outlook and values.

Keywords

College physics experiment; condensed matter physics experiment; scanning tunneling microscope; innovative thinking training; ideological and political education in courses

Physics experiments are one of the core compulsory courses for physics majors, and they play an irreplaceable role in improving students' hands-on skills and training their scientific research literacy. By introducing large-scale experimental instruments, such as scanning tunneling microscopes (STM), into daily experimental courses, not only can junior undergraduates be exposed to scientific research life as early as possible, but their innovative ability can also be cultivated [1]. This teaching model has been favored by more and more universities. The cultivation of innovative ability should first help students form innovative thinking [2]. However, many universities currently equate the cultivation of innovative ability with simply letting students participate in science and technology competitions or innovation and entrepreneurship projects, thereby neglecting the training of students' innovative thinking.

The scanning tunneling microscope (STM) is a large-scale experimental instrument that uses a scanning probe to characterize and manipulate atoms (molecules) [3]. Its basic working principle is: a very sharp metal needle tip is brought close to the surface of the material being measured. When the distance between the needle tip and the material is within a few angstroms, the electron wave function at the tip of the needle tip overlaps with the electron wave

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function on the surface of the material. At this time, if a bias voltage is applied between the material and the needle tip, it will cause current to flow. This phenomenon is called the quantum tunneling effect. The tunneling current is extremely sensitive to the distance between the needle tip and the material. The needle tip can be precisely controlled using a piezoelectric ceramic sensor with picometer-level accuracy, so the STM also has unparalleled real-space resolution [4].

From the perspective of teaching practice, it is of great significance to strengthen and improve the comprehensiveness, innovation and cutting-edge nature of university physics experimental courses. This paper introduces the cutting-edge research results of current condensed matter physics and designs a new experimental teaching plan and process using large instruments such as scanning tunneling microscopes. By guiding students to complete all experimental links, students can master advanced and comprehensive experimental methods and skills, deepen their understanding of some important concepts in courses such as quantum mechanics, thermodynamics, statistical physics and solid-state physics, broaden their knowledge, and cultivate their ability to explore physical problems and conduct scientific research [5].

1. Strengthen the integration of cutting-edge physics experiments and traditional physics teaching

1.1 Experimental design ideas

Condensed matter physics experiments have promoted the development of material physics and chemistry systems, and promoted human exploration of the physical and chemical properties of nanomaterials and a deeper understanding of their surface structures. At the same time, condensed matter physics has also achieved outstanding results in practical applications such as semiconductor device manufacturing, adhesives, fuel cells, heterogeneous catalysis and self-assembled monolayers. The cutting-edge experiments selected in this hot field will undoubtedly greatly stimulate students' curiosity and interest in physical experiments. Among the many material surface analysis and measurement technologies, scanning tunneling microscopy (STM) can characterize the surface of conductive materials at the atomic level, so this paper selects STM as the experimental operation instrument. By guiding students to operate the scanning tunneling microscope to obtain atomic-resolution structural images of nanomaterials in real space, it is helpful to help students understand the application of quantum tunneling effect in the industrial field [6], improve students' practical application-oriented experimental skills, and deepen students' understanding of physical concepts such as crystal structure, Fermi level and surface state.

In the field of surface physics, nanoscale thin film assembly methods, as an important technology in surface science, have been studied for more than 30 years. Among them, the self-assembled structure of thiol molecules on the Au (111) surface is the most typical nanostructure prepared by the nanoscale thin film assembly method. In this experiment, we used scanning tunneling microscopy technology and selected the controlled variable method as the most basic research method to guide students to deeply explore the self-assembled structure of ethanethiol (CH_3CH_2S) molecules on the Au (111) surface in the close-packed phase [7], and guide students how to use this method to explore the influence of different scanning conditions on the molecular structure of ethanethiol. By letting students operate by themselves, they can be encouraged to think deeply about the physical laws contained therein and how to apply these physical laws in actual situations, and ultimately cultivate students' innovative thinking and improve their innovative ability.

The main idea of our experimental design is to use an alkylthiol molecule deposition device on the metal surface to introduce alkylthiol molecules into an ultra-high vacuum chamber. The molecules will then bond to form strong gold-sulfur chemical bonds on the metal surface, thereby forming a highly ordered porous skeleton structure of alkylthiol molecules. In the process of characterizing and analyzing the two-dimensional structure using a scanning tunneling microscope, we change the relative distance between the needle tip and the structural units on the metal surface by changing the scanning conditions, such as fixing the scanning bias and changing the tunnel current, or fixing the tunnel current and changing the scanning bias. In this way, during the close-range scanning process, the needle tip is used to induce the alkyl chain to change its relative position, ultimately changing the basic configuration of the surface structural units in the same area. The specific experimental operation process is as follows:

1.2 Experimental implementation process

Au (111) surface while keeping the tunnel current unchanged (as shown in Figure 1). We will find that the ethanethiol molecules will be arranged more closely.

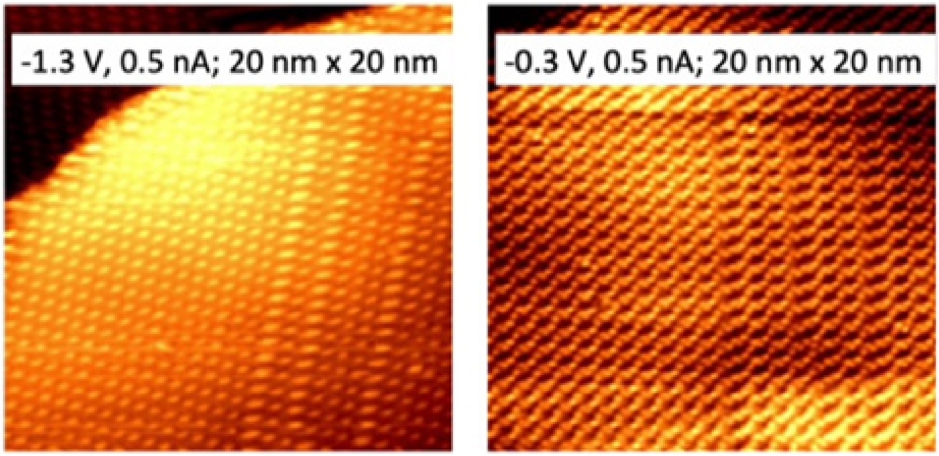

Figure 1. Changes in the close-packed structure of ethanethiol molecules under different bias voltages.

This phenomenon of molecular structure change caused by changes in scanning conditions will prompt students to further explore the impact of changing other scanning conditions on molecular configuration. At the same time, by allowing students to observe changes in molecular structure with the help of scanning tunneling microscopes, they can deepen their understanding of crystal molecular structure knowledge and master the corresponding relationship of STM images of ethanethiol molecules in real space.

STM image of ethanethiol molecules. We found that when the scanning bias is kept constant and different tunneling current values are changed (such as 0.5 nA and 0.5 nA), the conformation of ethanethiol molecules will also change, as shown in Figure 2. We can also obtain STM images showing different electronic state density states (as shown in Figure 2 (a) and Figure 2 (b)). Then guide students to further analyze the deep physical principles behind the images. When the tunneling current is different, the relative distance between the needle tip and the surface molecule (about 0.2 nm) will change (as shown in Figure 2 (c)). As the needle tip gets closer to the surface molecule, the alkyl chain in the alkylthiol molecule will change its position relative to the gold surface due to the induction of the needle tip. After that, the alkyl chain is lifted from the surface by the needle tip and tilted at a certain angle to the gold surface, thus changing the surface configuration of the chain molecule.

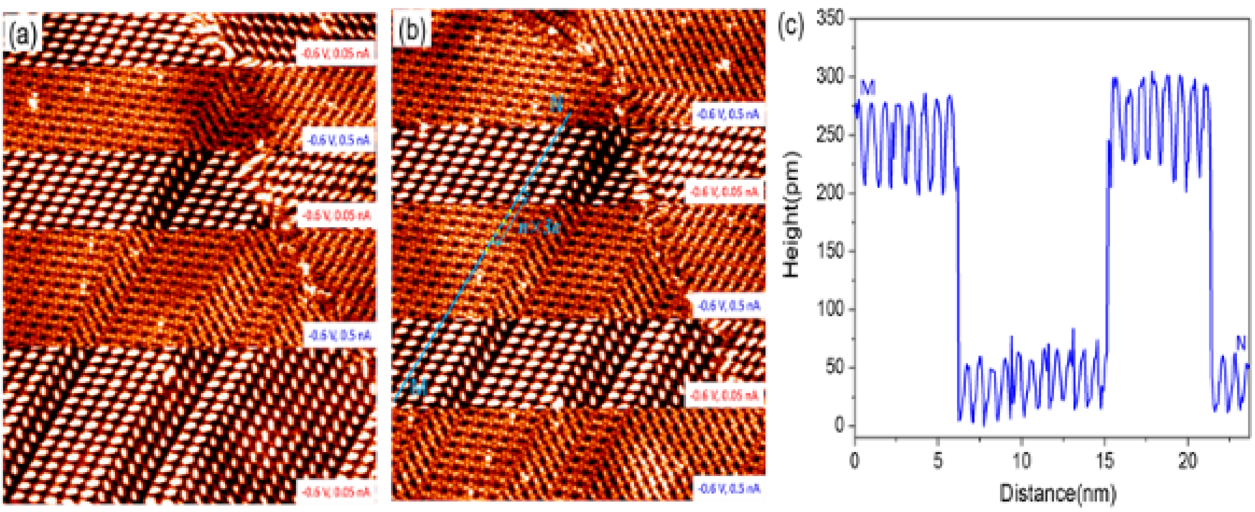

Figure 2. Changes in the close-packed structure of ethanethiol molecules under different tunneling currents.

Through the experiments in the second part, students can understand that when the tip is used to induce a stable change in the surface molecular configuration, its STM image will present us with high-resolution surface electronic state density information of different configurations, which is helpful for us to analyze the principles of molecular structure changes.

The third step is to guide students to further explore the causes of the experimental phenomenon and try to explain the occurrence of the phenomenon with the knowledge of quantum mechanics. The following are the specific steps: First, by analyzing the above experimental phenomena, we can conclude that the bands with different brightness in the STM image correspond to different components in the thiol molecules. Based on the basic working principle of the scanning tunneling microscope, the functional relationship between the tunnel current I and the scanning bias V and the relative distance Z between the needle tip and the surface molecules, we found that when the scanning bias is constant, the larger the tunnel current, the smaller the relative distance between the needle tip and the surface molecules. When the needle tip is close enough to the molecule, it will induce a change in the configuration of the surface molecule. At this time, the relative position of the alkyl chain (CH_3CH_2) and the gold surface changes, from the original flat structure to an upright shape (as shown in Figure 3).

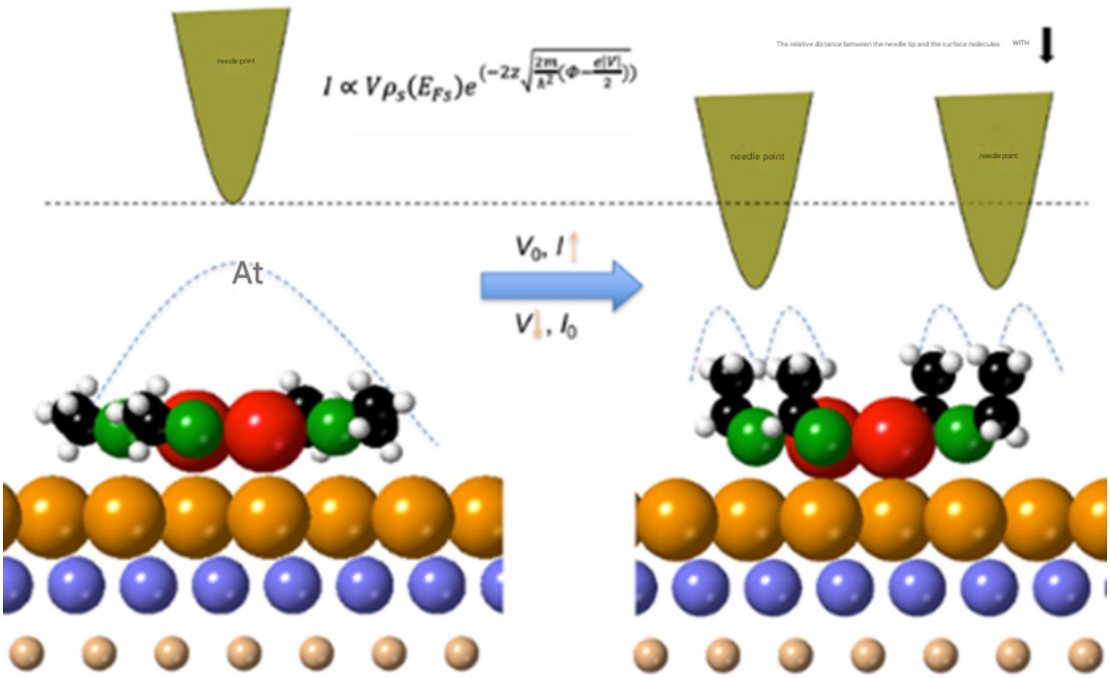

Figure 3. Theoretical explanation for the conformational changes of ethanethiol molecules.

Allowing students to independently explore the reasons for the experimental results will help them become familiar with the physical explanation of the quantum tunneling effect, understand how theory is combined with specific experimental phenomena, and how to use scientific inquiry methods such as asking questions, making hypotheses, designing experiments, analyzing results and theoretical explanations. At the same time, the completion of the entire experiment is a training for students' innovative thinking, which will have a positive effect on the formation of students' experimental habits and the improvement of their experimental literacy.

2. Integrating ideological and political education into condensed matter physics experimental teaching

The thiol molecular self-assembly experiment teaching program adopts the most scientific research method, from raising questions to guiding students to scientifically observe and analyze experimental phenomena in the experiment, and then proposing scientific hypotheses on this basis, and then repeatedly verifying them, and finally forming a scientific theoretical system. This research method has become the mainstream method at home and abroad in today's scientific research development.

In the pursuit of scientific and technological development and progress and the path of becoming a scientific and technological power, China has always adhered to the integration of socialist core values [8]. In the grand cause of rejuvenating the country through science and education, it focuses on cultivating scientific workers with the "four confidences" of socialism with Chinese characteristics, and adheres to the educational line of educating people for the country and cultivating talents for the party. Xi Jinping Thought on Socialism with Chinese Characteristics for a New Era embodies the scientific nature and truthfulness of Marxist theory. In the process of experimental teaching, by refining the scientific ideas behind the condensed matter physics experiment, it not only helps to further deepen the understanding of the experiment itself, but also helps to deepen students' understanding of Xi Jinping Thought on Socialism with Chinese Characteristics for a New Era through analogy and association, and successively establish the "four confidences" of China's path, theory, system and culture.

The development of modern physics over the past century is inseparable from the help of experiments [9], and the history of the development of modern Chinese physics has a profound inspirational effect on the young generation to summarize historical experience and establish the "four confidences". In addition, the scientific ideas behind the experiment are highly consistent with Mao Zedong Thought and Xi Jinping Thought on Socialism with Chinese Characteristics for a New Era, so the ideological and political education of the experiment can be carried out from the following aspects.

2.1 Contributions of Chinese physicists

The vigorous development of condensed matter physics in the world today is inseparable from the outstanding contributions of Chinese scientists. In the process of experimental teaching, we review the history of the development of condensed matter physics and the special contributions of Chinese physics giants, which not only allows students to appreciate the thinking process of great physicists, but also helps to deepen students' patriotism.

2.2 Reform and opening up and developing the country through science and education

The development of condensed matter physics in China is a history of continuous emancipation of the mind. As the country strongly supports the development of scientific research, it has launched scientific programs such as the "863" program, the "climbing" program and the "973" program to promote the development of condensed matter physics. At the same time, in the teaching process, we must pay attention to the cultivation of young talents. The young generation shoulders the mission of the times and should continuously strengthen their own scientific culture and moral qualities, comprehensively improve themselves, and contribute to the prosperity of the motherland.

2.3 Seeking truth from facts and scientific experiments

"Seeking truth from facts" is the ideological line of the Communist Party of China and Mao Zedong's great contribution to the sinicization of Marxism. In the experimental process of modern physics, the scientific thought of seeking truth from facts is also indispensable. In the process of scientific experiments, experiments and theories complement each other. Through the exploration process of this physical experiment, it helps students establish the world outlook and methodology of dialectical materialism and grasp the essence of Mao Zedong Thought.

3. Conclusion

The condensed matter physics experimental teaching program mentioned in this article takes the self-assembly structure of ethanethiol molecules on the gold surface in the field of nanomaterials as the starting point, and uses the characterization function of the scanning tunneling microscope as a means to guide students to use the control variable method to explore the influence of different scanning conditions on the molecular structure of ethanethiol, thereby strengthening students' understanding of important concepts and physical laws in quantum mechanics and solid state physics, helping students to cultivate a spirit of exploration and innovation awareness [10], and output a group of innovative and practical talents for the society to meet the needs of the discipline construction vigorously promoted by the country. At the same time, by introducing ideological and political elements into the experimental course, briefly reviewing the development history of Chinese condensed matter physics and studying and learning the glorious deeds of Chinese physics pioneers, it can deepen students' understanding of the core socialist values and guide young students to firmly believe in the core values of socialism. "Four Confidences" cultivates students' patriotism. Through analogical reasoning and inductive summary, students can understand the high consistency between the scientific research ideas behind the experiment and Marxist thought, Mao Zedong Thought and Xi Jinping Thought on Socialism with Chinese Characteristics for a New Era, guide students to have a deeper understanding of the strategic principles and policies of the Party and the country, and encourage students to consciously integrate their personal ideals and pursuits into the cause of the country and the nation, and be brave to be pioneers and pioneers at the forefront of the times.

References

[1] Ma Shihong, Zhao Zaizhong, Wang Yu, Shen Yuanhua. Establishing experimental elective courses to cultivate students' innovative abilities [J]. Physics Experiment, 2002(03):27-29.

[2] Ying Zhouwu. Cultivation of students' innovative thinking ability in experimental teaching [J]. Physics Experiment, 2007, No. 197(01): 24-26.

[3] Xuan Kai. Analysis of the principle of scanning tunneling microscope based on computer simulation[J]. Electronic Manufacturing, 2019(14):17-21.

[4] Huang Siyuan, Tian Huanfang, Zheng Dingguo, Li Zhongwen, Zhu Chunhui, Yang Huaixin, Li Jianqi. Development and application of high spatial and temporal resolution transmission electron microscopy [J/OL]. World Science and Technology Research and Development: 1-17 [2022-04-26].

[5] Liu Yi. Physical concrete course design of Fourier series [J/OL]. College Physics: 1-4 [2022-04-28].

[6] Wang Zhaoyang, Wang Hongwei. Computer simulation of quantum tunneling effect atomic model in STM [J]. Journal of Shenyang University of Aeronautics and Astronautics, 2014, 31(02): 84-86.

[7] Ding H, Gao J, Zhao H, et al. Perturbational Imaging of Molecules with the Scanning Tunneling Microscope[J]. The Journal of Physical Chemistry C, 2020, 124(47): 25892-25897.

[8] Chen Guohua, Cheng Minxi. A review on integrating ideological and political education into university physics classes[J]. Bulletin of Physics, 2021(03):2-6.

[9] Chao Luomeng, Liu Jia. Discussion on the Reform of Modern Physics Experiment Teaching under the New Situation[J]. Science and Technology Vision, 2021(05):25-26.

[10] Wang Xinshun, Wang Benyang, Zhang Libin. Training and improvement of students' innovative thinking in college physics experiments[J]. Laboratory Research and Exploration, 2021, 40(02): 244-247.