ABSTRACT FOR GENERAL PUBLIC

In a particular group of materials called *strongly correlated electron systems* the significant strength of interactions between electrons drive a number of exotic physical phenomena like e.g. unconventional superconductivity and Mott insulating state. In the former electrons create pairs what allows them to travel through the sample without resistance, while in the latter no current can flow because the mutual repulsion between particles pins them in place. In many of the compounds one can switch between the two antagonistic states by changing the number of charge carriers (electrons). Unusual physical features like those mentioned above make strongly correlated electron systems very interesting, and the prospects for their applications particularly exciting. Unfortunately, in spite of extensive theoretical and experimental analysis many of the observed phenomena still remain unclear. At the same time, novel materials are being discovered which may shed new light on the physics of strong electronic correlations. This project aims at better understanding of the rich correlated electron phenomena by carrying out extensive theoretical research of the new generation of strongly correlated systems which are the quasi-two-dimentional moiré superlattice systems (MSS).

A prominent example of MSS is the twisted bilayer graphene which consists of two single-atom-thick layers of carbon (two graphene sheets) placed one over another and rotated by the so-called magic angle. It appears that the specific moiré pattern of carbon atoms in such system enhances the role of electron-electron interactions leading to features similar to those known from strongly correlated materials such as high temperature superconductors. Shortly after the discoveries on twisted bilayer graphene, it was established that also other moiré superlattices systems (MSS) can be synthesized with similar properties. The significant advantage of MSS is that they are clean, the strength of correlations can be tuned by changing the twist angle, and one can easily modify the number of electrons by changing the voltage applied to the sample. In the previously known correlated materials such as copper-based high temperature superconductors, one had to insert atoms of different elements in order to change the number of electrons. This means that entirely new samples had to be made for each point of the phase diagram. Moreover, the latter precess leads to unwanted effects of structural distortion. Due to advantageous features of MSS, it is believed that these materials will allow to unlock the secrets of interacting-electron phenomena with unprecedented control and tunability. The new understanding of superconductivity in the analyzed systems might help guide the search for new superconductors with record high T_C's. This would be an invaluable accet when it comes to advance in many modern technologies. At the same time, the theoretical description of the physics of MSS is on a very early stage of development. With this respect the main unanswered questions concern the origin and characteristics of the superconducting state as well as the relation between the insulating phase and superconductivity. It is important to verify if both effects may have the same origin which could be the strong electronic repulsion, or a more conventional scenario takes place according to which electron pairing appears as a byproduct of the interplay between the particles and vibrations in their atomic lattice. It should be noted that this important question is directly related to the fundamental aspect of the proper theoretical model appropriate for the description of the analyzed MSS structures and the problem of inclusion of the correlation effects with satisfactory precision within the chosen approach. Providing significant insight into the mentioned issues is the main goal of the proposed project. In spite of the similarities between MSS and other correlated systems, the former also provides an experimental access new non-trivial phenomena such as unconventional topological properties of the superconducting and insulating states as well as exotic magnetic phases. Those are also within the area of interest of this project.

In addition to the research aimed at understanding the exotic properties of the electron interacting systems in MSS, the aim of this project is also to simulate selected nanodevices, which are now starting to be fabricated by using MSS. Due to the rich physics of MSS on the one hand and the high degree of tunability on the other, it is believed that MSS-based nanodevices may be used in modern-day electronics. It has already been shown that Josephson junctions and gate-defined nanowires can be realized with the use of twised bilayer graphene structures. The *in situ* electrostatic control of the phases formed in such nanostructures offers an easy access to a large number of configurations and operational regimes. This opens a route to improvement in the field of superconducting electronics where so far the conventional Josephson junctions were used to produce, e.g., magnetic devices for monitoring electrical activity in the brain or ultrasensitive magnetometers. Another possible application of MSS is the quantum information technology. Namely, quantum computers developed with the use of conventional Josephson junctions have properties that are fixed during fabrication. To operate qubits, the junctions must be manipulated jointly in cumbersome ways. With twisted graphene, qubits could come from single junctions that are smaller and easier to control. Moreover, the MSS-based nanosystems may serve as a platform for the realization of Majorana zero modes which have gathered a significant amount of interest in the recent years and also can be used in potential realization of a topogically protected qubits.