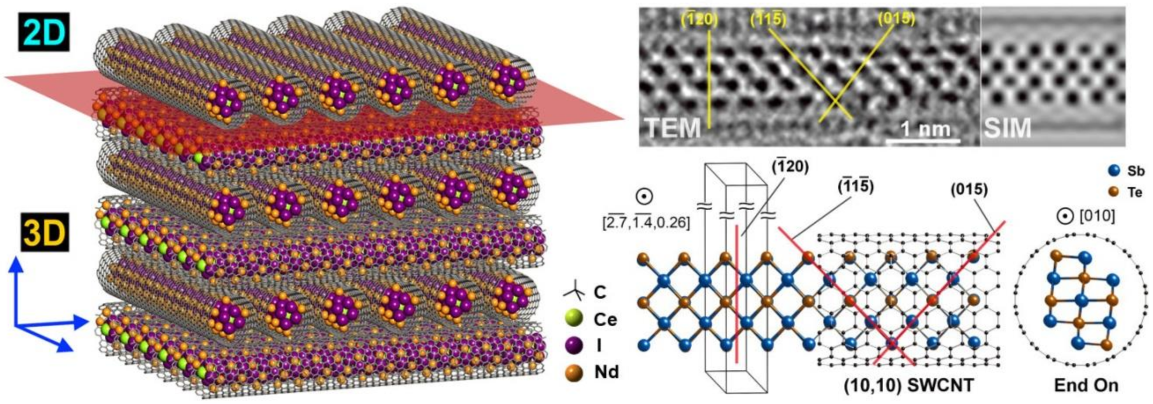
We will create and examine the magnetic properties of highly aligned nano-superstructures formed from single-walled carbon nanotubes filled with magnetic materials. The material inside the nanotubes has dimensions of the order of one nanometer, i.e. ~10,000 times less than the diameter of hair and almost 10 times less than most advanced integrated circuits. Single-walled carbon nanotubes themselves are hollow and exhibit interesting properties – depending on the structure they can show metal or semiconductor properties.

Recently, a simple way of filling these nanotubes with very thin aligned crystals has been discovered. Only a few atoms can fit within the diameter of nanotube. In addition, the walls of nanotubes are one of the most resistant materials (graphene) and exert a very high pressure – several dozens of GPa – on these crystals, to pressures observed in the upper mantle of the earth. Due to this pressure the arrangement of atoms inside the nanotube can be completely different from those observed in the crystal under normal conditions.

For example, you can turn a metal into a semiconductor and vice versa while maintaining the same chemical composition. We intend to stuff nanotubes with halides (iodides, bromides, chlorides) with atoms of metal elements such as chromium, iron, neodymium, europium or dysprosium, which have strong magnetic properties. In this way we will create long, one-dimensional periodic chains of magnetic atoms (neodymium atoms in the figure). The physical properties of such structures are not yet known.

Due to the dimensions of nanotubes we expect to observe quantum effects. There is no concise theory, which would describe crystallography of this type of hybrid nanostructures, on the base of atomic resolution electron microscopy observation we perform reconstruction of their atomic configurations which will also allow simulation of their properties using *Ab initio* methods. By using different techniques of purification and segregation into fraction of nanotubes filled with magnetic phases and then orienting them with the use of electric and magnetic fields in a liquid, we will create nano-superstructures in the form of 2D layers and 3D assemblies.



Left: Atomic model of the hypothetical nano-superstructure containing Neodymium (Nd) and Cerium (Ce) which we can sort into ‘2D’ or ‘3D’ layers by different processing. Right: experimental HRTEM image of antimony telluride inside the carbon nanotube and computer simulation of the TEM image (SIM). On the basis of the HRTEM image we assemble the highly aligned model of crystal inside SWCNT. This structure can also be made magnetic by doping with chromium.

Our main goal is to experimentally investigate the physical properties, atomic structure of the nano-superstructure and link them to magnetic properties.

Modern transmission electron microscopes allow observation and determination of the position of individual atoms. At the same time, electrons that allow seeing the atomic structure interact with the magnetic field of the examined objects, slightly changing their trajectories.

Electronic holography allows detection of these subtle changes and, as a result allows visualization and even measurement of the magnetic field force of nano-superstructures. Such tests can be carried out over a wide temperature range, since there is the possibility to cooling and heat the objects examined in the transmission electron microscope (*In-situ* investigation). We expect to see changes in structure and properties as a function of temperature starting from liquid helium temperatures up to ~1000K.

In addition, by observing the sample in Lorentz Electron Microscopy mode it is possible to magnetize the sample without interrupting the observation using the very strong magnetic field of the objective lens. We expect to study the classic ferromagnetics and antiferromagnetic phases but it is also possible that our Project can lead to discoveries in the field of nanomagnetism, perhaps to obtain an unusual type of magnetism such as quantum spin liquid (not freezing spin due to small dimension), or it will be possible to obtain highly anisotropic configuration of the spins what will allow observation of spin waves.

Finally, it is not difficult to imagine many practical applications of this type of nano-superstructures. Such as data storage, nano-actuators, spectrally tuned light sensors, magnetic field sensors not requiring external power supply, magneto vision cameras. Thanks to the carbon coating, super-nanostructures will be bio-compatible, and thanks to their sensitivity to light, it may be possible for example to build sensors based on them to improve eye photoreceptors powered by the electromagnetic waste field.