



Moving Monopoles Caught on Camera

Researchers make visible the movement of monopoles in an assembly of nanomagnets

For decades, researchers have been searching for magnetic monopoles – isolated magnetic charges, which can move around freely in the same way as electrical charges – since magnetic poles normally only occur in pairs. Now a team of researchers at the Paul Scherrer Institute PSI in Switzerland and University College Dublin have managed to create monopoles in the form of quasiparticles in an assembly of nanoscale magnets and to observe how they move using a microscope at the Swiss Light Source (SLS) to make the magnetic structures visible. As with the elementary monopoles, which were first predicted by the British physicist Paul Dirac in 1931, each monopole is connected by a ‘string’ to a monopole of opposite charge. The two monopoles can nevertheless move independently of each other. These results are not only of scientific interest, but could also provide a basis for the development of future electronic devices. These results will be published online in Nature Physics on 17 October .

Magnetic poles always appear in pairs – on dividing a bar magnet with a north and south pole into two, you do not end up with individual poles, but rather with two magnets, each with a north and a south pole. This is similar to what would happen if you break a stick in half; you do not get two separate ends, but rather two sticks with two ends. However, the British physicist Paul Dirac, predicted in the 1930s that the monopole pairs can be separated, as long as a connection remains between them that transports the magnetic flux – the so-called ‘Dirac String’. In the last year, a team of researchers were able to create such monopoles in a magnetic material for the first time. However in their case the associated Dirac Strings could only be observed indirectly with the help of neutron scattering and at temperatures close to absolute zero.

Nanomagnets generate monopoles

Now researchers at the Paul Scherrer Institute und the University College Dublin have been able to observe magnetic monopoles and their associated Dirac Strings directly at room temperature. In order to do this, the researchers put together a two dimensional assembly of tiny magnets, only 500 nanometres (= a millionth of a millimeter) long and 150 nanometres wide. In this way, they were able to create an artificial two dimensional magnetic material, whose smallest constituent parts were the nanomagnets. In their experiment, the magnets were arranged in a hexagonal design, so that the end of each magnet met the ends of two other magnets. Due to a similarity with the arrangement of atoms in normal ice, this structure is referred to as an artificial spin ice. “For our experiment we



prepared the nanomagnets in such a way that meeting points with two north poles and a south pole alternated with points where two south poles and a north pole meet each other” explains Laura Heyderman, who led the project on the part of PSI. “With the help of an external magnetic field, one can flip the magnetization of one of the magnets, so that at the ends of the magnet two defects in the original order appear. These defects behave like magnetic monopoles.” explains Heyderman further.

“If the external magnetic field is made stronger, the magnetization in neighbouring magnets flips too. This reversing of magnetization continues like a line of toppling dominoes, so that the two monopoles in the pair move away from each other – one to the right, the other to the left” explains Elena Mengotti, who is a PhD student at PSI working on artificial spin ice and performed the bulk of the experiments. “During this process the two monopoles are always connected by a one dimensional line of magnets, where the north pole of each magnet is next to the south pole of its neighbour, and so form the Dirac string. When the external field is turned off, the monopoles stay in the same place. You might say that they are ‘frozen’ in spin ice.”

Synchrotron Light shows Magnetism

At a measurement station for magnetic investigations at the Swiss Light Source SLS, Paul Scherrer Institute, the researchers could observe how the magnetization direction of the individual nanomagnets changed and therefore show how the monopoles move. Here it is possible to image the magnetization of the magnets directly and so for the first time make visible the movement of the monopoles and with this, the growth of the Dirac Strings. These experiments could be performed at room temperature.

The Theory behind the Experiment

The avalanche-like reversal of magnetization along a one dimensional Dirac String, that could be observed here, is a new magnetic phenomenon and is very different to processes in other magnetic materials such as those currently used in magnetic hard drives. The observed behaviour could be explained by the theoretical studies of the team at University College Dublin. “Our results are not only a breakthrough in terms of the direct observation of monopoles and Dirac strings in artificial spin ice, but also have shown for the first time how their motion can be manipulated.” explains Hans-Benjamin Braun, who is responsible for the project at University College Dublin.

‘Digital Components that use Magnetic Current’

“The knowledge we have gained could also be central in the architecture of new magnetic storage devices. Indeed, it is likely that the next generation of data storage media will be composed of isolated macrospins – like our nanomagnets.” says Braun. Laura Heyderman adds: “As a next step, we would like to find a way to precisely manipulate the monopoles at even smaller dimensions to be able to use them for storage or logic operations. The idea is to develop digital



components, which make use of currents of magnetic monopoles instead of electric currents”

The Team

Elena Mengotti is a PhD student at the Paul Scherrer Institute. She is supported by the Swiss National Science Foundation and performed the experimental work in the framework of this project.

Frithjof Nolting and Arantxa Fraile Rodríguez from PSI are experts for magnetic spectroscopy and microscopy. They led the experimental work at the Swiss Light Source SLS.

Hans-Benjamin Braun (Group Leader) and Remo Hügli (Postdoctoral Research Assistant) from University College Dublin developed the theory behind the experiments and performed the numerical simulations of the system. Their research is supported by the Science Foundation of Ireland.

Laura Heyderman (Leader of the Group “Magnetic Nanostructures” at the Paul Scherrer Institute) and Hans-Benjamin Braun led this joint research work.