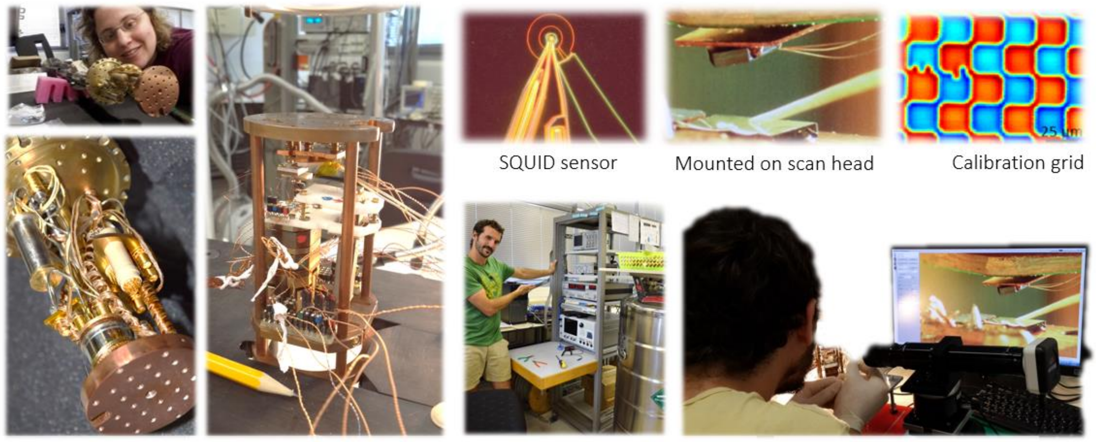
PUBLISHABLE SUMMARY – Final report

Magnetic nanoparticles (nanomagnets) have a number of present and proposed applications in biology and medicine. Nanomagnets play also an important role in future high density data storage, spintronic devices, or as catalysts in fuel cells. In addition, nanomagnets are of high interest because their physical properties vary dramatically from the properties of the same material in the bulk. This is true for all nanoparticles. Nonetheless, the case of nanomagnets is especially interesting because their size is comparable to the critical size below which a single domain behaviors is established.

Due to their technological importance, many efforts have been invested by chemist and biologists in developing new synthesis strategies of magnetic nanoparticles. These efforts require parallel efforts to develop characterization tools capable of characterizing nanoparticles. Therefore developing sensitive detection and manipulation techniques of nanomagnets is essential for the progress of both research and applications in physics, biology and medicine.

In our "NANOMAG-SQ" project, we set up a highly sensitive scanning SQUID system capable of detecting nanoparticles on an individual basis. In particular, we developed capabilities for manipulating nanoscale magnetic objects. We focused on magnetic vortices in a superconductor, with magnetic core of few nanometers, and found that we can deterministically move them by inducing local mechanical strain. This way we can control individual nanoscale magnetic objects.

More details about our project:



4K insert   Homemade piezo scanner   Scanning system electronics   Sample-probe alignment

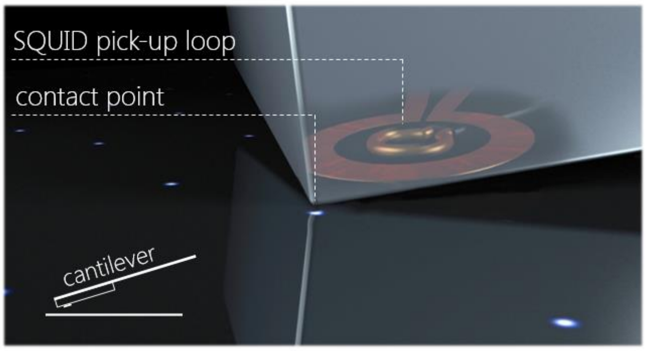
We established a functional lab oriented to sensitive magnetic imaging, and layout the foundations for scanning SQUID microscopy, including a 4K vacuum insert for variable temperature measurements in liquid helium environment. We have also designed and built the various tools required to make the microscope itself and a basic form of the SQUID probe. Preparing the microscope and scan head, which are completely homemade, is composed of many stages and has been quite a complicated task.

As planned, the SQUID sensor was integrated in the microscope, mounted on a cantilever which allows us to capacitively sense and determine the surface.

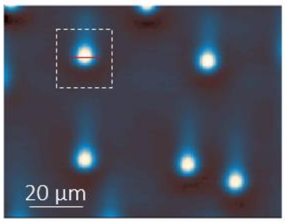
For calibrating the microscope we have used superconductors and for calibrating its scanner we used a gold meander.

Towards measuring individual nanomagnets we continued the study of magnetotactic bacteria. We also mapped the landscape of internal magnetic fields in natural sands.

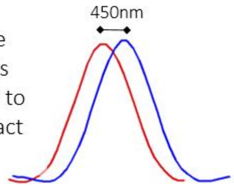
We used Nb and NbN thin films to determine the SQUID's point spread function. This study in the past several months, has led to an interesting new research about vortex dynamics in superconducting thin films.

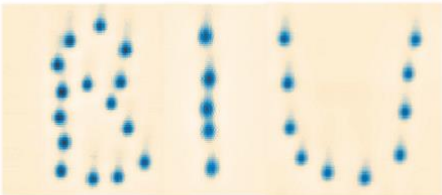


We press the cantilever into the sample so that the tip of the chip contacts the sample

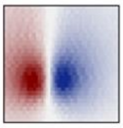


A single vortex is attracted to the contact point





Vortices deterministically moved to a new location



The difference in magnetic signal before and after contact was made

We studied the interaction between strain and nanomagnetic objects in system of vortices in a superconductor thin film. Vortices can be manipulates by applying magnetic field of current but does techniques are either non-local or confined the magnetic field strength.
We used scanning SQUID microscopy to investigate the behavior of vortices in the presence of local physical contact. Contact with the film resulted in a movement of vortices to a new location. We found that vortices are attracted to the contact point, relocated, and remain stable at their new location. The effect is reversible; after cycling through Tc, a new configuration of vortices on the same region of the sample displayed no memory. We utilized this interaction to move individual vortices via local mechanical contact, without magnetic field or current.

Papers which benefited from this project and therefore the CIG was acknowledged:

1. Scanning SQUID Study of Vortex Manipulation by Local Contact.
   Eylon Persky, Anna Kremen, Shai Wissberg, Yishai Shperber, Beena Kalisky.
   J. Vis.Exp. (120), e54986, doi: 10.3791/54986, (2017)

2. Vortex configuration in the presence of local magnetic field and locally applied stress
   Shai Wissberg, Anna Kremen, Yishai Shperber, Beena Kalisky

Physica C: Superconductivity and its applications, 533, 114–117, (2016)

3. Anisotropic Transport at the LaAlO3/SrTiO3 Interface Explained by Microscopic Imaging of Channel-Flow over SrTiO3 Domains.
Yiftach Frenkel, Noam Haham, Yishai Shperber, Christopher Bell, Yanwu Xie, Zhuoyu Chen, Yasuyuki Hikita, Harold Y. Hwang and Beena Kalisky.
ACS Appl. Mater. Interfaces, 8, 12514–12519, April 25 (2016)

4. Defect-Free Carbon Nanotube Coils.
Nitzan Shadmi, Anna Kremen, Yiftach Frenkel, Zachary J. Lapin, Leonardo D. Machado, Sergio B. Legoas, Ora Bitton, Katya Rechav, Ronit Popovitz-Biro, Douglas S. Galvão, Ado Jorio, Lukas Novotny, Beena Kalisky, and Ernesto Joselevich.
Nano Letters, 16 (4), pp 2152–2158, April 13 (2016)

5. Mechanical Control of Individual Superconducting Vortices.
Anna Kremen, Shai Wissberg, Noam Haham, Eylon Persky, Yiftach Frenkel and Beena Kalisky.
Nano Letters 16 (3), pp 1626–1630, February 2 (2016)

6. Optical study of tetragonal domains in LaAlO3/SrTiO3.
JZ. Erlich, Y. Frenkel, J. Drori, Y.Shperber, C. Bell, H. K. Sato, M. Hosoda, Y. Xie, Y. Hikita, H. Y. Hwang and B. Kalisky
Journal of Superconductivity and Magnetism, 28, 1017 (2015)

7. Direct measurement of internal magnetic fields in natural sands using scanning SQUID microscopy.
Walbrecker, J.O., Kalisky, B., Grombacher, D., Kirtley, J., Moler, K.A., Knight, R. Journal of Magnetic Resonance 242, 10 (2014)

8. Locally enhanced conductivity due to the tetragonal domain structure in LaAlO3/SrTiO3 heterointerfaces. Beena Kalisky, Eric M. Spanton, Hilary Noad, John R. Kirtley, Katja C. Nowack, Christopher Bell, Hiroki K. Sato, Masayuki Hosoda, Yanwu Xie, Yasuyuki Hikita, Carsten Woltmann, Georg Pfanzelt, Rainer Jany, Christoph Ritcher, Harold Y. Hwang, Jochen Mannhart and Kathryn A. Moler
Nature Materials 12, 1091 (2013)

A successful completion of this project is aimed at establishing the scanning SQUID micorsope as a characterization tool for individual nanomagnetic characterization; identifying essential data about particles of interest, providing their physical properties and their variability; and providing access to physical questions such as the nature of interactions between small numbers of particles and the dynamics of these particles.