Abstract Book

International workshop on vortex matter in superconductors.

The Abrikosov prize 2015 will be awarded during the workshop.

More information at www.vortex2015.org
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Aim and Scope

The purpose of the Workshop is to promote international collaboration and exchange of ideas in the field of vortex physics. This time the workshop will take place in El Escorial, in the premises of the Centro María Cristina. Local organizers belong to the Universidad Autónoma de Madrid and the Universidad Complutense de Madrid.

Topics include:

- Vortex pinning and phase diagrams; single and multicomponent superconductors.
- Vortex dynamics: dynamic phase diagram and single vortex motion.
- Materials for applications: tapes and wires.
- Vortex imaging in real and reciprocal space: scanning microscopies, neutron and muon scattering.
- 2D Vortex lattices.
- Devices for high frequency radiation and detection. SQUIDs and junctions.
- Materials: pnictides, cuprates, heavy fermions, chalcogenides, etc.
- Irradiation and nanostructuring for vortex pinning.
- Magnetic skyrmions: lattices and dynamics.
- 2D films and layered materials. Superconductor to insulator transitions. Electric field induced superconductivity.
- Vortices in topological and in strongly correlated electron superconductors.
- Vortices in superconducting/ferromagnetic hybrids.
- Thermal and disorder induced transitions.
Organizers

International Advisory Committee

- Gianni Blatter, ETH, SWITHERLAND
- Mauro Doria, University of Rio de Janeiro, BRAZIL
- Morten Eskildsen, University of Notre Dame, USA
- Arun K. Grover, Tata Institute of Fundamental Research, INDIA
- Laura H. Greene, University of Illinois Urbana Champaign, USA
- Boldizsár Janko, University of Notre Dame, USA
- Kazuo Kadowaki, Tsukuba University, JAPAN
- Marcin Konczykowski, Ecole Polytechnique, FRANCE
- Vladimir Krasnov, Stockholm University, SWEDEN
- Wai-Kwong Kwok, Argonne National Lab, USA
- Atsutaka Maeda, University of Tokyo, JAPAN
- Victor Moshchalkov, KU Leuven, BELGIUM
- Xavier Obradors, ICMAB-CSIC, SPAIN
- Wilson Ortiz, University of Sao Carlos, BRAZIL
- José Luis Vicent, Universidad Complutense de Madrid, SPAIN
- Valerii Vinokur, Argonne National Lab, USA
- Hai-Hu Wen, Nanjing University, CHINA
- Eli Zeldov, Weizmann Institute of Science, ISRAEL

Organizers

- Elvira González, UCM
- Isabel Guillamón (vice chair), UAM
- José Gabriel Rodrigo, UAM

- Hermann Suderow (chair), UAM
- Sebastián Vieira, UAM
- José Luis Vicent, UCM

Local organizing committee:

- José Benito, UAM
- Antón Fente (scientific secretary), UAM
- Edwin Herrera, UAM

- Alexander Stangl, ICMAB-CSIC
- Javier del Valle, UCM
- Ferran Valles, ICMAB-CSIC
Sponsors & Supporters

- ICAM
  http://icam-i2cam.org/index.php

- National Science Foundation
  http://www.nsf.gov/about/

- Universidad Autónoma de Madrid
  http://www.uam.es/

- Campus de Excelencia UAM+CSIC
  http://campusexcelencia.uam-csic.es/

- Universidad Complutense de Madrid
  http://www.ucm.es/

- Instituto Nicolás Cabrera
  http://www.uam.es/inc

- Condensed Matter Physics Center, IFIMAC
  http://www.uam.es/otroscentros/ifimac/

- PCE Iberica
  http://www.pce-iberica.es/

- Lake Shore Cryogenics
  http://www.lakeshore.com/Pages/Home.aspx

- Imdea Nanociencia
  http://www.nanociencia.imdea.org/
Invited Speakers

Albino AGUIAR, Recife
Satyajit BANERJEE, Kanpur
Tatyana BATURINA, Novosibirsk
Kees van der BEEK, Paris
Victoria BEKERIS, Buenos Aires
Leonardo CIVALE, LANL
Peter CURRAN, Bath
Oleksandr DOBROVOLSKIY, Frankfurt
Mauro DORIA, Rio de Janeiro
Lior EMBON, Weizmann
Morten ESKILDSEN, Notre Dame
Yanina FASANO, Bariloche
Yuri GALPERIN, Oslo
Vadim B. GESHKENBEIN, Zürich
Thierry GIAMARCHI, Geneva
Vladimir N. GLADILIN, Leuven
Andreas GLATZ, ANL
Isabel GUILLAMÓN, Madrid
Alexander GUREVICH, Old Dominion
Tetsuo HANAGURI, Riken
Xiao HU, NIMS
Pavel A. IOSELEVICH, Stuttgart
Kazuo KADOWAKI, IMS Tsukuba
Beena KALISKY, Bar-Ilan
Serghei KLIMIN, Antwerpen
Marcin KONCZYKOWSKI, Paris
Alex KOSHEV, ANL
Vladimir KRASNOV, Stockholm
Lia KRUSIN, New York
Wai KWOK, ANL
David LARBALESTIER, Florida
Dingping LI, Beijing
Wei LIU, Geneva
Yanwei MA, Beijing
Kazushige MACHIDA, Kyoto
Atsutaka MAEDA, Tokyo
Ivan MAGGIO-APRILE, Geneve
Boris MAIOROV, LANL
Ana MALDONADO, St Andrews
Milorad MILOSEVIC, Antwerpen
Victor MOSCHCHALKOV, KU Leuven
Thomas NATTERMANN, Köln
Nobuhiko NISHIDA, Toyota
Tsutomu NOJIMA, Tohoku
Satoshi OKUMA, Tokyo
Wilson ORTIZ, Sao Carlos
Anna PALAU, Barcelona
Gabriela PASQUINI, Buenos Aires
Christian PFLEIDERER, Munich
Ruslan PROZOROV, Ames
Carsten PUTZKE, Bristol
Pratap RAYCHAUDHURI, Mumbai
Charles REICHHARDT, LANL
Dimitri RODITCHEV, Paris
Jacobo SANTAMARÍÁ, Madrid
Dan SHAHAR, Weizmann
Zhixiang SHI, Southeastern
Takasada SHIBAUCHI, Tokyo
Peter SPRAU, Cornell
Setsuko TAJIMA, Osaka
Tsuyoshi TAMEGAI, Tokyo
Javier DEL VALLE, Madrid
Ferran VALLES, Barcelona
Maria VÉLEZ, Oviedo
Javier VILLEGAS, Paris
Valerii VINOKUR, ANL
Vitalii K. VLASKO-VLASOV, ANL
Peter WAHL, St. Andrews
Jian WANG, Beijing
Ulrich WELP, ANL
Hai Hu WEN, Nanjing
Roland WILLA, Zürich
Roger WÖRDENWEBER, Jülich
Yosi YESHURUN, Bar-Ilan
Eli ZELDOV, Weizmann
**Venue and travel information**

**VENUE**

The workshop will take place very close to Madrid, Spain, in the city of El Escorial. El Escorial is located at 46 km at the north of Madrid, within a mountain area.

El Escorial is used by the largest Spanish university (Universidad Complutense de Madrid) for summer courses and other activities. It is known because of the green environment and of the sightseeing places located within the city.

Madrid and other interesting places such as Toledo and Segovia can be conveniently reached by a modern and dense public transport system. You can find some info about the workshop location (in Spanish) at **Real centro universitario Escorial – María Cristina**. GPS location: 40°35'19.2"N 4°09'02.6"W.

Registration desk will be opened at the main entrance of **Real Centro Universitario El Escorial – María Cristina** from 17:00 to 20:00 on Sunday May 10th and between 08:30 and 9:00 from Monday 11 to Friday 15.

Registration fee covers participation in the workshop, abstract book and daily coffee breaks and lunch at the conference site for all participants. Breakfast and dinner at the workshop site are only reserved for those participants lodged at residence (included in the accommodation costs). Participants staying outside the workshop site will have to arrange the rest of meals by themselves. You can find **here** a list of restaurants at a walking distance from the workshop site.

The conference dinner on Tuesday 12 will take place at the Restaurant “Puerta 57” located inside the Santiago Bernabéu Stadium, home of Real Madrid soccer team.

Internet can be accessed through a local wifi network with free access at the workshop site (password will be given during the conference).
TRAVEL INFORMATION

A bus service "Adolfo Suárez Madrid-Barajas Airport ↔ María Cristina residence” will be organized for participants arriving Sunday May 10th and departing Friday 15. Details will be given through the web page and email.

To reach El Escorial, please follow instructions given below. You can also check google transit. (Tip: How to pronounce Escorial (if you are an English-speaker): try to say “Sco-real”, putting the strength on the “a” instead of on the “e”).

...how to arrive in 3 steps

1. From Adolfo Suárez Madrid – Barajas Airport to El Escorial Train Station
   There is a train connection to El Escorial train station from the Madrid Barajas airport. The train entrance is well indicated to “Renfe Cercanías” (marked with a red circle with an inverted white C), you can buy the tickets at machines in different languages, your destination is “El Escorial”, BE CAREFUL you need a transfer train in Chamartin station from Line C-1 to Line C-8a (See timetables below). You can visit the webpage www.renfe.com or “Cercanías” (Commmuter trains).

   Aeropuerto T4 – El Escorial

   | Week Day | Line | Depart. | Arrival | Departure |
   |----------|------|---------|---------|-----------|
   | Line  | C1  | 05.59   | 06.11   | 06.36   |
   |       | C1  | 06.28   | 06.40   | 07.05   |
   |       | C1  | 06.28   | 07.10   | 07.23   |
   |       | C1  | 07.28   | 07.40   | 08.04   |
   |       | C1  | 08.28   | 08.40   | 09.33   |
   |       | C1  | 09.28   | 09.40   | 10.55   |
   |       | C1  | 10.28   | 10.40   | 11.09   |
   |       | C1  | 11.28   | 11.40   | 12.14   |
   |       | C1  | 12.28   | 12.40   | 13.49   |
   |       | C1  | 13.28   | 13.40   | 14.41   |
   |       | C1  | 14.28   | 14.40   | 15.04   |
   |       | C1  | 14.28   | 15.10   | 15.35   |
   |       | C1  | 15.28   | 15.40   | 16.01   |
   |       | C1  | 16.28   | 16.40   | 16.49   |
   |       | C1  | 16.28   | 17.10   | 17.29   |
   |       | C1  | 17.28   | 17.40   | 18.00   |
   |       | C1  | 17.58   | 18.10   | 18.41   |
   |       | C1  | 18.58   | 19.10   | 19.35   |
   |       | C1  | 19.28   | 19.40   | 19.58   |
   |       | C1  | 20.28   | 20.40   | 20.50   |
   |       | C1  | 21.28   | 21.40   | 21.53   |
   |       | C1  | 22.28   | 22.40   | 22.50   |
   |       | C1  | 23.28   | 23.40   | 23.48   |

   | Weekend | Line | Depart. | Arrival | Departure |
   |---------|------|---------|---------|-----------|
   | Line  | C1  | 06.28   | 06.40   | 06.49   |
   |       | C1  | 07.28   | 07.40   | 07.51   |
   |       | C1  | 08.28   | 08.40   | 08.51   |
   |       | C1  | 09.28   | 09.40   | 09.49   |
   |       | C1  | 10.28   | 10.40   | 10.50   |
   |       | C1  | 11.28   | 11.40   | 11.49   |
   |       | C1  | 12.28   | 12.40   | 12.49   |
   |       | C1  | 13.28   | 13.40   | 13.52   |
   |       | C1  | 14.28   | 14.40   | 14.50   |
   |       | C1  | 15.28   | 15.40   | 15.50   |
   |       | C1  | 16.28   | 16.40   | 16.49   |
   |       | C1  | 17.28   | 17.40   | 17.50   |
   |       | C1  | 18.28   | 18.40   | 18.50   |
   |       | C1  | 19.28   | 19.40   | 19.50   |
   |       | C1  | 20.28   | 20.40   | 20.58   |
   |       | C1  | 21.28   | 21.40   | 21.53   |
   |       | C1  | 22.28   | 22.40   | 22.50   |
   |       | C1  | 23.28   | 23.40   | 23.48   |

2. From El Escorial Train Station to San Lorenzo Bus Station
   In front of the El Escorial train station (exit: Casa Príncipe) you can take a bus...
to San Lorenzo Bus Station Line 1. You can buy the ticket to the bus driver with banknotes smaller than 20 € (see timetables below).

3. From San Lorenzo de El Escorial bus station to the María Cristina Royal University Centre on foot:
There is a short walk from where the buses leave you, which is the San Lorenzo bus station. As you can see in the map below, you must go from the Bus Station to the “Plaza de la Virgen de Gracia” (Virgen de Gracia Square), from where you will perfectly see the Monasterio. Then walk always with the Monasterio to your left (along the “Avenida de Juan de Borbón y Battemberg”. The main entrance of the RCU Maria Cristina is at your right, in front of a park.
ACCOMMODATION

Hotel Information

The city (A short break in San Lorenzo de El Escorial) has convenient hotels located at walking distance.

1. Hotel NH Victoria Palace ****
   www.nh-hoteles.es
   Calle Juan de Toledo 4
   Tel: +34 91 896 98 90

2. Hotel Florida ***
   www.hflorida.com
   Calle Floridablanca 12-14
   Tel: +34 91 890 15 20

3. Hotel Parrilla Príncipe ***
   www.parrillaprincipe.com
   Calle Mariano Benavente 12
   Tel: +34 91 890 15 48

4. Hotel Miranda & Suizo ***
   hotelmirandasuizo.com
   Calle Floridablanca 20
   Tel: +34 91 890 47 11

5. Hotel Los Lanceros ***
   www.loslancers.com
   Calle Calvario, 47
   Tel: +34 918 90 80 11

3. Hotel Posada Don Jaime **
   www.posadadonjaime.es
   Calle San Antón, 24
   Tel: +34 619 30 89 36
MADRID RELATED LINKS

Madrid can be reached using public transportation (train or bus) in approximately an hour. The C8 a train line connects Atocha train station with El Escorial in approximately one hour. Check timetable at www.renfe.com. You may alternatively take the buses 661 or 664 from Moncloa exchanger, which is usually faster. More information here.

In the case that you want more information about Madrid, here are some related links that could be of interest for you:

TRANSPORTS INFORMATION SYSTEM OF MADRID
http://www.ctm-madrid.es/

TRAINS
http://www.renfe.es/

TOURIST INFORMATION OF EL ESCORIAL
http://www.sanlorenzoturismo.es/?language=en

TOURIST INFORMATION OF MADRID
http://www.gomadrid.com/
http://www.aboutmadrid.com/
http://www.descubremadrid.com/en/index.asp/

MUSEUMS
http://museoprado.mcu.es/
http://www.museoreinasofia.es/
http://www.museothyssen.org/thyssen/

FILMS, SHOPS, BARS, TAPAS, ETC.
http://www.softdoc.es/

WEATHER INFORMATION
http://weather.yahoo.com/forecast/SPXX0050_f.html/
http://espanol.wunderground.com/global/stations/08221.html/
ABRIKOSOV PRIZE IN VO RTEX PHYSICS 2015

The Abrikosov prize in Vortex Matter was initiated in 2011 to celebrate the 100th year anniversary of the discovery of superconductivity. The prize recognizes outstanding achievements in the basic science of vortex behavior, and is presented every two years at the International Workshop on Vortex Matter in Superconductors.

ALEXEI ABRIKOSOV’S VO RTEX LATTICE

The field of vortex physics was launched in the 1950s by Alexei Abrikosov’s brilliant discovery of superconducting vortices, for which he received the Nobel Prize in Physics in 2003. He was the first to propose the concept of “type-II superconductors” in 1952 and constructed the theory of their magnetic properties, known as the Abrikosov vortex lattice.

The importance of his discovery is embodied in the fact that all present applied superconducting materials are type II superconductors and the vortex lattice discovered by Abrikosov is responsible for the entire electromagnetic behavior of all applied superconductors! This includes their lossless current carrying capacity, their high frequency response, and their shielding of strong magnetic fields. The concept of vortex lattice laid the foundation for all of the basic science, materials discovery and technological applications based on superconductor, including superconducting magnets for research, MRI for medical diagnosis, levitating Maglev trains, ultra-sensitive magnetic field detection with Superconducting Quantum Interference Devices (SQUIDs), high power superconducting generators and motors, and wires for lossless delivery of electricity to customers.
PREVIOUS RECIPIENTS OF THE ABRIKOSOV PRIZE

2011 Abrikosov Prize – Prof. Peter Kes from Leiden University, the Netherlands

Citation: “for his lifetime contributions to the field of vortex matter in disordered superconductors and his magnanimous efforts in growing the field by mentoring young and established researchers.”

2013 Abrikosov Prize – Prof. Francisco de la Cruz from the Atomic Institute in Bariloche, Argentina

Citation: “for his lifetime contributions to the field of vortex matter in superconductors, in particular the experimental determination of vortex melting and vortex matter properties in layered superconductors, for his exceptional perseverance in creating a renowned low-temperature laboratory specializing in vortex physics and for his tireless efforts in bringing forth generations of young and established researchers”.
## Schematic Program

| May 11 Monday | May 12 Tuesday | May 13 Wednesday | May 14 Thursday | May 15 Friday |
|---------------|----------------|------------------|-----------------|---------------|
| 08:50         | Opening        |                  |                 |               |
| 09:00-10:55   | Multiband SC   | Nanostructuring  | Unconventional  | Vortex States | Vortex Dynamics |
|               | Wen            | and irradiation  | Superconductors | Cuevas        | Zeldov         |
|               |                | for SC (I)       | (I)             |               |               |
| 09:00         | Moshchalkov    | Konczykowski     | Kadowaki        | Geshkenbein   | Banerjee       |
| 09:25         | Machida        | Glatz            | Li              | Maggio-Aprile | Nishida        |
| 09:50         | Milosevic      | Tamegai          | Tajima          | Krasnov       | Palau          |
| 10:15         | Hu             | Villegas         | Prozorov        | Roditchev     |                 |
| 10:40         | Gladilin       | Valles           | Curran          | Maldonado     | Brisbois       |
| 10:55         | Coffee Break   |                  |                 |               |               |
| 11:30-13:25   | Vortices in   | Nanostructuring  | Unconventional  | Quantum       | SC for         |
| SCES Machida  | Topological    | and irradiation  | Superconductors | behavior in   | applications   |
|               | and SCES       | for SC (II)      | (II)            | low dimensional |              |
|               |                | Vicent           | Bascónes        | dimensional SC | Palau          |
|               |                |                  |                 | SC for         |               |
|               |                |                  |                 | applications   |               |
| 11:30         | Wahl           | Kwok             | Wen             | Vinokur       | Wördenerweber  |
| 11:55         | Krusin         | Dobrovolsky      | Maeda           | Shahar        | Ma             |
| 12:20         | Wang           | Okuma            | Hanaguri        | Baturina       | Larbalestier   |
| 12:45         | Ioselevich     | Koshelev         | Shibauchi       | Nójima        | Welp           |
| 13:10         | Nagai          | Del Valle        | Putzke          | Shklovskij    |                |
| 13:25-15:00   | Lunch and time |                  |                 |               |                |
| 15:00-16:40   | Vortex phase   | Nanostructuring  | Pinning in      | Skyrmions and |               |
| Eskildsen     | transitions    | and irradiation  | Superconductors | Condensates   |               |
|               |                | for SC (III)     | (I)             | Miranda       |               |
|               |                | Gonzalez         | Maeda           |               |               |
| 15:00         | Nattermann     | Bekeris          | Van der Beek    | Pfeiderer     |               |
| 15:25         | Fasano         | Ortiz            | Willa           | Reichhardt    |               |
| 15:50         | Guillamón      | Santamaria       | Maiorov         | Vélez         |               |
| 16:15         | Giamarchi      | Gurevich         | Civale          | Klmin         |               |
| 16:40         | Coffee Break   |                  |                 |               |                |
| 17:20-19:05   | Magnetic Imaging | SC heterostructures | Pinning in Superconductors (II) Kwo | Visit to El Escorial Monastery |
| Bekeris       |                | Santamaria       | Kwo             |               |
| 17:20         | Zeldov         | Liu              | Eskildsen       |               |               |
| 17:45         | Kalisky        | Doria            | Shi             |               |               |
| 18:10         | Galperin       | Aguilar          | Pasquini        |               |               |
| 18:35         | Yeshurun       |                  | Raychaudhuri    |               |               |
| 19:00         | Embon          |                  | Sprau           |               |               |
| 19:15         | Free discussion time | Abrikosov prize ceremony and dinner | Poster Session (I) | Poster Session (II) |               |

Chairmen are required to make sure that the schedule is strictly followed and that there is ample time for discussions.

- 25 minutes contribution: 20 minutes talk and 5 minutes for discussion.
- 15 minutes contribution: 12 minutes talks and 3 minutes for discussion.
### Detailed Program

#### Monday, 11 May 2015

| Time         | Session I                                                                 |
|--------------|---------------------------------------------------------------------------|
| 08:50-9:00   | Opening                                                                   |
| 09:00-10:55  | **Multiband Superconductivity**                                           |
| 09:00        | Scanning Hall probe microscopy of vortex matter in S/F hybrids, type-1, type-1.5 and type-2 superconductors | Moshchalkov Leuven |
| 09:25        | Pauli paramagnetic effects on multiband superconductors CeCu$_2$Si$_2$, UBe$_1$, and Sr$_2$RuO$_4$ | Machida Kyoto |
| 09:50        | Fractional vortices in multiband superconductors                          | Milosevic Antwerp |
| 10:15        | Novel Vortex States and Josephson Effects in Multiband Superconductors    | Hu NIMS |
| 10:40        | Bound vortex dipoles generated at pinning centers by Meissner current     | Gladilin Antwerpen |
| 10:55-11:30  | **Coffee Break**                                                          |
| 11:30-13:25  | **Vortices in topological and strongly correlated electron systems**      |
| 11:30        | Superconducting gap and vortex lattice of the heavy fermion compound CeCu$_2$Si$_2$ | Wahl St. Andrews |
| 11:55        | Emergent surface superconductivity of Dirac puddles                      | Krusin New York |
| 12:20        | Interface enhanced superconductivity at 2D limit and superconductivity in 3D Dirac semimetal | Wang Beijing |
| 12:45        | Josephson junctions between topological and conventional superconductors  | Ioselevich Stuttgart |
| 13:10        | Quasiparticle excitations in a nodal topological superconductor: Application to superconducting topological insulator Cu$_3$Bi$_2$Se$_3$ | Nagai CCSE |
| 13:25-15:00  | **Lunch**                                                                 |
| Time     | Session III                                      | Vortex phase transitions                      | Speaker               | Location    |
|----------|-------------------------------------------------|-----------------------------------------------|-----------------------|-------------|
| 15:00    | Vector chiral phases in frustrated 2D XY model  | Nattermann                                    | Köln                  |             |
|          | and quantum spin chains                         |                                               |                       |             |
| 15:25    | Size-induced depression of first-order transition lines and entropy-jump in extremely-layered nanocrystalline vortex matter | Fasano                                         | Bariloche             |             |
| 15:50    | Imaging an order-disorder transition in a 2D vortex lattice | Guillamón                                     | Madrid                |             |
| 16:15    | Thermal effects in disordered elastic systems   | Giamarchi                                     | Geneve                |             |
| 16:40-17:20 | Coffee Break                                      |                                               |                       |             |
| 17:20-19:15 | Session IV                                      | Magnetic Imaging                              |                       |             |
| 17:20    | Scanning nanoSQUID microscopy with in-plane and out-of-plane field sensitivity | Zeldov                                         | Weizmann              |             |
| 17:45    | Moving vortices with scanning SQUID             | Kalisky                                       | Bar-Ilan              |             |
| 18:10    | Ray optics behavior of flux avalanche propagation in superconducting films | Galperin                                       | Oslo                  |             |
| 18:35    | Dendritic flux instabilities in YBCO films exposed to ultra-fast field ramp | Yeshurun                                       | Bar-Ilan              |             |
| 19:00    | Study of dynamics and pinning of single vortices in type-II superconductors using a scanning SQUID-on-tip microscope | Embon                                         | Weizmann              |             |
| 19:15    | Free discussion time                             |                                               |                       |             |
### Tuesday, 12 May 2015

| Time   | Session V | Title                                                                                     | Speaker        | Location |
|--------|-----------|-------------------------------------------------------------------------------------------|----------------|----------|
| 9:00   |           | **Nanostructuring and irradiation for superconductors (I)**                                |                |          |
| 9:00   | Vortex    | Vortex pinning and creep regimes in BaK$_{122}$ family of iron based superconductors in various disorder landscape | Konczykowski   | Paris    |
| 9:25   | Towards   | Towards Critical Current by Design                                                          | Glatz          | ANL      |
| 9:50   | Effects   | Effects of Swift-Particle Irradiations in Iron-based Superconductors                        | Tamegai        | Tokyo    |
| 10:15  | Artificial | Artificial vortex pinning of switchable geometry in cuprate superconductors                | Villegas       | Thales   |
| 10:40  | Vortex    | Vortex pinning and dynamics studies in CSD YBCO nanocomposites from electric transport measurements | Valles         | Barcelona |
| 10:55  |           | **Coffee Break**                                                                           |                |          |
| 11:30  |           | **Session VI**                               **Nanostructuring and irradiation for superconductors (II)** |                |          |
| 11:30  | Enhancing | Enhancing Superconducting Critical Current by Randomness                                    | Kwok           | ANL      |
| 11:55  | Coupling  | Coupling effects in the vortex dynamics in Nb films with nanogroove arrays                 | Dobrovolskiy   | Frankfurt |
| 12:20  | Non-equilibrium | Non-equilibrium Phase Transitions in Driven Vortices                                       | Okuma          | Tokyo    |
| 12:45  | Optimization | Optimization of Vortex Pinning by Nanoparticles Using Large-Scale Simulations of Time-Dependent Ginzburg-Landau Equations | Koshelev       | ANL      |
| 13:10  | Tunable    | Tunable zero-field vortex ratchet in Nb thin films                                          | Del Valle      | Madrid   |
| 13:25  |           | **Lunch**                                   |                |          |
| Time        | Session VII                                      |
|-------------|-------------------------------------------------|
| 15:00-16:40 | **Nanostructuring and irradiation for superconductors (III)** |
| 15:00       | Superconducting heterostructures: examples of attractive and repulsive periodic pinning arrays | Bekeris Buenos Aires |
| 15:25       | Weak-link superconductivity in microstructured films | Ortiz Sao Carlos |
| 15:50       | Novel proximity phenomena at superconductor / ferromagnet oxide interfaces | Santamaria Madrid |
| 16:15       | Microwave suppression of nonlinear conductivity and dissipation limits in superconductors under strong electromagnetic rf fields. | Gurevich Old Dominion |
| 16:40-17:20 | **Coffee Break**                                |
| 17:20-19:15 | **Session VIII**                                |
|             | **Superconducting heterostructures**            |
| 17:20       | Magnetotransport Studies of Gated LaAlO₃/SrTiO₃ Interfaces | Liu Geneva |
| 17:45       | Topological Excitations in the LaAlO₃-SrTiO₃ interface | Doria Rio de Janeiro |
| 18:10       | Superconducting properties of Nb/Pb/Nb trilayer | Aguiar Pernambuco |
| 18:35-19:35 | **Abrikosov prize ceremony**                    |
| 19:45       | **Bus to Conference Dinner**                    |
### Wednesday, 13 May 2015

| Time     | Session IX | Unconventional superconductors (I) |
|----------|------------|-----------------------------------|
| 09:00-10:55 | Terahertz Emission and c-Axis Transport Phenomena in High-Temperature Superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+d}$ Single Crystals | Kadowaki Tsukuba |
| 09:00    | Strong thermal fluctuations in cuprate superconductors in magnetic field above Tc | Li Beijing |
| 09:25    | Optical Observation of Unusual Superconductivity Precursor in YBa$_2$Cu$_3$O$_y$ | Tajima Osaka |
| 09:50    | Upper Critical Field in Multiband Anisotropic Superconductors with Scattering | Prozorov Iowa |
| 10:15    | A field-driven structural transformation of the Josephson vortex lattice in highly anisotropic Bi$_2$Sr$_2$CaCu$_2$O$_{8+d}$ single crystals | Curran Bath |
| 10:35-11:10 | Coffee Break | |

### Session X

| Time     | Session X | Unconventional superconductors (II) |
|----------|-----------|---------------------------------------|
| 11:30-13:25 | Elongated Vortices in the New Superconductor Ta$_4$Pd$_3$Te$_{16}$ and Collective Vortex Pinning in Ba$_{1.5}$K$_{0.5}$BiO$_3$ Superconductors | Wen Nanjing |
| 11:55    | Superconductivity Obtained by Non-equilibrium Synthesis –β-Bi$_3$Pd and thin films of Fe chalcogenides– | Maeda Tokyo |
| 12:20    | Spectroscopic-Imaging STM studies of Vortices in FeSe | Hanaguri Riken |
| 12:45    | Exotic superconductivity of FeSe in the BCS-BEC crossover regime | Shibauchi Tokyo |
| 13:10    | Anomalous critical fields in quantum critical superconductors | Putzke Bristol |
| 13:25-15:00 | Lunch | |
### Session XI
**Pinning in superconductors (I)**

| Time   | Title                                                                                       | Speaker       | Institution   |
|--------|---------------------------------------------------------------------------------------------|---------------|---------------|
| 15:00  | Peak effect and Vortex Lattice Structural Transition in Optimally Doped Ba_{1-x}K_xFe_2As_2 | Van der Beek  | Paris         |
| 15:25  | The Campbell length in the presence of strong vortex pinning                               | Willa         | ETH           |
| 15:50  | Intrinsic and extrinsic pinning in Fe- and Cu-based Superconductors                          | Maiorov       | LANL          |
| 16:15  | Comparative analysis of vortex pinning and dynamics in oxide, iron-based and MgB_2 superconductors | Civale        | LANL          |

**Coffee Break**

### Session XII
**Pinning in superconductors (II)**

| Time   | Title                                                                                       | Speaker       | Institution   |
|--------|---------------------------------------------------------------------------------------------|---------------|---------------|
| 17:20  | Dynamic and Structural Studies of the Metastable and Ground State Vortex Lattice Domains in MgB_2 | Eskildsen     | Notre Dame    |
| 17:45  | Vortex configurations and vortex dynamics in layered superconductors with random pinning: Numerical study | Shi           | Southeastern  |
| 18:10  | Direct evidence of bulk dynamic vortex matter reordering in the order-disorder transitional region | Pasquini      | Buenos Aires  |
| 18:35  | Stepwise disordering of the vortex lattice through successive destruction of positional and orientational order in a weakly pinned Co_{0.0073}NbSe_2 single crystal | Raychaudhuri  | Mumbai        |
| 19:00  | Imaging Atomic-scale Effects of High Energy Ion Irradiation on Superconductivity and Vortex Pinning in Fe(Se, Te) | Sprau         | Cornell       |
| 19:15  |                                                                                             |               |               |
### Thursday, 14 May 2015

| 9:00-10:55 | Session XIII  |
|------------|---------------|
| **Vortex states** | | 
| 09:00 | *Dynamics of core-less Abrikosov vortices* | Geshkenbein ETH |
| 09:25 | *New light on the electronic vortex core structure and normal state in YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7}* | Maggio-Aprile Geneve |
| 09:50 | *Cryogenic memory element based on a single Abrikosov vortex* | Krasnov Stockholm |
| 10:15 | *STS of vortex cores in superconductors: From Abrikosov to Josephson* | Roditchev Paris |
| 10:40 | *Dirac surface states and superconductivity in noncentrosymmetric BiPd* | Maldonado St. Andrews |

| 10:35-11:10 | Coffee Break |

| 11:30-13:25 | Session XIV  |
|-------------|--------------|
| **Quantum behavior in low dimensional superconductors** | |
| 11:30 | *Dynamic Vortex Mott Transition in a Proximity Array of Superconducting Islands* | Vinokur ANL |
| 11:55 | *Little-Parks Oscillations in an Insulator* | Shahar Weizmann |
| 12:20 | *True versus ghost Berezinskii-Kosterlitz-Thouless transition in two-dimensional superconductors* | Baturina Novosibirsk |
| 12:45 | *Metallic ground states and enhanced upper critical fields in electric-field-induced superconductors* | Nojima Tohoku |
| 13:10 | *Pinning effect on the hot-electron vortex flow instability in superconducting films* | Shklovskij Kharkiv |
| 13:25-15:00 | Lunch |
| Time          | Session XV                      |
|--------------|---------------------------------|
| **15:00**    | *Skyrmions and condensates*     |
| **15:00**    | Skyrmion Lattices and Skyrmion Liquids in Chiral Magnets | Pleiderer Munich |
| **15:25**    | Nonequilibrium Dynamics of Skyrmion Lattices in Random and Ordered Substrates | Reichhardt LANL |
| **15:50**    | Topological defects in weak perpendicular magnetic anisotropy nanostructures | Vélez Oviedo |
| **16:15**    | Effective field theory and finite temperature vortices in cold Fermi gases | Klimin Antwerpen |
| **16:40**    | Coupled macroscopic quantum tunneling in intrinsic Josephson junctions in BSCCOs due to dynamical breaking of the charge neutrality of CuO$_2$ layers | Kakeya Kyoto |
| **16:55-19:00** | Visit to El Escorial Monastery |
| **19:00**    | Poster Session (II)             |
## Friday, 15 May 2015

| Time     | Session XVI                      | Vortex dynamics |
|----------|----------------------------------|-----------------|
| 09:00    | Large negative velocity events and validity of non-equilibrium fluctuation relation at the unjamming threshold in the driven vortex state of 2H-NbS$_2$ | Banerjee
|          |                                  | Kanpur          |
| 09:25    | STM/STS Observation of Vortex Motion in Non-equilibrium Superconducting States in Bi$_2$Sr$_2$CaCu$_2$O$_x$ and YNi$_3$B$_2$C | Nishida
|          |                                  | Toyota          |
| 09:50    | Vortex Cutting in Superconductors | Vlasko-Vlasov   |
|          |                                  | ANL             |
| 10:15    | Manipulating vortex dynamics in nanostructured YBCO films | Palau
|          |                                  | Barcelona       |
| 10:40    | Why are flux avalanches deflected by a metallic layer? | Brisbois
|          |                                  | Liège           |
| 10:55-11:30 | Coffee Break                  |                 |
| 11:30-13:25 | Session XVII                   | Superconductors for applications |
| 11:30    | Critical Properties of Large-Scale Deposited, All-Solution Coated Conductors | Wördenweber
|          |                                  | Jülich          |
| 11:55    | High critical current density in Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ tapes for magnet applications | Ma
|          |                                  | CAS             |
| 12:20    | Grain boundaries in HTS materials – still a challenge to understand and to control | Larbalestier
|          |                                  | Florida         |
| 12:45    | Pinning Landscapes for High-Performance Superconductors | Welp
|          |                                  | ANL             |
| 13:10    | Closure                         |                 |
| 13:25-15:00 | Lunch                        |                 |
Abstracts of Lecturers
SCANNING HALL PROBE MICROSCOPY OF VORTEX MATTER IN S/F HYBRIDS, TYPE-1, TYPE-1.5 AND TYPE-2 SUPERCONDUCTORS

Victor V. MOSHCHALKOV, J.Y. GE, J. GUTIERREZ, M. TIMMERMANS, J. VAN DE VONDEL, A.V. SILHANEK, L.F. CHIBOTARU, B.Y. ZHU, V. GLADILIN & J.T. DEVREESE

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Scanning Hall probe microscopy (SHPM) has been used to directly visualize vortex matter in S/F hybrids, type-1, type-1.5 and type-2 superconductors. In S/F hybrids domain wall and reverse domain superconductivity has been investigated. Vortex matter modifications in Pb wedge sample covering all the ranges from type-2 to type-1 superconductivity has been studied. Vortices in the intermediate state of a thick type-1 superconducting Pb film have been visualized for different Pb thicknesses. In low fields we have observed the presence of stable (or quasi stable) single flux quantum vortices, as well as a few flux quantas vortices. Unusual vortex patterns have been observed in the type-II/1 and type-II-2 regimes in the vicinity of the dual point $\lambda/\xi=1/\sqrt{2}$. The role of surface barriers in stabilizing these vortex patterns has been discussed.

The existence of the novel superconducting state has been demonstrated in two-component high quality MgB$_2$ single crystals where a unique combination of both type-1 and type-2 conditions is realized in the same material. Such materials are, in fact, neither type-1 nor type-2 superconductors and can be introduced as "type-1.5 superconductors". This leads to an appearance of unconventional vortex arrangements such as stable vortex stripes, clusters and gossamer-like vortex patterns. We have directly visualized these novel patterns by using scanning Hall probe microscopy (SHPM), Bitter decoration and scanning SQUID microscopy. The observed vortex patterns are in a good agreement with the molecular dynamics simulations based on the vortex-vortex interaction corresponding to type-1.5 superconductivity. In higher applied fields normal type-2 vortex patterns are recovered in MgB$_2$.

This work is supported by the COST Action MP1201, FWO projects and by the Methusalem Funding of the Flemish Government.

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PAULI PARAMAGNETIC EFFECTS ON MULTIBAND SUPERCONDUCTORS –CeCu$_2$Si$_2$, UBe$_{13}$ and Sr$_2$RuO$_4$–

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Motivated by curious magnetic behaviors found recently in heavy fermion superconductors CeCu$_2$Si$_2$ [1] and UBe$_{13}$ [2], and also in strongly anisotropic superconductor Sr$_2$RuO$_4$ [3,4], we theoretically study the Pauli paramagnetic effects on the vortex state of a type II superconductor with multiband on the basis of microscopic Eilenberger framework. We address the issue of the presence (Sr$_2$RuO$_4$) or absence (CeCu$_2$Si$_2$ and UBe$_{13}$) of the first order transition at $H_{c2}$ and investigate its origin in connection with the multiband effect that is common for the three compounds. After constructing an appropriate model system for each compound, we solve the Eilenberger equation to find various physical quantities, including total and local density of states, magnetization curves, magnetic torque curves, and vortex form factors that are all relevant for experiments done so far [1-4]. It is concluded that the interplay between the multiband effect and Pauli paramagnetic effect is a key to understand the electro-magnetic properties of the vortex state of those compounds [5].

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In this talk, I will discuss our recent findings on stable fractional vortex states in multiband superconductors, their origin, properties, unusual dynamics, and experimental observables.

The underlying mechanism for the vortex fractionalization in multiband superconductors can be the difference in characteristic length scales for the present quantum condensates [1], particularly enhanced close to hidden criticality [2], with a consequence of different action of pinning and sample boundaries on those condensates. In 3+ band systems, an alternative mechanism for fractionalization arises due to possible intrinsic frustration of phase-differences between the band-condensates – the so called chiral superconductivity [3]. The phase frustration can also arise in dirty two-band samples, where the interplay of currents can act against the direct coupling between the condensates and cause breakup of vortices even if the relevant length scales and inter-band phases are not in competition.

Besides the intriguing vortex states as a result of this fractionalization, the consequent dynamics of fractional vortex entry and motion under applied current is also novel and highly unusual, where band-fractions of a given vortex emulate particles on a spring, bound together by the elastic contour of fluxoid quantization. For this reason, both magnetic and transport measurements can reveal the existence of fractional vortices, and will require further modifications of the known vortex phase diagrams.

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NOVEL VORTEX STATES AND JOSEPHSON EFFECTS IN MULTIBAND SUPERCONDUCTORS

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In presence of repulsive inter-band couplings, a multi-band superconductor can exhibit an equilibrium state with double degeneracy characterized by chirality of gap functions where time-reversal symmetry is broken (TRSB) even without external magnetic field. It is shown explicitly that there are multiple divergent coherence lengths in this state [1], which leads to vortex clustering in contrast to conventional type I and type II superconductors [2]. Critical current of a Josephson junction between a TRSB superconductor and a single-component one is asymmetric with respect to current direction as a consequence of TRSB [3], which was observed experimentally based on an iron-pnictide superconductor [4]. In a loop of TRSB superconductor with two halves taking opposite chiralities, fractional flux plateaus are found in magnetization curve associated with free-energy minima, which form pairs with their heights related the flux quantum Φ₀ [5]. Massless Leggett mode appears at the phase boundary between a TRSB state and a state with TRS preserved [6]. Therefore, the TRSB superconducting state provides a novel chance to explore relative phase difference, phase kink and soliton in ubiquitous multi-band superconductivity.

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BOUND VORTEX DIPOLES GENERATED AT PINNING CENTERS BY MEISSNER CURRENT

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One of the phenomena that make superconductors unique materials is the Meissner-Ochsenfeld effect. This effect results in a state in which an applied magnetic field is expelled from the bulk of the material because of the circulation near its surface of resistance-free currents, also known as Meissner currents. Notwithstanding the intense research on the Meissner state, local fields due to the interaction of Meissner currents with pinning centers have not received much attention. Here we show that the Meissner currents, when flowing through an area containing a pinning center, generate in its vicinity two opposite sense current half-loops producing a bound vortex-antivortex pair (see Fig. 1), which eventually may transform into a fully developed vortex-antivortex pair ultimately separated in space [1]. We have used high-resolution low-temperature scanning Hall probe microscopy to visualize these bound vortex dipoles. By scanning various areas of the sample with pinning centers, we have found excellent correspondence between the observed orientations of the vortex dipoles and the direction of the Meissner screening current. Our experimental finding is supported by theoretical modelling in the framework of the time-dependent Ginzburg-Landau formalism. The generation of such vortex dipoles by Meissner currents is not restricted to superconductors; similar topological excitations may be present in other systems with Meissner-like phases.

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The order parameter and pairing mechanism for superconductivity in heavy fermion compounds are still poorly understood. I will present a characterization of superconductivity of the heavy fermion superconductor CeCu$_2$Si$_2$ by scanning tunneling microscopy and spectroscopy at ultra-low temperatures. The differential conductance spectra acquired at temperatures well below 100mK reveal a gap which is not fully formed. The gap structure observed in scanning tunnelling spectroscopy exhibits features which point to a complex superconducting order parameter. The STS data is found to be consistent with specific heat data, indicating that bulk superconductivity is probed.

Measurements in magnetic field show a predominantly triangular vortex lattice. The vortex lattice shows a distortion away from six-fold symmetry at specific fields. Observation of the vortex lattice as well as the behaviour of the tunneling spectra as a function of temperature and magnetic field demonstrate that the observed conductance gap is due to superconductivity in CeCu$_2$Si$_2$.

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EMERGENT SURFACE SUPERCONDUCTIVITY OF DIRAC PUDDLES

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Surfaces of three-dimensional topological insulators have emerged as one of the most remarkable states of condensed quantum matter. These surfaces host robust spin-protected helical Dirac particles that emerge from topological order and can support unusual electronic phases when electron correlations are at play. One particularly exciting phase is topological superconductivity which, if found, could lead to a paradigm change in quantum information. Here I will report a discovery of surface superconductivity in a hole-conducting topological insulator Sb$_2$Te$_3$ with transition to zero resistance induced through a minor tuning of growth chemistry that depletes bulk conduction channels. The depletion shifts Fermi energy towards the Dirac point as witnessed by about two orders of magnitude reduced hole density and by the largest carrier mobility (~25,000 cm$^2$/Vs) found in any topological material. The unconventional nature of this state is witnessed by the persistence of quantum oscillations inside the superconducting state and two-dimensional (2D) quantum beats arising from strong spin-orbit coupling. Direct evidence from scanning tunneling spectroscopy, unusual magnetic response, and transport reveal the superconducting condensate to emerge at first in surface puddles at unprecedentedly high temperatures, above 50 K and approaching liquid nitrogen. I will discuss how global coherence is mediated by interpuddle diffusion of quasiparticles and how the novel superconducting state we observe to form in puddles can be tuned by the topological material’s parameters such as Fermi velocity and mean free path.

This work was supported in part by the NSF DMR-1122594 and DOD-W911NF-13-1-0159. With L. Zhao, H. Deng, I. Korzhovska, J. Secor, M. Begliarbekov, Z. Chen, V. Oganessian, and A. Pasupathy.

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INTERFACE ENHANCED SUPERCONDUCTIVITY AT 2D LIMIT AND SUPERCONDUCTIVITY IN 3D DIRAC SEMIMETAL

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By direct transport and magnetic measurements, we provide first direct evidence for high temperature superconductivity in the one unit cell (1-UC) FeSe films on insulating STO substrates with the onset Tc and critical current density much higher than those for bulk FeSe. This work may pave the way to enhancing and tailoring superconductivity by interface engineering. [1-3] Furthermore, by both in situ scanning tunneling microscopy/spectroscopy and ex situ transport and magnetization measurements, we find that the two-atomic-layer Ga film with hexagonal structure on wide band-gap semiconductor GaN is superconducting with Tc up to 5.4 K. This work offers a new platform to study two-dimensional (2D) superconductivity in metal-semiconductor heterostructures. [4] In addition, we firstly observe the superconductivity in crystalline 3D Dirac semimetal Cd$_3$As$_2$ with some signatures showing the possibility of topological superconductivity. [5]

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During the last decade topological insulators and superconductors have become a major topic in condensed matter physics. Particular interest is paid to superconducting hybrid systems hosting localised Majorana zero modes. One major class of such systems are nanowires with strong spin-orbit interaction subject to magnetic field and induced superconductivity. Another important example are vortex cores on top of three-dimensional topological insulators with induced superconductivity. One of the main routes to directly observe the Majorana modes in such systems is to attach a tunneling probe to the structure. The zero mode induces resonant Andreev reflection resulting in a persistent zero-bias conductance peak. Here we consider what happens if the probe in such a setup is superconducting itself, forming a Josephson junction with the topological system. Time-reversal symmetry breaking is an essential element of such a junction and allows more complicated behaviour than in conventional Josephson junctions that are time-reversal invariant in their normal state. Studying a general class of topological superconductor - conventional superconductor junctions we derive some general formulae for the stationary Josephson effect. We find strong asymmetry with respect to the gaps in the two superconductors. For a particular tunneling junction we show that the critical current scales as $I_c \sim \Delta_{\text{top}} / R_n^2$, strongly violating the classical Ambegaokar- Baratoff relation.
We study the quasiparticle excitations around a vortex and impurities in the superconducting topological insulator Cu$_x$Bi$_2$Se$_3$, focusing on a superconducting state with point nodes. Inspired by the recent Knight shift measurements[1], we propose two ways to detect the positions of point nodes. The zero-energy local density of states around a vortex parallel to the c-axis has a twofold shape and splits along the nodal direction with increasing energy; these behaviours can be detected by scanning tunnelling microscopy. An angular dependence of the density of states with a rotating magnetic field on the a-b plane has deep minima when the magnetic field is parallel to the directions of point nodes, which can be detected by angular-resolved heat capacity and thermal conductivity measurements[2].

The possibility of the nodal gap function in Cu$_x$Bi$_2$Se$_3$ is very surprising and curious. Typically, this compound is considered to be dirty owing to the copper intercalated process. A nodal superconductivity is very fragile against nonmagnetic impurities, since the low-energy excitations are produced around the nodes in momentum space. We find that the topological superconductivity with/without point nodes is not fragile against nonmagnetic impurities[3,4], when the orbital imbalance is small. Exchanging the role of spin with the one of orbital, and vice versa, we find that in the "dual" space the nodal topological superconductor is regarded as the intraorbital spin-singlet s-wave one. Since the spin imbalance is induced by the Zeeman magnetic field, we shall name this key quantity for the impurity effects the Zeeman "orbital" field. The topological superconductivity is not fragile in dirty materials, even with nodes. Thus, the topological superconductors cannot be simply regarded as one of the conventional unconventional superconductors.

In this talk, we also show that the on-site interaction induces the rotational-symmetry-broken superconductivity with nodes in the superconducting topological insulator.

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VECTOR CHIRAL PHASES IN FRUSTRATED 2D XY MODEL AND QUANTUM SPIN CHAINS

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The phase diagram of the frustrated 2D classical and 1D quantum XY models is calculated analytically. Four transitions are found: the vortex unbinding transitions triggered by strong fluctuations occur above and below the chiral transition temperature. Vortex interaction is short range on small and logarithmic on large scales. The chiral transition, though belonging to the Ising universality class by symmetry, has different critical exponents due to nonlocal interaction. In a narrow region close to the Lifshitz point a reentrant phase transition between paramagnetic and quasi-ferromagnetic phase appears. Applications to antiferromagnetic quantum spin chains and multiferroics are discussed.

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SIZE-INDUCED DEPRESSION OF FIRST-ORDER TRANSITION LINES AND ENTROPY-JUMP IN EXTREMELY-LAYERED NANOCRYSTALLINE VORTEX MATTER

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The persistence of the first-order solidification and solid order-disorder transition lines in the phase diagram of nanocrystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ vortex matter is detected down to a system size of less than hundred vortices. The temperature-location of the vortex solidification transition line $H_{FOT}$ is not altered by decreasing the number of vortices down to less than hundred, although there is a depletion of the entropy-jump of the transition with respect to macroscopic vortex matter. Direct imaging of nanocrystalline vortex matter indicates this entropy-depletion is due to the nucleation of a more disordered vortex solid structure in the case of micron-sized samples due to the register of vortex lines with the sample edge. The solid order-disorder phase transition field $H_{SP}$ moves upward on decreasing the system size due to the increase of the surface-to-volume ratio of vortices entailing a decrease on the average vortex binding energy. The onset of irreversible magnetic response is also affected by confinement with a noticeable enlargement of the irreversible vortex region above $H_{SP}$ on decreasing the number of vortices. Precise and highly-sensitive to bulk currents ac magnetization techniques proved to be mandatory in order to obtain this information.

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Disorder dramatically modifies the properties of superfluids, quantum condensates or correlated electron systems, eventually inducing new phases in matter. In two dimensional (2D) systems, it is thought that random disorder destroys long range correlations driving a transition to a glassy state.

Here, I will present the direct visualization of an order-disorder transition in a 2D superconducting vortex lattice. We determine the critical behavior of the transition and discuss the driving microscopic mechanism. We measure, using a very low temperature scanning tunneling microscope (0.1 K), a superconducting film with a thickness far below the penetration depth. The film is nanostructured with a very weak 1D modulation of less than 1% of the overall thickness. We image up to several thousands of vortices one by one and track the modification in the 2D vortex arrangements while increasing the vortex density by three orders of magnitude. At low fields, we observe how the perfect hexagonal lattice changes from a locked to a floating solid. Upon further increasing the magnetic field, the 2D floating lattice disorders. We observe that the order-disorder transition is mediated by dislocations and disclinations and accompanied by an increase in vortex density fluctuations. We calculate positional and orientational correlation functions and the displacement correlator vs distance. We find logarithmically increasing displacement correlator showing that the transition is driven by random quenched disorder. The 1D modulation becomes incommensurate with the vortex lattice and behaves as a scale-invariant disorder potential. The critical points and exponents characterizing the transition are well above theoretical expectations for uncorrelated random disorder. Our results show that long range 1D correlations inhibit the effect of random disorder and enhance the stability range of the ordered phase in a 2D vortex lattice.

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THERMAL EFFECTS IN DISORDERED ELASTIC SYSTEMS

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Many different microscopic systems such as vortices or domain walls in ferroic systems can be described by the general formalism of disordered elastic systems.

The properties of such systems are described by a zero temperature fixed point in which the competition between the elasticity and the disorder leads to a host of novel glassy properties.

If the properties at zero temperature are by now well understood it is far from being the case for the finite temperature case, both for the equilibrium and the driven situation where the system is subjected to an external force.

I will discuss in this talk recent progress made in understanding how a finite temperature affects the properties of such systems both for periodic ones such as vortices or single domain walls. I will in particular discuss the connection with recent experiments in domain wall propagation in magnetic materials.

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SCANNING nanoSQUID MICROSCOPY WITH IN-PLANE AND OUT-OF-PLANE FIELD SENSITIVITY

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A scanning magnetic probe microscope based on a nanoSQUIDs fabricated on the apex of a quartz tip has been developed. The nanoSQUID-on-tip devices made of various superconductors including Al, Nb, and Pb have been fabricated with diameters down to 50 nm [1,2]. The devices reach spin sensitivity of better than $\mu_B/\sqrt{Hz}$ and operate in magnetic fields of up to 1 T. One of the limitations of the SQUIDs, however, is that they are sensitive only to the out-of-plane component of the field. We have recently developed nanoscale three-junction Pb nanoSQUID-on-tip by pulling a quartz tube with a “θ” shaped cross section. This geometry gives rise to two parallel SQUID loops sharing a common branch. Using a focused ion beam, we then trim the tip so that the two SQUID loops become oblique with respect to each other giving rise to a two-dimensional interference pattern. As a result of the 3D structure, the θ-SQUID can be tuned in-situ to be sensitive to either in-plane or out-of-plane fields. The θ-SQUID-on-tip is integrated into a scanning probe microscope providing high-spatial resolution independent imaging of the different components of the magnetic field demonstrating its potential as a local probe of nanoscale magnetic structures.

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MOVING VORTICES WITH SCANNING SQUID

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Vortex motion in a superconductor is typically generated by electrical currents or by magnetic fields. In addition, controlling vortex motion is done by altering the pinning landscape or by structuring local constraints on the superfluid density. Here we show different ways to manipulate vortices with scanning SQUID.

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RAY OPTICS BEHAVIOR OF FLUX AVALANCHE PROPAGATION IN SUPERCONDUCTING FILMS

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Experimental evidence of wave properties of dendritic flux avalanches in superconducting films is reported. Using magneto-optical imaging the propagation of dendrites across boundaries between a bare NbN film and areas coated by a Cu-layer was visualized, and it was found that the propagation is refracted in full quantitative agreement with Snell’s law. For the studied film of 170 nm thickness and a 0.9 μm thick metal layer, the refractive index was close to n=1.4.

The origin of the refraction is believed to be caused by the dendrites propagating as an electromagnetic shock wave, similar to damped modes considered previously for normal metals. The analogy is justified by the large dissipation during the avalanches raising the local temperature significantly.

Additional time-resolved measurements of voltage pulses generated by segments of the dendrites traversing an electrode confirm the consistency of the adopted physical picture.

More details are given in Ref. [1].

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DENDRITIC FLUX INSTABILITIES IN YBCO FILMS EXPOSED TO ULTRA-FAST FIELD RAMP

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We have recently developed a novel magneto-optical system that enables real time imaging at rates of ~ 70,000 frames per second. The system is also capable of very fast field ramping, at rates exceeding 3000 T/s. This new system has been exploited in the study of flux avalanches, focusing on dendritic flux patterns in YBCO films. We report on first observation of dendritic avalanches in these films triggered by rapid field ramping and discuss effects of different substrates on dendritic formation. The ability to routinely generate dendritic avalanches allows the first study of the experimental conditions for the instability, in particular the thresholds temperatures and ramp rates for the appearance of dendrites. The results will be discussed in the framework of recent turbulent dynamics theories.

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**STUDY OF DYNAMICS AND PINNING OF SINGLE VORTICES IN TYPE-II SUPERCONDUCTORS USING A SCANNING SQUID-ON-TIP MICROSCOPE**

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The dynamics of quantized magnetic vortices and their pinning by materials defects determine the electromagnetic properties of superconductors, particularly their ability to carry non-dissipative currents. Despite recent advances in the understanding of the complex physics of vortex matter, the behavior of vortices driven by current through the potential created by actual materials defects is still not well understood, mostly due to the scarcity of appropriate experimental tools capable of tracing vortex trajectories on nanometer scales. Using a novel scanning SQUID-on-tip microscope \([1]\) we have carried out an investigation of controlled dynamics of vortices in Pb films with sub-Angstrom sensitivity to vortex displacement \([2]\). We measured, for the first time, the fundamental dependence of the elementary pinning force of multiple defects on the vortex displacement, revealing a far more complex behavior than has previously been recognized. Our results indicate the importance of thermal fluctuations even at 4.2 K and of the vital role of small ripples in the pinning potential, giving new insights into the mechanisms of magnetic relaxation and electromagnetic response of superconductors.

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VORTEX PINNING AND CREEP REGIMES IN BAK122 FAMILY OF IRON BASED SUPERCONDUCTORS IN VARIOUS DISORDER LANDSCAPE

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Irreversible magnetization of Ba₁₋ₓKₓFe₂As₂ superconductors exhibits characteristic magnetic field dependence identifying distinct types of vortex pinning:

(1) Star shaped hysteresis loop with \(1/\sqrt{B}\) variation of the critical current characteristic of the strong pinning regime. [1]

(2) Second peak at higher magnetic fields originating from weak collective pinning [2].

(3) Flat, field independent irreversible magnetization in presence of columnar defects.

Modification of the disorder landscape leading to different pinning regimes was realized by irradiation with heavy – ions and electrons producing correlated and point – like disorder, respectively. I will report a systematic study of pinning and creep on pristine and irradiated optimally doped Ba₁₋ₓKₓFe₂As₂ crystals (x~0.4). We find that high quality (as judged by transport, magnetic and penetration depth measurements) pristine samples exhibit exclusively strong pinning regime. Introduction of point defects by low temperature 2.5 MeV electron irradiation leads to the emergence of the second magnetization peak and weak collective pinning regime. Heavy ion irradiation results in a Bose - glass type of pinning with almost field independent critical current and rectangular magnetization loops.

Furthermore, the introduction of artificial pinning centers of both types does not suppress the omnipresent and quite substantial flux creep. Analysis of magnetic decays recorded in a wide range of temperatures by miniature Hall sensor array allowed determination of current dependence of the effective energy barrier and identification of the flux creep mechanism [3].

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TOWARDS CRITICAL CURRENT BY DESIGN

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Understanding the dynamic behavior of vortex matter in complicated pinning landscapes is a major challenge for both fundamental science and energy applications. In particular, optimizing type, size and density of pinning centers can significantly enhance the critical current. Based on the time-dependent Ginzburg-Landau equation, we developed a numerical approach towards finding these optimal pinning configurations.

Performing large-scale simulations of the vortex dynamics [1,2], we analyzed a number of different inclusion types and found optimal pinning configurations corresponding to the largest critical current in the geometries under consideration. In particularly, we studied the interplay between vortex-vortex and vortex-inclusion interactions in a system including nanorod and columnar defects. This system represents a superconducting tape irradiated by heavy ions at an angle (see Fig.). Our simulation results agree with several experimental results and predict how the observed critical current could be further increased [tba].

\textbf{Figure:} Vortex lines (red) pinned on an array of nanorods and columnar defects oriented at $45^\circ$ with respect to the nanorod orientation.

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EFFECTS OF SWIFT-PARTICLE IRRADIATIONS IN IRON-BASED SUPERCONDUCTORS

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Since the discovery of superconductivity in iron-based superconductors (IBSs), vast amount of research activities have been devoted to clarify the mechanism of superconductivity and to demonstrate possible applications of this kind of materials [1]. We have been applying irradiations of swift particles into IBS to study two aspects of superconductivity in this system; (1) pairing symmetry [2,3] and (2) pinning properties [4-6]. In this presentation, the latter topics will be presented exclusively.

Defects created by swift particles irradiations in a superconductor can pin vortices, leading to an enhancement of critical current density (Jc). In cuprate superconductors, significant increase in Jc has been reported by proton [7] and heavy-ion irradiations [8]. We have demonstrated that 200 MeV Au irradiation into Ba(Fe,Co)2As2 is effective in creating columnar defects and enhance Jc by a factor of 5 even at the lowest temperature [4]. Similar effects have been demonstrated by 800 MeV Xe and 1.4 GeV Pb ions. The effect is much more dramatic in (Ba,K)Fe2As2, as high as 6 MA/cm2 at 5 K has been reported in the case of 1.4 GeV Pb (Bo=210 kG) [9]. Here, we report that 320 MeV Au irradiation in (Ba,K)Fe2As2 at Bo=80 kG can enhance Jc up to 10 MA/cm2 at 5 K [10]. Furthermore, magnetic field dependence of Jc becomes very weak and pinning force density at 5 K and 40 kOe reaches 280 GN/m³, which is even larger than 2G-YBCO coated conductors and demonstrate a strong potential of IBS to high-field application. Changes in Jc and vortex dynamics in IBSs induced by swift-particle irradiations will be extensively discussed.

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ARTIFICIAL VORTEX PINNING OF SWITCHABLE GEOMETRY IN CUPRATE SUPERCONDUCTORS

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We combine e-beam lithography and O\(^+\) ion irradiation to create ordered pinning in YBa\(_2\)Cu\(_3\)O\(_{7-x}\) thin films. This technique allows us to design the vortex energy landscape through a nanoscale spatial modulation of the superconducting critical temperature. This yields very strong field matching effects [1]. The ion irradiation has collateral effects on the vortex matter properties, such as an increase on the anisotropy, a decrease of the dimensionality [2] and an unusual vortex-velocity dependent behaviour [3]. Interestingly, by judiciously choosing the irradiation and lithography parameters, we can obtain energy landscapes whose geometry can be switched using temperature as the control knob. This is shown in vortex energy landscapes that present a variable degree of geometric frustration depending on the temperature [4].

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The insertion of randomly oriented nanoparticles in low cost and scalable Chemical Solution Deposition YBCO has enabled the chance to finely tune the nanostructure of the superconductor and therefore obtain a new vortex pinning and dynamics landscape that is foreseen to very effectively enhance the performance of long length coated conductors at high magnetic fields.

We have demonstrated that these CSD YBCO nanocomposites provide huge isotropic pinning forces arising from the strained regions associated to a network of intergrowths (mainly Cu-O chains) emerging from the incoherent interface between the nanoparticles and the YBCO matrix. A novel pinning mechanism has been proposed coupling the lattice distortions with superconducting pairing [1].

Correlation between electric transport measurements and STEM and XRD investigations has been crucial to deeply understand the origin of this high isotropic pinning. In particular, we have measured IV curves over an extensive range of temperatures, magnetic fields and orientations of the magnetic field that have provided very interesting information allowing to quantify the effectiveness of the intergrowths-originated strains in terms of vortex dynamics domination.

Comparison between nanocomposite films and pristine YBCO films for H||c and H||ab orientations have enabled to analyze the anisotropic pinning and dynamics contributions coming from twin boundaries, intrinsic pinning and stacking fault pinning and identify the relevant role of isotropic contributions in nanocomposites.

We conclude that vortex pinning and dynamics landscape in CSD YBCO nanocomposites can be modified and highly optimized by a proper tuning of the length, density and distribution of the intergrowths controlled by the processing of the inserted second phase nanoparticles.

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ENHANCING SUPERCONDUCTING CRITICAL CURRENT BY RANDOMNESS

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It is well known that a key ingredient to achieve high critical currents in type-II superconductors is defect-sites that pin vortices. With the advent of nanofabrication, there have been numerous reports advocating the remarkable enhancement of the critical current with various nano-patterned ordered arrays of pinning sites to localize the vortex lattice structure. Here, we show that a random pinscape, an often overlooked pinning system in nano-patterned superconductors, can lead to a more significant critical current enhancement at high magnetic fields than an ordered array of vortex pin sites. We demonstrate the pinning effects of random hole-arrays with and without a global density gradient and gauge their behavior against a square array and a conformal array of hexagonal lattice of holes in a multi-patterned MoGe micro-bridge for a direct comparison. We used a Voronoi diagram approach to visualize and quantify the distribution of local density of pinning sites (LDOPS), and elucidate the role of LDOPS distribution in enhancing the critical current at high magnetic fields. We found that a properly tailored LDOPS in a random orientation has the best potential for enhancing the critical current over a wide range of magnetic fields. Our results provide a deeper insight to the often overlooked random pinscape.

This work was supported by the Department of Energy, Office of Basic Energy Sciences which also funds Argonne’s Center for Nanoscale Materials (CNM) and Electron Microscopy Center (EMC) where the nano-patterning and morphological analysis were performed. L.R.T. and Z.L.X. acknowledge NSF Grant No. DMR-1407175 and NIU’s Nanoscience Graduate Fellowship.

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The dc voltage response and the microwave power absorption in nanopatterned Nb microstrips, as theoretically considered in [1-3], are studied by combined microwave and dc electrical transport measurements [4]. The microstrips are made from epitaxial Nb films [5] with weak intrinsic pinning while the nanopatterns are arrays of nanogrooves fabricated by focused ion beam milling and induce a strong pinning of the washboard type [6]. In the presentation, the following particular effects are addressed: (i) Due to spatial commensurability of the vortex lattice with the underlying washboard pinning landscape, the microwave loss is minimal for the fundamental matching field value. (ii) As a consequence of the dc/ac interference, mode-locking fringe-like features are observed in the microwave power - dc voltage response and are complementary to Shapiro steps in the dc current - dc voltage curve [7]. (iii) In the absence of a dc bias current, the response of vortices is weakly dissipative at low frequencies when they are driven over the grooves and it is strongly dissipative at high frequencies when the vortices are oscillating within one groove [8,9]. The addition of a dc bias allows one to tune the crossover (depinning) frequency separating the above-named regimes [10]. The reported results unveil advanced microwave functionalities of superconducting films with washboard pinning landscapes and are relevant for tuning the microwave loss in superconducting planar transmission lines.

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NON-EQUILIBRIUM PHASE TRANSITIONS IN DRIVEN VORTICES

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The non-equilibrium phase transition of a reversible–irreversible flow transition (RIT) has been reported in a slowly sheared colloidal particle system placed between concentric cylinders [1]. The underlying physics for RIT is random organization of particles subject to periodic shear [1,2]. The distance the particles are sheared over per cycle, d, turns out to be a key quantity determining the final steady state: When d is smaller than a certain characteristic value $d_c$, all the particles return to their initial position after each periodic shear, which is called reversible flow. On the other hand, when $d > d_c$, some particles do not return to their initial position. This is called irreversible flow. A relaxation time for the system to settle into the steady state diverges as a power-law on both sides of $d_c$.

We have obtained evidence of RIT using a vortex system confined in a Corbino-disk (CD) [3] of amorphous (a-)Mo$_x$Ge$_{1-x}$ films with weak pinning, where the vortices are driven periodically in the circumferential direction by feeling a large global shear due to the ac current applied radially [4]. The results strongly suggest the universality of RIT. In strip-shaped films where the vortices feel a local shear resulting from random pinning [2], we again obtain evidence of RIT with a critical behavior similar to that for CD, consistent with the numerical simulation [2]. Furthermore, we have conducted the same experiment in the presence of a superimposed dc force, thus varying d in moving frame with a fixed dc velocity. We again observe the critical behavior of RIT with $d_c$ that is dependent on the dc velocity. This method may enable us to study the effects of effective pinning on RIT by simply changing the dc velocity of the moving frame.

In this talk, I present novel dynamic transitions found in the ac- and/or dc-driven vortex system of a-Mo$_x$Ge$_{1-x}$ films, which include the general phenomena of RIT [1-3] and a plastic depinning transition [4-9] as well as the dynamic ordering and reorientation of the driven Abrikosov lattice [10,11].

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OPTIMIZATION OF VORTEX PINNING BY NANOPARTICLES USING LARGE-SCALE SIMULATIONS OF TIME-DEPENDENT GINZBURG-LANDAU EQUATIONS

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Vortex pinning by self-assembled nanoparticles is a very efficient route to enhance current-carrying capabilities of practical superconductors. We explored vortex pinning by randomly distributed metallic spherical inclusions using large-scale simulations of time-dependent Ginzburg-Landau equations (see Ref. [1] for description of the code). We found optimal size and density of the inclusions at which the highest critical current is achieved for fixed magnetic field. For better understanding of pinning mechanisms, we traced vortex lines and analyzed in detail statistical properties of vortex configurations. For every particle size the critical current reaches maximum at optimal particle density, typically corresponding to 15-22% of the volume fraction occupied by the particles, which is close to the percolation threshold. The optimal particle density increases with the magnetic field. Studying different particles sizes, we found that the optimal particle diameter is close to four coherence lengths. The figure shows the surface plot summarizing the dependence of the critical current on the particle diameter and density for the magnetic field equal to 10% of the upper critical field. The maximum corresponds to 6.6% of the depairing current. Our results provide guidance for pinning optimization in superconducting wires.

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TUNABLE ZERO–FIELD VORTEX RATCHET IN Nb THIN FILMS

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Superconducting thin films with asymmetric pinning potentials are known to show ratchet effect [1]. Asymmetry induces a preferential direction of motion for vortices. The origin of the potential asymmetry can be geometric, magnetic or a mixture of both.

We have grown superconducting Nb thin films on top of arrays of Co/Pd triangular pinning centers. Co/Pd multilayers show strong out-of-plane magnetic anisotropy, and magnetized Co/Pd triangles will produce intense stray fields in the Nb film, inducing several vortex-antivortex pairs per unit cell of the array. The presence of these V-AV pairs allows us to observe intense zero-field ratchet signal.

By reverting the magnetic state of the triangles, ratchet signal is also reverted. By carefully controlling the magnetic history of the triangles remanent magnetization can be tuned, and zero-field ratchet intensity can be continuously varied from $V_{\text{max}}$ to $-V_{\text{max}}$.

Ratchet sign and intensity can also be modified applying a magnetic field for a given magnetic state of the sample.
SUPERCONDUCTING HETEROSTRUCTURES: EXAMPLES OF ATTRACTIVE AND REPULSIVE PERIODIC PINNING ARRAYS

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We studied vortex lattice dynamics in ac susceptibility experiments in two heterostructures. The first one combines two type-II superconductors: a niobium film and a dense triangular array of submicrometric vanadium (V) pillars [1]. The second structure is a superconducting film grown on top of a two-fold symmetry array of submicrometric magnetic dots [2]. In the first case, a sudden increase in ac penetration, above a magnetic field, \( H^* (T) \), that decreases linearly with temperature, reveals a sudden decrease in pinning. Additionally, temperature independent matching effects, for one or two vortices per primitive cell, at \( H_1 \) and \( H_2 \) are observed. The angular dependence of \( H_1 \), \( H_2 \) and \( H^* (T) \) shows that matching is determined by the normal applied field component, while \( H^* (T) \) is independent of the applied field orientation. This important result identifies \( H^* (T) \) with the critical field boundary for the normal to superconducting transition of V pillars. Below (above) \( H^* (T) \), superconducting V pillars repel (attract) vortices, and matching effects are observed in both cases implying the presence of ordered vortex configurations for ‘anti-pinning’ or ‘pinning’ arrays. In the second studied heterostructure the induced ac currents flow parallel to the short and to the long side of the pinning array in different areas of the samples simultaneously. This behavior produces remarkable effects in the vortex lattice dynamics. Competing unstable vortex configurations seem to lead to an increase in vortex mobility precluding the reconfiguration transition, earlier reported in transport experiments. At high temperatures, the magnetic permeability of the dots is the mechanism that governs \( J_c \), while a crossover to pinning by interstitial point defects is observed as the temperature is reduced.

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WEAK-LINK SUPERCONDUCTIVITY IN MICROSTRUCTURED FILMS

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Although studied in depth before the 1980’s [1], weak-link (WL) superconductivity was brought to scene as a major player after discovery of superconductivity in ceramic cuprates [2]. The importance of WLs is closely related to the fact that, ultimately, it is their capability to transport supercurrents that defines the critical current of a granular sample. After almost three decades of dedicated studies aiming at producing high current-carrying granular materials of practical use, WL superconductivity in the micrometric scale is still an issue of undeniable importance.

Our approach to the study of WL superconductivity employs a toy-model system, comprising two rectangular superconducting islands (the grains) interconnected through a weak superconducting link. Samples are prepared starting from an excellent-quality superconducting film, with borders sharply defined using optical lithography. The WL is created by excavation of a submicrometric groove between the grains, made in a Focused Ion Beam (FIB) apparatus. Such a WL can be either a “through groove”, i.e., crossing the entire extension of the film all the way from one border to the opposite one; or a “contained groove”, in which case a frame of pristine material is left during the FIB excavation, to protect the WL from the exterior. Samples are investigated using global techniques, e.g., magnetometry and magneto-transport measurements, as well as local probing methods, such as micro-Hall sensing and magneto-optical imaging (MOI).

Among other relevant results [3], we have detected that, while decreasing the field in a hysteresis loop, an anomaly on the magnetization curve is seen, also manifested in MOI experiments as a sudden fade-out of the so-called d-lines. The complete understanding of the phenomenon was made possible by simultaneous measurements of the local magnetic fields at the superconducting islands and at the WL, demonstrating that the field-dependent critical currents at both regions become equal momentarily, being this the reason for the corresponding transitory suppression of the d-lines.

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The discovery of unexpected properties at the interfaces between complex oxides has triggered the launch of a novel field of research which has produced a number of exciting results in recent years. Modern growth technique allows controlling interface growth with atomic precision, which has raised the possibility of tailoring their electronic structure of interfaces for specific functionalities. Modified bonding at the interface has been shown to be the origin of an interesting form of interfacial magnetism at interfaces between magnetic and non magnetic oxides. Its origin is the new interfacial superexchange path and ideally it could be manipulated by external stimuli (strain or electric fields) through their effect on orbital symmetry and filling. In this talk I will examine several interface problems in oxide heterostructures with special focus on the possibility of creating novel interfacial magnetic states at the interface between a cuprate superconductor and a ferromagnetic manganite. I will discuss novel proximity phenomena arising from the induced spin polarization in the superconductor at the interface. Furthermore, I will discuss the possibility of novel forms of interplay between magnetism and superconductivity based on these these low dimensional magnetic states to tailor novel behaviors of interest in vortex physics.

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MICROWAVE SUPPRESSION OF NONLINEAR CONDUCTIVITY AND DISSIPATION LIMITS IN SUPERCONDUCTORS UNDER STRONG ELECTROMAGNETIC RF FIELDS

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Microwave suppression of dissipative nonlinear conductivity $\sigma_1(\omega, H_a)$ in the Meissner state of s-wave superconductors under strong electromagnetic fields $H(t) = H_a \cos(\omega t)$ at low temperatures $T << T_c$ is discussed. Solving the time-dependent Usadel equations in a nonequilibrium dirty limit shows that $\sigma_1(\omega, H_a)$ and the surface resistance $R_s(\omega, H_a)$ have a minimum as a function of the field amplitude $H_a$. The microwave suppression of $\sigma_1(\omega, H_a)$ caused by a low frequency ($\omega << T$) magnetic field mostly results from field-induced temporal oscillations of the quasiparticle density of states rather than the microwave stimulation of superconductivity [1]. The calculated field dependence $R_s(\omega, H_a)$ is in good agreement with recent experiments on alloyed Nb resonator cavities. Applying superimposed dc and ac fields, $H(t) = H_0 + H_a \cos(\omega t)$, can be used to reduce the rf dissipation in thin film nanostructures by tuning $\sigma_1(\omega, H_a)$ with the dc field, as was observed in earlier experiments on thin films. I will also discuss ways of increasing the field onset for penetration of vortices by thin film S-I-S multilayers or by dirty layers deposited on the surface of a superconductor. Such structures can fully screen the applied magnetic field exceeding the superheating fields $H_s$ of both the superconducting layers and the substrate, the maximum Meissner field is achieved at an optimum multilayer thickness [2].

The S-I-S layer structures also inhibit penetration of dendritic thermomagnetic vortex avalanches.

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MAGNETOTRANSPORT STUDIES OF GATED \textit{LaAlO}_3/\textit{SrTiO}_3\ INTERFACES

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The two-dimensional electron liquid (2DEL) present at the interface between the insulating oxides LaAlO$_3$ and SrTiO$_3$ exhibits several fascinating properties, including superconductivity and a large spin-orbit coupling \cite{1}. This system has attracted much attention for fundamental and applied studies due to the rich physics displayed and the possibilities offered to realize field-effect transistors and nanoscale devices \cite{2}. Both the superconducting transition temperature and the spin-orbit interaction are tunable by an electric field using the SrTiO$_3$ substrate as a back gate dielectric \cite{3,4}.

In this work, we report a detailed characterization of the magneto-transport and superconducting properties of top- and back-gated LaAlO$_3$/SrTiO$_3$ heterostructures. Efficient field effect tuning is achieved by using the LaAlO$_3$ film and SrTiO$_3$ substrate as top and back gate insulators respectively. A large asymmetry in the evolution of the sheet resistance, Hall resistance, and magneto-resistance is observed between top- and back-gate operation modes. These asymmetric behaviors might be explained by the different effects of the top and back gates on the confinement potential of the electrons. I will also mention some recent work on the realization of bi-interfaces.

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\end{enumerate}

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TOPOLOGICAL EXCITATIONS IN THE LaAlO$_3$/SrTiO$_3$ INTERFACE

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Interfaces are promising candidates for the construction of electronic devices based on high temperature superconductivity now that monolayers of iron selenide grown on top of the insulator LaAlO$_3$ were found with a critical temperature above the 100 K [1]. It is remarkable that in the interface between two insulators, LaAlO$_3$ and SrTiO$_3$, a two-dimensional electronic liquid is formed and displays the coexistence of magnetism and superconductivity. High-resolution magnetic torque magnetometry and transport measurements give direct evidence of magnetic ordering of this two-dimensional electron liquid at the interface from well below the superconducting transition to up to 200 K. Interestingly there is an in-plane magnetic moment that persists even to the lowest applied field perpendicular of 5 mT to the interface [2]. Superconductivity in the LaAlO$_3$-SrTiO$_3$ interface was shown to emerge with the appearance of strong spin–orbit interactions described by the Rashba term, arising from the breaking of structural inversion symmetry [3]. Here we propose the presence of topological excitations in this interface, which are admixtures of vortices and skyrmions to account for the torque measurements. Our theoretical framework allows for a fit of the experimental measurements of Lu-Li et al., given in Ref. [3], and is formulated from the kinetic energy of a quasi-two-dimensional condensate at the interface that evanesces away from it. Features such as the Rashba interaction and the breaking of the inversion symmetry stem from our approach, which is based on the topological equations [4], those being generalizations of the Abrikosov-Bogomolny equations of the Ginzburg-Landau theory [3]. The trapped magnetic field streamlines around the interface leads to the skyrmions solutions [5], and, in a resulting net magnetic moment oriented along the interface. Our fitting parameters to the experimental measurements are the distinct mass anisotropies and the heights at the two sides of the interface.

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SUPERCONDUCTING PROPERTIES OF Nb/Pb/Nb TRILAYER

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Fabrication of superconducting layered systems offers fascinating possibilities to observe novel superconducting phenomena. In this talk I will present results on the magnetic and electrical transport measurements a new nanostructured superconducting Nb/Pb/Nb trilayer [1] was grown by magnetron sputtering. The magnetization and resistivity have been analyzed as functions of the temperature and magnetic field applied perpendicularly to the layers. The sample presents sharp resistive and magnetic transitions at $T_C = 7.2$ K. Vortex avalanches attributed to thermomagnetic instabilities were observed in magnetization versus applied field loops. The temperature dependence of $\mu_0H_{c2}$ presents a positive upward curvature at low temperatures, indicating a crossover which is consistent with the Takahashi-Tachiki model for superconducting superlattices. The temperature dependence of the lower critical field $\mu_0H_{c1}(T)$ presents an unconventional feature consistent with a multicomponent behavior with spatially separated components.

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TERAHERTZ EMISSION AND C-AXIS TRANSPORT PHENOMENA IN HIGH-TEMPERATURE SUPERCONDUCTOR Bi₂Sr₂CaCu₂O₈₊δ SINGLE CRYSTALS

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The high temperature superconductor Bi₂Sr₂CaCu₂O₈₊δ (Bi-2212) is known to be composed of a stack of superconducting CuO₂ layers sandwiched by insulating Bi₂O₂ layers, forming multi-stacked intrinsic Josephson junctions (IJJs) along the c-axis. When the dc voltage is applied to a mesa structure fabricated from Bi-2212 single crystals by bringing it in the resistive state, strong, coherent and continuous electromagnetic waves (EMWs) can be generated [1,2]. The reason for this fascinating phenomenon is so far understood by the two fundamental principles regarding EMW emission from charged particles. The first one is the ac-Josephson effect occurring across an individual IJJ junction[3], and the many stacked IJJs work coherently, exciting the collective Josephson plasma (Jp) mode along the c-axis (in fact it is the longitudinal plasma mode). This Jp mode is selectively enhanced by the second principle, i.e., the cavity resonance determined by the geometrical shape of the mesa, which actually confines the superconducting electrons within a box. The emission frequency is determined by the ac-Josephson relation: \( f_{J} = \frac{2eV}{h} \), where \( V \) is the voltage appearing across the double CuO₂ layers of the IJJ, \( e \) and \( h \) are the elementary charge and the Planck constant, respectively. This relation has been well proven experimentally [4,5]. It has also been proved that the longitudinal Jp (Jp) mode is nothing but the Nambu-Goldstone mode of the superconducting electrons with an energy gap (Anderson-Higgs-Kibble) at \( k_z = 0 \) [6]. It is well established in a conventional s-wave superconductor that the energy gap \( \Delta E_{Jp} \) is determined by the superconducting gap \( 2\Delta \). In Bi-2212 however, widely believed to be a d-wave superconductor, surface measurements indicate that the gap energy varies depending on the \( k \) direction from zero to the maximum gap \( 2\Delta_{\text{max}} \sim 30-60 \text{ meV} \), depending on the doping level [7]. Experimentally, the observed EMWs are monochromatic and lie in the THz range for frequencies up to 2.4 THz (\( \sim 10 \text{ meV} \)), which strongly suggests the existence of a minimum \( \Delta_{\text{min}} \sim 5 \text{ meV} \) in the superconducting state. Some implications of the finite gap observed in Bi-2212 in the THz emission phenomena will be discussed.
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STRONG THERMAL FLUCTUATIONS IN CUPRATE SUPERCONDUCTORS IN MAGNETIC FIELD ABOVE $T_c$

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Recent measurements of fluctuation diamagnetism in high temperature superconductors show distinct features above and below $T_c$, which cannot be explained by simple gaussian fluctuation theory. Self consistent calculation of magnetization in layered high temperature superconductors, based on the Ginzburg-Landau-Lawrence-Doniach model and including all Landau levels is presented. The results agree well with the experimental data in wide region around $T_c$, including both the vortex liquid below $T_c$ and the normal state above $T_c$. It is demonstrated that the intersection point of magnetization curves appears in the region where the lowest Landau level contribution dominates and magnetization just below $T_c$ is nonmonotonic. Our calculation supports the phase disordering picture of fluctuations above $T_c$. The transport properties like fluctuation conductivity and Nernst effects will be also studied here within time dependent Ginzburg Landau theory.

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OPTICAL OBSERVATION OF UNUSUAL SUPERCONDUCTIVITY PRECURSOR IN YBa$_2$Cu$_3$O$_y$

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We have systematically studied the c-axis polarized optical spectra for Zn-doped YBa$_2$Cu$_3$O$_y$ over a wide range of oxygen and Zn-contents. Subtracting the normal components carefully, we found finite superconducting condensates at the temperatures far above Tc but below the pseudogap temperature T*. This temperature for precursor of superconductivity (T$_p$) is sensitive to the Zn-doping like Tc, which indicates that this phenomenon is linked to superconductivity but different from the pseudogap. On the other hand, the carrier doping dependence of T$_p$ is similar to that of T*, namely, T$_p$ increases with underdoping.

These results suggest that as the system approaches a Mott insulator the pairing interaction becomes stronger but the simultaneously developed competing order (pseudogap) suppresses superconductivity. Although these two (superconductivity and pseudogap) are distinct orders, they may originate from the same interaction (strong correlation with large U).

Since our recent study of oxygen isotope effect in YBa$_2$Cu$_3$O$_y$ suggests that the charge channel is involved in the competing order, the coexistence of spin and charge order such as the stripe order could be the origin of the pseudogap. The recently reported charge density wave near T$_p$ can be understood along this line.

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UPPER CRITICAL FIELD IN MULTIBAND ANISOTROPIC SUPERCONDUCTORS WITH SCATTERING

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The problem of the orbital upper critical field, \(H_{c2}(T)\), is extended (from the original Helfand and Werthamer (HW) theory) to the cases of arbitrary Fermi surface, multiband superconductivity and presence of magnetic and non-magnetic scattering. A variety of different temperature–dependent behaviors of \(H_{c2}(T)\) and its anisotropy for \(\parallel ab\)-plane and \(\parallel c\)-axis directions is found. For comparison with the experiment, results in single crystals of iron-based superconductor, \(\text{Ba}_x\text{K}_x\text{Fe}_2\text{As}_2\), will be presented. Specifically, we study the evolution of \(H_{c2}(T)\) with the superconducting transition temperature, \(T_c\), changed in two ways – by potassium doping level, \(x\), and due to pair-breaking effects of a controlled point-like disorder introduced by 2.5 MeV electron irradiation. The upper critical field response is opposite in these two cases. If time permits, the question of the determination of the type of superconductivity will be discussed. We show that conventional boundary based on Ginzburg-Landau parameter \(\kappa=\lambda/\xi\) is not a good criterion at any temperature, except for \(T_c\). We suggest a new criterion based on the ratio of the upper and thermodynamic critical fields and discuss some unusual predictions that in low-\(\kappa\) materials the type of superconductivity may change from type-II to type-I with increasing magnetic scattering, changing temperature and even orientation of the magnetic field with respect to anisotropic superconducting sample.

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A FIELD-DRIVEN STRUCTURAL TRANSFORMATION OF THE JOSEPHSON VORTEX LATTICE IN HIGHLY ANISOTROPIC Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ SINGLE CRYSTALS

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Due to its highly anisotropic crystal lattice, the cuprate superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) plays host to two orthogonal vortex species that can coexist in tilted fields, and interact to form crossing vortex lattices.[1,2] It is well known that within London theory, and in the absence of out-of-plane fields, the in-plane Josephson vortex (JV) lattice exhibits two energetically degenerate structures, with stack spacings $c_y = \sqrt{\gamma_{eff}} \frac{\Phi_0}{2\sqrt{3}B_x}$ and $\sqrt{3}\gamma_{eff} \frac{\Phi_0}{2B_x}$ respectively, where $\gamma_{eff}$ is the effective anisotropy parameter and $B_x$ is the in-plane magnetic induction. Here we employ ac magnetic field “dithering” techniques [3] to realise equilibrium lattice configurations in a largely unexplored magnetic field regime. Vortex-resolved scanning Hall probe microscopy measurements of crossing vortex lattices have been used to extract systematic field dependencies of the JV stack spacing in this regime. We observe, for the first time, a decrease in $c_y$ at constant $B_x$ driven by the perpendicular magnetic field, corresponding to a transformation in the JV lattice between the two degenerate structures. Furthermore, the JV stack spacing exhibits clear oscillations as a function of in-plane field as a consequence of the nucleation of discrete numbers of rows of interstitial pancake vortices between them. Our experimental results are in reasonable qualitative agreement with theoretical calculations.

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We will report the studies on vortex physics in two superconducting systems: Ta₄Pd₃Te₁₆ and Ba₁₋ₓKₓBiO₃.

The Ta₄Pd₃Te₁₆ is a newly discovered superconductor with $T_c = 4.5$ K. Here we report results based on the scanning tunneling microscopy/spectroscopy measurements on this new superconductor. The chain-like conducting channels of PdTe₂ in Ta₄Pd₃Te₁₆ make a significant anisotropy of the in-plane Fermi velocity. We suggest at least one anisotropic superconducting gap with gap minima or possible node exists in this multiband system. In addition, elongated vortices are observed with an anisotropy of $\frac{\xi_{b}}{\xi_{\perp}} \approx 2.5$. Our results will initiate the study on the elongated vortices and superconducting mechanism in the new superconductor Ta₄Pd₃Te₁₆.[1]

We have also conducted extensive investigations on the magnetization and its dynamical relaxation on Ba₁₋ₓKₓBiO₃ single crystals. It is found that the magnetization relaxation rate is rather weak compared with that in the cuprate superconductors, indicating a high collective vortex pinning potential (or activation energy). Detailed analysis leads to the following discoveries: (1) A second-peak (SP) effect on the magnetization-hysteresis-loop was observed in a very wide temperature region. Its general behavior looks like that in YBCO; (2) Associated with the second peak effect, the magnetization relaxation rate is inversely related to the transient superconducting current density; (3) A detailed analysis based on the collective creep model reveals a large glassy exponent $\mu$ and a small intrinsic pinning potential $U_c$. Finally, a vortex phase diagram is drawn for showing the phase transitions or crossovers between different vortex phases[2].

In collaboration with: Zengyi Du, Jian Tao, Delong Fang, Zhenyu Wang, Yufeng Li, Guan Du, Huan Yang and Xiyu Zhu

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SUPERCONDUCTIVITY OBTAINED BY NON-EQUILIBRIUM SYNTHESIS
–β-Bi₂Pd AND THIN FILMS OF Fe CHALCOGENIDES–

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Preparation of crystals by nonequilibrium technique is extremely useful in many cases. In this presentation, we introduce two such examples of superconductors; (1) β-Bi₂Pd, which can be obtained only by rapid quenching from high temperatures, and (2) the so-called 11 Fe chalcogenides, FeSeₓTe₁₋ₓ, with x covering whole range between 0 and 1, which are obtained only in the form of thin films.

β-Bi₂Pd is a superconductor with Tc=5.4 K[1]. Specific heat data and upper critical field data suggest that this material is a new member of multi-gap superconductor[1]. Subsequent band calculation also showed that the material has complicated band structure with many Fermi surfaces. Particularly interesting is that the material is considered to be a topological material with the characteristic surface state. We performed the complex conductivity measurement at microwave frequencies. The data clearly exhibits the manifestation of multi-gap superconductivity. Details, together with the point contact spectroscopy data and flux flow data, will be presented.

Fe chalcogenides are interesting in the sense that the materials have good potential as a very high Tc superconductors. Indeed, early study of application of pressure, K substitution, intercalation of several molecules, fabrication of monolayer film on STO; all of these approaches lead to higher Tc. Thus, systematic study of physical properties in Fe-chalcogenides are important to realize higher Tc in a controllable manner. However, the 11 chalcogenides, FeSeₓTe₁₋ₓ, has a large region of phase separation between x=0.1 and x=0.4, and the 122 chalcogenide always has a mesoscopic phase separation, which hinders systematic studies. Recently, we succeeded in obtaining FeSeₓTe₁₋ₓ films with x values covering the whole range from x=0 to x=1 using the PLD technique[2]. Resultant Tc takes the maximum value, 23.5 K, which is about 1.5 times as large as the maximum value in bulk crystals, at x=0.2, which used to be in the phase separation region, and decreased suddenly at x=0.1. In order to investigate the origin of these behaviour, the upper critical fields in various field directions, and Hall effect are now investigated, and will be presented in the meeting.

As for the 122 chalcogenides, we will represent a direct evidence of mosaic structure in the complex conductivity using microwave microscope developed by ourselves[3].
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SPECTROSCOPIC-IMAGING STM STUDIES OF VORTICES IN FeSe

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In contrast to its simple crystal structure, the electronic structure of the iron-based superconductor FeSe (T_c ~ 9 K) is rich and attractive in various aspects. First, the superconductivity occurs in the non-magnetic orthorhombic phase, which is related to the orbital ordering [1]. Second, FeSe possesses node in the superconducting gap [2]. Third, effective Fermi energy is as small as the superconducting gap amplitude; FeSe is in the BCS-BEC crossover regime [3]. These features should result in non-trivial electronic states around the local defects such as vortices and impurities. Here we performed low-temperature spectroscopic-imaging STM on high-quality single crystals of FeSe to investigate the spatial variation of electronic states in and around the vortex core.

Figure shows the image of single vortex obtained by mapping the tunnelling conductance at the Fermi energy. Apparently, vortex-core state exhibits strong in-plane anisotropy [2], which may be associated with the gap node and/or anisotropic Fermi velocity due to orbital ordering. Spatial evolutions of the vortex-core states along the principle axes are also shown in the Figure. The conductance evolution along the horizontal (shorter) direction is smooth and particle-hole symmetric. On the contrary, there appears oscillatory behaviour along the vertical (longer) direction, where the intensities of vortex bound states exhibit anti-correlation between filled and empty states. Such a feature is characteristic of vortex core in the quantum limit [4], being consistent with the small Fermi energy.

This work has been done in collaboration with the groups of Prof. Y. Matsuda (Kyoto), Prof. C. Meingast (Karlsruhe) and Prof. H. v. Löhneysen (Karlsruhe).

Figure:
Tunneling conductance map at the Fermi energy and its linecuts along the principle axes (Fe-Fe directions). Data were taken on the in-situ cleaved (001) surface at temperature 0.4 K and magnetic field 0.1 T perpendicular to the surface.
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EXOTIC SUPERCONDUCTIVITY OF FeSe IN THE BCS-BEC CROSSOVER REGIME

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Uniquely amongst the Fe-based superconductors, the tetragonal FeSe undergoes an orthorhombic distortion at 90 K without an accompanying long-range magnetic ordering at any temperature, and therefore provides a unique opportunity to probe its unusual electronic behavior from which its superconductivity emerges below 9 K.

We show that the pure single crystals of superconducting FeSe offer the possibility to enter the previously unexplored realm where the three energies, Fermi energy, superconducting gap, and Zeeman energy, become comparable. Through the superfluid response, transport, thermoelectric response [1], and quantum oscillations [2,3], we demonstrate that the Fermi energy of FeSe is extremely small, with the ratio of the gap to Fermi energy is of the order of unity. Moreover, thermal-conductivity measurements give evidence of a distinct phase line below the upper critical field, where the Zeeman energy becomes comparable to Fermi energy and the gap [1].

Moreover, the torque magnetometry reveals distinct diamagnetic signal below ~20 K indicating that the superconducting fluctuations above the transition temperature are strongly enhanced from the standard Gaussian theory [4]. The results provide strong evidence for preforming Cooper pairs in FeSe.

These observations provide insights into previously poorly understood aspects of the strongly interacting electrons in the BCS-BEC cross-over regime.

This work has been done in collaboration with S. Kasahara, T. Watashige, T. Hanaguri, T. Yamashita, Y. Shimoyama, Y. Mizukami, R. Endo, H. Ikeda, K. Aoyama, T. Terashima, S. Uji, M. D. Watson, A. I. Coldea, W. Knafo, M. Nardone, J. Beard, T. Wolf, F. Hardy, C. Meingast, H. von Lohneysen, A. Levchenko, and Y. Matsuda.

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ANOMALOUS CRITICAL FIELDS IN QUANTUM CRITICAL SUPERCONDUCTORS

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BaFe2(As0.3P0.7)2 presents one of the cleanest and clearest systems in which to study the influence of quantum critical fluctuations on high temperature superconductivity. In this material a sharp maximum in the magnetic penetration depth has been found at the quantum critical point (QCP x=0.3) where T_c is maximal [1]. Specific heat and de Haas-van Alphen effect measurements [2] show that this peak is driven by a corresponding increase in the quasiparticle effective mass. Based on these previous results a simple one-band theory would suggest that at the QCP we should expect a large increase in H_c2 and a corresponding dip in H_c1. Actual measurements of these critical fields, which we present here, shows quite different behavior, which we suggest, is caused by an anomalous enhancement in the vortex core energy close to the QCP.

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PEAK EFFECT AND VOERTEX LATTICE STRUCTURAL TRANSITION IN
OPTIMALLY DOPED Ba$_{1-x}$K$_x$Fe$_2$As$_2$

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We have used small-angle neutron scattering to study the vortex lattice (VL) in high quality optimally doped Ba$_{1-x}$K$_x$Fe$_2$As$_2$ single crystals. Where previous SANS studies, as well as real-space imaging methods have consistently reported highly disordered vortex structures in single crystalline Ba$_{1-x}$K$_x$Fe$_2$As$_2$, Co$^-$, and P-substituted BaFe$_2$As$_2$ [1]-[7], the present SANS study reveals sharp vortex lattice Bragg peaks. This is the first iron-based superconductor, apart from the “clean” end compound KFe$_2$As$_2$ [8], in which a triangular VL is observed.

In this contribution we present SANS data taken in a magnetic field ranging between 0.25 and 2 Tesla, performed on optimally doped Ba$_{1-x}$K$_x$Fe$_2$As$_2$. The data show clear resolution-limited Bragg spots, indicating the existence of a long-range ordered vortex phase. The magnetic field dependence of the vortex structure factor, obtained by correction of the intensity by the field-dependent vortex form factor, shows a sharp drop well below the second critical field. This vortex structural transition shows a clear correlation with features observed around the so-called “second magnetization peak” observed in isothermal hysteresis loop measurements, and the behavior of magnetic hysteresis between zero-field cooling and field-cooling.

Results are discussed in the framework of the origin of the peak effect transition in High temperature superconductors. The precise role of field cooling and vortex quenching is also explicitly discussed.

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THE CAMPBELL LENGTH IN THE PRESENCE OF STRONG VORTEX PINNING

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The two prevailing paradigms in the description of vortex pinning are the weak collective pinning theory, successfully applied to high-\(T_c\) superconductors, and the strong pinning theory relevant for novel materials such as organic and pnictide superconductors. Recent work on strong vortex pinning addressed the critical current as well as the full current-voltage characteristics, providing both qualitative and quantitative results [1]. Here, we study the ac-response of a vortex lattice in type-II superconductors under strong pinning conditions and provide quantitative results for the ac penetration depth \(\lambda_C\), the so-called Campbell length. Contrary to the common belief that \(\lambda_C\) is related to the curvature (second derivative) of the pinning potential at its minimum, we show that the Campbell length relates to the slope (first derivative) of the potential, evaluated at a position that depends on the preparation of the state, e.g., field cooled or zero-field cooled (Bean state). Consequently the Campbell length differs (in some cases even parametrically) for different modes of sample preparation. We find that under specific conditions \(\lambda_C\) exhibits hysteretic behavior upon thermal cycling. Our theory agrees well with recent experiments by Prozorov et al. [2] probing different vortex states and opens the possibility for a detailed characterization of the pinning landscape.

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INTRINSIC AND EXTRINSIC PINNING IN Fe- AND Cu-BASED SUPERCONDUCTORS

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Besides strong thermal fluctuations due to the small coherence length and relatively high critical temperature, vortex matter in Fe and Cu-based superconductors share other characteristics such as their layered structure. This intrinsic layering gives rise to the electronic mass anisotropy as well as a periodic planar pinning potential. Depending on the insulating layer size the anisotropy of the compound can vary from close to 1 up to hundreds for Bismuth- or Mercury-based superconductors.

The relative size of the coherence length and the insulating layers has important consequences in determining how vortices are trapped by this pinning potential. The effect on vortices, also known as intrinsic-pinning, of these periodic planar potentials should not depend on the specifics of different materials but rather be universal.

Angular dependent critical current measurements are extremely useful to determine in which way vortices are trapped and how effective different pinning centers are. It is also important to extract all the information available about vortex dynamic from non-linear transport experiment; namely analyze the power-law dependence often found between electric field and applied current. The exponent $N$, gives important microscopic information about the depinning processes that vortices undergo.

In this talk I will show transport measurements, consistent of critical current and $N$ values, of the different angular regimes of the vortex dynamics that confirm the generality of the intrinsic pinning found in YBCO films as well as in iron based superconductors.

I will explore theoretical description of these angular regimes, both in the 3D vortex regime where vortices are considered as continuous lines, as well as in the 2D regime where vortices along the ab-planes are considered to be pancake like.

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COMPARATIVE ANALYSIS OF VORTEX PINNING AND DYNAMICS IN OXIDE, IRON-BASED AND MgB₂ SUPERCONDUCTORS

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Since the discovery of the oxide high temperature superconductors (HTS) two driving forces have sustained the interest on vortex physics, on one hand the attractive new physics and on the other the pursuit of technological uses. The complex vortex phenomena in these materials arise from the strong influence of thermal fluctuations, which is a consequence of the small superconducting coherence length (ξ) and the large anisotropy (γ). Paradoxically these fluctuations are a big obstacle for applications; moreover the problem is general and will also occur in any new-discovered superconductor operating at high temperatures. The control of vortex matter for performance enhancement requires the design of the pinning landscape by nano-engineering of the material disorder at the scale of ξ, a few nm in HTS. Although the HTS vortex behavior contrasts with the simpler physics in conventional low Tc superconductors, there is no sharp boundary between them. However, modern vortex matter models have been developed to describe the oxide HTS, thus it is important to test them in different systems. Our approach is to perform comparative studies on a variety of materials covering a broad spectrum of properties. The iron-based superconductors provide an opportunity to “bridge the gap” and check the validity of vortex models in a new family of materials with broad ranges of Tc, ξ and γ. On the other hand, the multi-band superconductivity in the Fe-based compounds introduces a new level of complexity, requiring a re-evaluation of the concept of anisotropy in the vortex behavior. Valuable information can also be obtained from MgB₂, a chemically simpler two-band superconductor.

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DYNAMIC AND STRUCTURAL STUDIES OF THE METASTABLE AND GROUND STATE VORTEX LATTICE DOMAINS IN MgB₂

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The vortex lattice (VL) in type-II superconductors depends sensitively on the anisotropy of the screening current plane, and in many cases undergoes a structural phase transition as the magnetic field and/or temperature is varied. In the case of MgB₂, the ground state VL is always triangular but undergoes a continuous, second-order rotation transition. Our small-angle neutron scattering (SANS) studies of the VL in MgB₂ have revealed an unprecedented degree of metastability, which is unexpected for a second-order phase transition and can not be understood based on the single VL domain free energy [1]. Further SANS studies provided definitive proof that the VL metastability is not the result of vortex pinning [2], and raised the question of what novel mechanism is responsible for the observed behavior?

To address this question we have used a stop-motion technique to study the metastable to ground state transition dynamics, and recently combined this with structural studies of the VL. Extensive measurements were performed on the MgB₂ VL as it was driven from a metastable to the ground state by a controlled number of small-amplitude AC magnetic field cycles [3]. This revealed a two-step power law behavior, indicating a slow nucleation of ground state domains followed by a faster growth. The observed power-laws constitute a novel kind of VL dynamics, reminiscent of jamming of soft, frictionless spheres. Although granular jamming has been applied to individual vortices flowing through superconductors with artificially engineered pinning potentials, this is the first time it has been proposed for vortex lattice domains acting as granular entities. Regardless of whether jamming is ultimately responsible for the metastability, our results demonstrate the importance of VL domains that have to date not been studied in detail.

Structural studies were carried out to investigate possible differences in the VL ordering between metastable and ground state VL domains. Furthermore spatially resolved SANS measurements were able to resolve the VL domain distribution within the MgB₂ single crystal, providing limits an upper limit on size of both metastable and ground state domains.

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**VORTEX CONFIGURATIONS AND VORTEX DYNAMICS IN LAYERED SUPERCONDUCTORS WITH RANDOM PINNING: NUMERICAL STUDY**

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Vortex configurations and vortex dynamics in layered superconductors were studied by molecular dynamics (MD) simulation. Various static configurations were characterized by calculating radius distribution function (RDF) and the inter-layer correlation function. We constructed a static phase diagram in the plane ‘pinning strength $f_p$- inter layer coupling strength $s_m$’ and studied vortex dynamics and hysteretic effects for various $f_p$ and $s_m$. By reducing dimension, vortices in systems with infinite length in the direction perpendicular to the superconducting layer were studied. We calculated the static configurations for various pinning strength $f_p$ and vortex density $n$. A new explanation to the “second magnetization peak effect” was proposed.

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DIRECT EVIDENCE OF BULK DYNAMIC VORTEX MATTER REORDERING IN THE ORDER-DISORDER TRANSITIONAL REGION

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The order-disorder transition (ODT) in the vortex matter of type II superconductors and the associated history effects have been subject of study and controversies for many years. In materials with very low pinning, as clean NbSe2, most of the vortex phase diagram is well described by a dislocation free Bragg Glass (BG) phase that, with increasing field and/or temperature undergoes an ODT to a strongly pinned disordered phase. The fingerprint of the transition is the sudden rise of the effective pinning known as Peak Effect (PE). While a field-cooled (FC) vortex lattice (VL) remains trapped below the PE in a disordered metastable configuration, it can reach the stable ordered BG with the help of high dc currents or large shaking magnetic fields. In this framework, the existence of an in-between transitional region has been reported[1,2], where effective pinning can be partially decreased or even increased by applying dc currents or ac fields, yielding highly reproducible intermediate final responses independent of any previous history. In our earlier work[1,3] we have proposed that these “in-between” responses are originated from bulk VL configurations with intermediate degree of disorder, accessible from stationary dynamic states. In this work[4] we present results obtained in a recent experiment, combining small angle neutron scattering (SANS), with in-situ linear ac susceptibility measurements in a clean NbSe2 single crystal. Our findings show a clear connection between the linear ac response, related to the effective pinning, and the bulk spatial correlation of the VL. Configurations with intermediate degree of disorder were obtained by shaking the VL in the proposed transitional region, and remained traceable down to low temperatures. Our findings support the existence of the transitional region where, for the first time, a dynamic reordering into robust bulk configurations with intermediate degree of disorder was directly evidenced.
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STEPWISE DISORDERING OF THE VORTEX LATTICE THROUGH SUCCESSIVE DESTRUCTION OF POSITIONAL AND ORIENTATIONAL ORDER IN A WEAKLY PINNED $\text{Co}_{0.0075}\text{NbSe}_2$ SINGLE CRYSTAL

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The vortex lattice in a Type II superconductor provides a versatile model system to investigate the order-disorder transition in a periodic medium in the presence of random pinning. Using scanning tunnelling spectroscopy in a weakly pinned $\text{Co}_{0.0075}\text{NbSe}_2$ single crystal, we show that the vortex lattice in a 3-dimensional superconductor disorders through successive destruction of positional and orientational order, as the magnetic field is increased across the peak effect. At the onset of the peak effect, the equilibrium quasi-long range ordered state transforms into an orientational glass through the proliferation of dislocations. At a higher field, the dislocations dissociate into isolated disclination giving rise to an amorphous vortex glass. We also observe that the orientation of the vortex lattice is strongly pinned to the crystal lattice at fields larger than 5 kOe. In addition, we also observe a variety of additional non-equilibrium metastable states, which can be accessed through different thermomagnetic cycling.

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IMAGING ATOMIC-SCALE EFFECTS OF HIGH ENERGY ION IRRADIATION ON SUPERCONDUCTIVITY AND VORTEX PINNING IN Fe(Se, Te)

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The maximum sustainable supercurrent density, $J_C$, may be greatly enhanced by preventing dissipative motion of quantized vortices. Irradiation of superconductors with heavy ions is often used to create nanoscale defects with deep pinning potential for the vortices and this approach holds great promise for high current applications of iron-based superconductivity. However, for these compounds virtually nothing is known directly about the atomic-scale interplay between the crystal damage from high-energy ions, the superconducting order parameter, and the vortex pinning processes. Here, we visualize the atomic-scale effects of irradiating FeSe$_{0.45}$Te$_{0.55}$ with 249 MeV Au ions and find two distinct forms of damage: compact regions of crystal disruption ascribable to the actual ion trajectory along with single atomic-site ‘point’ defects. We show directly that the superconducting order is virtually annihilated within the former while it is strongly altered by the latter. Simultaneous atomically-resolved images of the crystal defects, the superconducting density-of-states, and the vortex cores, then reveal how the vortex pinning evolves with increasing field in irradiating FeSe$_{0.45}$Te$_{0.55}$ [1].

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DYNAMICS OF CORE-LESS ABRIKOSOV VORTICES

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One usually considers two types of vortices in superconductors, Abrikosov vortices in the bulk and Josephson vortices inside the Josephson junction or in strongly layered superconductors when the magnetic field is parallel to the layers. There are situations where vortices are something in between. Away from the core they look like conventional Abrikosov vortices, but inside the core the order parameter is not fully suppressed. Examples are vortices on plane defects or junctions with transparency \( \sim 1 \) (they are similar to Abrikosov Josephson vortices introduced in [1], and vortices in layered superconductors with relatively low anisotropy \( \xi_c \ll d \), [2]. For both examples the order parameter inside the core is not fully suppressed, thus they don't have an Abrikosov core. On the other hand, when the transparency of the boundary (or the anisotropy) is \( \xi_c \leq 1 \), one cannot talk about a Josephson core anymore. This incomplete suppression of the order parameter in the core does not affect the properties of the vortex in the London region. Also if the order parameter drops, e.g., to the half of the equilibrium value within the same coherence length, pinning would be qualitatively the same. However, the low temperature dynamics of such a vortex would be completely different. A non-vanishing order parameter induces an energy gap for quasi-particles and thus their absence at low temperatures. As a result, the Bardeen Stephen dissipation vanishes when \( T \rightarrow 0 \). The dynamics then would be given by the electromagnetic vortex mass. In weakly layered materials this vanishing dissipation can be probed by measuring of the imaginary part of the ac susceptibility (penetration depth measurement) for both dc and ac fields parallel to the layers. The current voltage curve would show hysteresis with a voltage jumping from zero below the critical current to a finite voltage \( \sim B \nu_0/c \) with \( \nu_0 \sim \Delta \xi_c \), where \( \xi_c \) is the appropriate core dimension along the vortex motion.

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NEW LIGHT ON THE ELECTRONIC VORTEX CORE STRUCTURE AND NORMAL STATE IN YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-δ}

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The interaction responsible for high-temperature superconductivity in the cuprates has remained elusive until now. Various charge orders suggest that the electronic matter in these compounds experiences competing interactions, while some spectroscopic data support the scenario of preformed pairs gaining coherence at low temperature. The vortices offer a chance to disentangle the spectral features related to pairing from those that are unrelated. In this context, the observation of discrete low-energy states in the vortex cores [1] has been a considerable challenge for the theory, because the expected tunneling spectrum in a vortex of $d_{x^2-y^2}$ symmetry presents a broad continuous maximum centered at zero bias. We performed high-resolution STM measurements in optimally doped YBa$_2$Cu$_3$O$_{7-δ}$ single crystals, and found that the low-energy states are not exclusively bound to vortices. This spectral feature is ubiquitous in zero field, even in spectra without superconducting coherence peaks. The new phenomenology reshuffles the cards for the theory of vortex cores.

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CRYOGENIC MEMORY ELEMENT BASED ON A SINGLE ABRIKOSOV VORTEX

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Growing power consumption in supercomputers is becoming an increasing problem. For an exaflop computer it is predicted to be on a hundred MW level [1]. Such power dissipation is unmanageable for the present semiconductor-based technology. The corresponding costs exceed the cost of refrigeration of the system to cryogenic temperatures. Therefore, efforts are taken for development of superconducting computers [2], which would not only drastically decrease the consumed power, but could also greatly increase the operation speed. The “main obstacle to the realization of high performance computer systems and signal processors based on superconducting electronics” [3] is a lack of suitable cryogenic random access memory (RAM). Today the most developed superconducting RAM is based on a storage of a flux quantum in a SQUID loop [4]. However, such RAM is difficult to miniaturize due to a finite SQUID loop size, complex read/write architecture and a major scalability problem in the write circuit [3].

It was shown previously that a single Abrikosov vortex in a mesoscopic superconducting structure can be used for storing a bit of information [5]. This work presents a proof of principle for a simple superconducting memory cells, in which the information bit is stored as a single Abrikosov vortex (AV). The AV is trapped at an artificial pinning center in a thin superconducting electrode, which simultaneously acts as a read and write line. We demonstrate controllable, high endurance write and erase operation by short current pulses, as well as two different ways of readout using an in-situ spin valve or a Josephson junction. The latter provides an infinite magnetoresistance between 0 and 1 states. We show that such an AVRAM cell can be scaled down to submicron size, limited by the smallest length scale for storing magnetic information in superconductors - the London penetration depth ~100 nm.

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In this talk we will discuss the spectroscopic signatures of vortex cores in superconductors recently revealed by Scanning Tunneling Spectroscopy. Starting from the well-known case of Abrikosov vortex lattice in bulk materials, we will present several cases emerging in nano-structured superconductors.

We will first focus on effects of lateral confinement in superconducting islands of a size close to the coherence length [1]. Then we will discuss the vortex phases observed in ultra-thin films such as single atomic layers of Pb grown on Si(111). We will show that in these ultimate superconductors two kinds of vortices, namely Abrikosov (Pearl) and mixed Abrikosov-Josephson vortices [2], coexist [3]. Finally, we will demonstrate that Josephson vortices inside S-N-S Josephson junctions are also characterized by normal cores, and can be measured by Scanning Tunneling Spectroscopy [4].

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DIRAC SURFACE STATES AND SUPERCONDUCTIVITY IN NONCENTROSYMMETRIC BiPd

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The absence of a center of inversion symmetry in materials which exhibit a strong spin-orbit coupling lifts the spin degeneracy due to the so-called Rashba effect. Thus, their Fermi surfaces show an intricate spin texture. The order parameter of the superconducting state arising in this kind of materials will generally contain an admixture of singlet and triplet character [1-3]. In this talk, I will present a study in noncentrosymmetric BiPd, where we have examined the possible triplet component of its superconducting pairing wavefunction by combining macroscopic experiments, atomic-scale-ultra-low-temperature scanning tunnelling spectroscopy and relativistic first-principles calculations [4]. The superconducting phase of this material appears to be topologically trivial and follows BCS theory; however, its normal-state band structure shows the appearance of Dirac-cone surface states.

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Transport measurements on a square array of superconducting islands placed on a normal metal reveal vortex Mott insulator and dynamic Mott insulator-to-metal transition. We demonstrate dynamic scaling behaviour of differential resistivity near the Mott critical points as function of the applied current and magnetic field and establish that Mott dynamic transitions at integer and fractional filling factors belong in different universality classes. Using quantum mechanics-statistical physics mapping we derive critical exponents for Mott transition. The experimentally determined critical exponents are in excellent agreement with the values expected from the out-of-equilibrium mean field considerations. We demonstrate that the dynamics of the vortex Mott state is governed by the thermally activated vortex motion establishing thus the real physical content of the quantum mechanics-statistical physics mapping where thermally activated dynamics of classical objects corresponds to quantum tunnelling of quantum particles.

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LITTLE-PARKS OSCILLATIONS IN AN INSULATOR

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When the disorder of a superconducting material is high enough it can undergo a transition into an insulating state. Paradoxically, this insulating state has been suggested to arise from superconductivity itself. We have conducted a study of a highly disordered InO films that were patterned with an array of holes. With the right treatment, the films could be driven across the superconductor-insulator transition. We found that the Little-Parks oscillations in the superconducting state persisted, virtually uninterrupted, into the insulator, supporting the role played by superconducting correlations in the insulating phase.

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TRUE VERSUS GHOST BEREZINSKII-KOSTERLITZ-THOULESS TRANSITION IN TWO-DIMENSIONAL SUPERCONDUCTORS

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We study the Berezinskii-Kosterlitz-Thouless (BKT) transition in thin disordered superconducting TiN film. The BKT transition is a binding-unbinding phase transition that occurs in two-dimensional (2D) systems of particles with logarithmic interaction. The BKT transition is a central paradigm to physics of 2D superconductors, which is at the heart of the nature of intriguing Bose metal and Cooper pair insulator states, and its observation is the focal point of the current experimental studies of 2D superconducting systems. One of the widely used tools to identify this transition is the monitoring of the drastic change from the linear to the power law behavior of the current-voltage ($I$-$V$) dependences when going across $T_{\text{BKT}}$. Here we present an experimental evidence for the two distinct BKT-transition-like evolutions of $I$-$Vs$ in the progression to superconductivity \cite{1,2}. We show that it is the lower-temperature $I$-$V$'s change that marks the true BKT transition, while the higher temperature ghost BKT transition-like behavior stems from electron-phonon decoupling favored by diverging lifetime of fluctuation Cooper pairs on approach to the critical superconducting temperature, $T_c$. We uncover the underlying mechanisms of the nonlinear transport at and near the superconducting transition and identify and separate intertwined effects of quantum superconducting fluctuations, electron-phonon decoupling, and BKT topological phenomena.

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METALLIC GROUND STATES AND ENHANCED UPPER CRITICAL FIELDS IN ELECTRIC-FIELD-INDUCED SUPERCONDUCTORS

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Along with the recent developments of electric double layer transistor (EDLT), the electric-field-induced superconductivity has been reported in various materials [1-3]. In most case this superconductivity occurs in the two dimensional (2D) electron system accumulated on atomically flat surfaces of single crystals, providing us the perfect opportunity to examine the vortex state of less-disordered 2D superconductors. On the other hand, the effect of spin-orbit coupling (SOC) with broken inversion symmetry, which is inherent in this system, on the upper critical field $H_{c2}$ and the superconducting state is another attractive subject. In this presentation, we discuss our recent results on the magnetotransport related to these questions for the EDLTs of SrTiO$_3$, MoS$_2$ and ZrNCl single crystals, which show the electric-field-induced superconductivity by gating at $T_C = 0.4$ K, 7 K and 15 K, respectively.

In the magnetic fields perpendicular to the conducting plane, the superconducting transitions for all the EDLT devices observed in the temperature dependence of resistance $R(T)$ are remarkably broadened, showing ideal the nature of 2D superconductivity. Especially, we found a common trend that $R(T)$ levels off toward $T = 0$ with a finite value, implying the existence of a metallic ground state. This behavior can be described as the vortex dynamics with a quantum mechanical process and indicates the potential of electric-field-induced superconductivity as a new platform of quantum state addressed in clean 2D superconductors.

In the parallel magnetic fields, the transitions of $R(T)$ become as sharp as that in zero magnetic fields. The values of $H_{c2} (T \rightarrow 0)$ derived from $R(T,H)$ are enhanced to be 4.3$T_C$ for EDLT-SrTiO$_3$ and 8$T_C$ in EDLT-MoS$_2$, which are much larger than the Pauli-Clogston-Chandrasekhar limit. These results are explained with the Rashba-type SOC and Zeeman-type SOC, respectively, both of which result in protecting the superconducting phases against paramagnetic depairing effect.

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PINNING EFFECT ON THE HOT-ELECTRON VORTEX FLOW
INSTABILITY IN SUPERCONDUCTING FILMS

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Hot-electron vortex flow instability in superconducting films in magnetic field $B$ at substrate temperature $T_0 \ll T_c$ is theoretically considered in the presence of pinning. The magnetic field dependence of the instability critical parameters (electric field $E^*$, current density $j^*$, resistivity $\rho^*$, power density $P^*$ and vortex velocity $v^*$ is derived for a cosine \cite{1} and a saw-tooth \cite{2} washboard pinning potential and compared with the results obtained earlier by Kunchur \cite{3} in the absence of pinning. It is shown that the $B$-behavior of $E^*$, $j^*$ and $\rho^*$ is monotonic in $B$, whereas the $B$-dependence of $v^*$ is quite different, namely $dv^*/dB$ may change its sign twice with decreasing $B$ as it was observed in some experiments \cite{4-9}. The simplest heat balance equation for electrons in low-$T_c$ superconducting films \cite{10} in the two-fluid approach \cite{11} is considered. It allows one to show that the instability critical temperature $T^* \approx 5T_c/6$ at $T_0 < T^*/2$ with $T^*$ independent of $B$.

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SKYRMION LATTICES AND SKYRMION LIQUIDS IN CHIRAL MAGNETS

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Skyrmions in chiral magnets are a kind of magnetic whirls, sharing remarkable similarities with vortices in superconductors. The emergence, stability and decay of skyrmions in chiral magnets and the associated emergent electrodynamics are reviewed, emphasising similarities and differences with vortices in superconductors. The non-zero topological winding of the skyrmions, which corresponds precisely to one quantum of emergent magnetic flux, mediates an extremely efficient coupling between the conduction electrons and the magnetic properties. This emergent flux leads to a topological Hall signal, spin transfer torques at ultra-low current densities and emergent electric fields. Additionally skyrmions are characterised by an exceptional stability, which cannot be simply suppressed under large hydrostatic pressures or doping.

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Skyrmion lattices in chiral magnets were recently discovered in 2009 [1] and have generated growing interest both in terms of basic science as a new type of topological object in a magnet [2] and for potential applications in spintronics [3]. Skyrmion lattices have many features in common with vortex lattices in type-II superconductors: both can be set into motion by an applied current, and both can be pinned by defects. The very low critical current required to produce skyrmion motion is desirable for applications, but also implies that a wide range of skyrmion dynamic phases should be accessible. Many of the ideas developed for vortex dynamic phases in superconductors with random, ordered, and asymmetric pinning arrays can be explored in skyrmion systems. Using both continuum and particle-based simulations, we show that skyrmions interacting with random pinning arrays exhibit rich dynamical phases, including a transition from a fluctuating moving skyrmion liquid to an ordered moving crystal. We show that there are significant differences between skyrmion and vortex motion due to the large Magnus term in the skyrmion system. We demonstrate that pinning strongly affects the Hall angle for skyrmion motion as well as the dynamical ordering transition. When periodic pinning is added to the sample, we find that under an increasing driving current, the Hall angle is quantized due to a series of directional locking steps produced by the Magnus term. We also show that when skyrmions are driven over a one-dimensional periodic substrate with an ac drive, a new type of Shapiro step effect can arise in which the ac drive is applied parallel rather than perpendicular to the substrate troughs. When an asymmetry is added to the pinning array, we observe a skyrmion ratchet effect that is absent in the vortex system. We term this a Magnus ratchet, and find that skyrmion ratchet motion can be induced in two directions simultaneously using only a unidirectional drive.

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Complex spin textures found in different kinds of magnetic systems can be described in terms of topological defects in the magnetization such as vortices in magnetic dots, half vortices and domain walls in nanowires, dislocations and disclinations in weak stripe domains [1] or skyrmions in helical magnets. These magnetic defects usually present an enhanced stability due to their non-trivial topology which makes them interesting for magnetic logic and memory devices. Also, interplay between complex magnetic configurations and superconductivity provides a rich playground to tune the phase diagram of superconducting/magnetic hybrids [2].

In this work, we present a study of topological defects in weak perpendicular magnetic nanostructures fabricated by e-beam lithography and sputtering on amorphous Nd-Co films and multilayers. First, periodic film thickness modulations have been used to fabricate lateral magnetic multilayers in the magnetic stripe domain pattern. During in-plane hard axis magnetization reversal, magnetic stress at the interfaces leads to the dissociation of high-Burgers vector dislocations into ½ disclination pairs. Coupling between in-plane closure domain structure and ½ disclinations leads to the nucleation of arrays of ½ skyrmion (meron) magnetic textures (see Fig. 1) depending on magnetic history and nanostructure geometry. Then, micromagnetic simulations and microscopy techniques have been used to analyse the conditions for magnetic meron nucleation and propagation during magnetization reversal of extended thin films and multilayers of weak perpendicular anisotropy materials.

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**Figure 1.** Magnetic Force Microscopy image of an array of ½ topological defects within the stripe pattern of a weak perpendicular anisotropy nanostructured films. Coupling between in-plane and out-of-plane magnetization components during in-plane magnetization reversal leads to the nucleation of these magnetic textures that combine a ½ disclination within the out-of-plane stripe domain pattern with an in-plane half vortex. At the core of each texture lies a ½ magnetic skyrmion (meron) indicated by blue dots.
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EFFECTIVE FIELD THEORY AND FINITE TEMPERATURE VORTICES IN COLD FERMI GASES

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Recently, a description of Fermi superfluids in terms of an effective field theory (EFT) for the pairing order parameter is developed [1, 2]. The present EFT improves on the existing Ginzburg - Landau theory for superfluid Fermi gases in that it is not restricted to temperatures close to the critical temperature. This is achieved by taking into account long-range fluctuations to all orders. In addition, we extend the effective field theory to the case of a two-band superfluid. The developed method allows us to reveal the presence of two healing lengths in the two-band superfluids and to obtain the ground state parameters and spectra of collective excitations. For the Leggett mode our treatment provides an interpretation of the observation of this mode in two-band superconductors. The theory has been recently applied to dark solitons in cold Fermi gases [3]. The results of the present effective field theory compare well with the results obtained in the framework of the Bogoliubov – de Gennes (BdG) method.

Here, we focus on the application of the effective field theory to finite temperature vortices throughout the BCS-BEC crossover. The obtained parameters of a vortex are compared with recent results derived using the BdG theory [4, 5]. The agreement between BdG and EFT is gradually better for higher temperatures and/or when moving to the BEC side, where EFT retrieves the Gross-Pitaevskii theory. The obtained parameters for finite temperature vortices are in agreement with the recent work [5] where a long-wavelength approximation has been developed for the BdG equations. The advantage of the current formalism is that the coefficients of the derived effective action functional are closed and tractable expressions, which turn to the known GL coefficients near the critical temperature, and are fast to compute.

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Switching dynamics of intrinsic Josephson junction (IJJ) involved by BSCCOs reveals microscopic nature of interaction between superconducting CuO$_2$ layers because the adjacent IJJs are strongly coupled due to the common CuO$_2$ atomic layers thinner than the charge screening length. This breaking of the charge neutrality of a CuO$_2$ layer yields the capacitive coupling\cite{1}. Furthermore, the number of atomic-scale junctions at the voltage (superconducting) state can clearly be identified in the current-voltage characteristics of a stack consist of a few IJJs. Macroscopic quantum tunnelling (MQT) has been observed in Bi$_{2212}$\cite{2} and other cuprates\cite{3}, however, none of unique phenomena essentially relevant to the strong interaction between IJJs has been reported so far.

We have investigated switching dynamics in three BSCCO IJJs, Bi$_{2201}$, Bi$_{2212}$, and Bi$_{2223}$, with CuO$_2$ single-, double-, and triple-layer constructing a superconducting electrode of an IJJ, respectively. We focus on the second switch, where an IJJ neighbouring to the resistive IJJ switches. It is found that the MQT rate of the second switch is strongly enhanced in Bi$_{2201}$ and Bi$_{2212}$ comparing with the first switch, whereas these switches are almost identical in Bi$_{2223}$. Figure 1 depicts the effective temperature $T_{\text{eff}}$ of the both switches in the Bi$_{2201}$ IJJ as a function of bath temperature $T_{\text{bath}}$. This is presumably attributed to the capacitive coupling because of following two reasons: (1) The charge screening length is estimated as an order of 1 nm, same as the thickness of the IJJ electrodes. (2) The capacitive coupling modifies the quantum fluctuation rather than the thermal fluctuation. Thus the thermal activation rate looks trivial ($T_{\text{eff}} = T_{\text{bath}}$) for both switches \cite{4}.

Fig.1 Plots of $T_{\text{eff}}$ (solid symbols refer to left axis) and fluctuation-free critical current $I_{\text{c0}}$ (open symbols refer to right axis) versus $T_{\text{bath}}$ for the first (red) and second (green) switches of the Bi$_{2201}$ IJJ. The broken line represents $T_{\text{eff}} = T_{\text{bath}}$ and solid lines are guides for the eyes.
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LARGE NEGATIVE VELOCITY EVENTS AND VALIDITY OF NON EQUILIBRIUM FLUCTUATION RELATION AT THE UNJAMMING THRESHOLD IN THE Driven VORTEX STATE OF 2H-NbS₂

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Time series measurements of voltage fluctuations in the driven vortex state in 2H-NbS₂ single crystals has revealed signatures of jamming phenomenon in the driven vortex state. By either waiting for long enough time at a fixed drive or by applying large drives, the vortex state dynamically transforms from a moving state into a zero-velocity state, viz., a Jammed state. At drives close to the unjamming threshold and well below the free flow regime we find a unique fluctuating regime with giant velocity fluctuations[1]. The vortex velocity distribution is bimodal in this state where the lower peak corresponds to low vortex velocities close to the depinning threshold and the higher peak corresponds to larger velocities close to the freely flow regime. Upon reducing the drive from this regime towards the unjamming threshold the velocity distribution evolves towards an unusual non-Gaussian shape which exhibits significant number of negative velocity events. These unusual events correspond to trajectories of vortices drifting opposite to the drive. While at first glance such a distribution seems unusual however our analysis reveals that the velocity distribution in the driven vortex state obeys a general non-equilibrium fluctuation relation (FR) [1], which governs the probability of observing entropy consuming and entropy producing trajectories in a non-equilibrium system. We find regimes not only where the FR is valid but also where it fails [1]. We propose an understanding [1] of our results on the basis of an interface depinning model where we suggest that the vortex state possess an interface separating moving phases with different densities. Localization of the interface on a network of strong pins precipitates the jamming transition. Spatial and temporal density fluctuations along the interface at the unjamming threshold results in significant vortex reorganization producing drifts of the interface in a direction opposite to the net drive and the observation of the peculiar negative velocity events.

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STM/STS OBSERVATION OF VORTEX MOTION IN NON-EQUILIBRIUM SUPERCONDUCTING STATES IN Bi$_2$Sr$_2$CaCu$_2$O$_x$ AND YNi$_2$B$_2$C

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STM is the only method to visualize vortices of type-II superconductors in high magnetic fields such as 10-15T. The vortex motion has been measured by scanning the STM tip with high speed. In YNi$_2$B$_2$C the motion of vortex bundles influenced by the presence of the vortex lattice dislocation has been observed [1]. However, due to a limitation of the scanning velocity of STM tip, the observed velocity of vortices is less than 1nm/sec. To observe the vortex motion with higher velocity, the tunnelling current or the Z-piezo bias voltage are measured continuously by using the STM with high spatial stability (xy-drift: 0.1nm/day) at the fixed point on the surface of the superconductor. When the vortex core pass through under the STM needle, the tunnelling current is increased and the motion of the vortex is able to be detected. From the time spectra, we succeeded in observing the vortex motion up to a few 100nm/sec. In a very clean YNi$_2$B$_2$C, the vortices were driven by sweeping the applied magnetic field at 4.2K. The time spectra exhibited the vortex flow behaviour and sometimes discontinuous jumps probably due to the boundaries of vortex bundles. The speed and the direction of the vortex motion have been obtained from the time spectra. In Bi$_2$Sr$_2$CaCu$_2$O$_x$, where electronic inhomogeneities due to excess oxygen are present, different from the case in YNi$_2$B$_2$C, discontinuous jumps of vortex creep have been observed in non-equilibrium vortex states prepared by changing applied magnetic field at 4.2K. From the time spectra, the statistical property of the time interval between two successive vortex creep events have been measured. The power law have been found and will be discussed from the self-organized critical states. I think that this is the first study of the magnetic relaxation from observing individual vortices.

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We present detailed magneto-optical studies of flux patterns in a high-quality YBCO crystal under crossing magnetic fields. The dynamics of vortex motion under crossed-magnetic field is highly anisotropic with preferred vortex motion along in-plane components $H_p$ of the applied field as opposed to strongly suppressed vortex motion transverse to $H_p$. In tilted fields we observe multiple vortex instabilities resulting in filamentation of the field induced currents and formation of differently oriented vortex domains in a finite range of field angles. The vortex dynamic behavior in the crossing and tilted fields can be explained by the flux cutting processes and by the staircase vortex structure expected in anisotropic superconductors. The stripe domains of vortices with different tilt angles are associated with a type-I phase transition in the vortex lattice accompanied by a sharp jump in the vortex orientation with respect to the crystal’s basal plane. We further elucidate the scenario of the crossing-field magnetization using time-dependent Ginzburg-Landau simulations, which reveal fine details of the individual vortex cutting and reconnection events at a moderate density of vortices. The simulations demonstrate left-handed helical vortex instabilities and confirm formation of sharp vortex tilt fronts in support of our experimental observations.

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MANIPULATING VORTEX DYNAMICS IN NANOSTRUCTURED YBCO FILMS

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Tailoring vortex pinning landscape in high temperature superconductors and in particular of YBa₂Cu₃O₇₋ₓ (YBCO) is one of the major challenges nowadays for its relevance in applications requiring manipulation of flux quanta or enhanced critical currents. However, artificial control and guidance of vortex dynamics in YBCO films is a complex issue, especially due to their high thermal excitations and their already strong intrinsic pinning capabilities. Thus, artificial nanofabrication strategies able to generate competing effects with intrinsic microstructural defects need to be used.

In this work, we have used high resolution nanofabrication tools; Focused Ion Beam (FIB), E-beam (EBL) and Current Scanning Probe Microscopy (C-SPM), to artificially and locally modify the superconducting material and generate nano-regions where collective vortex dynamic behaviour can be manipulated and controlled.

Stripes, antidots, ferromagnetic nanostructures or high resistive regions are some of the nanofabricated structures which have resulted in several new phenomena. In particular, we have observed collective direct and reversal ratchet effects, nano Nano-wall vortex pinning, ferromagnetic-superconducting cooperative effects and electrically-driven local resistive switching phenomena all in high current density YBCO films. In this presentation, I will report on our understanding on all these effects and potential expectations.

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WHY ARE FLUX AVALANCHES DEFLECTED BY A METALLIC LAYER?

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Sudden avalanches of magnetic flux bursting into a superconducting sample are deflected from their trajectories when they encounter a conductive layer deposited on top of the superconductor. Remarkably, in some cases the flux is totally excluded from the area covered by the conductive layer. Even if this phenomenon has been known for a few years [1], there is currently no theoretical model describing it. Moreover, the question whether the deflection would also be observed for a single vortex entering the region covered by a metallic layer is still unanswered.

In this work [2] we use the magneto-optical imaging (MOI) technique, based on the Faraday effect, to show that a conductive layer (Cu) can repel flux avalanches triggered in an underlying superconducting film (Nb) (see figure). We present a simple classical model that accounts for the deflection of a single vortex and considers a magnetic monopole approaching a semi-infinite conductive plane. This model suggests the important role played in the avalanche deflection by electromagnetic braking, arising from the eddy currents induced by the moving vortex in the metal. Moreover, we have found a decrease of the vortex damping coefficient due to the metallic sheet at large vortex velocities, correcting early theoretical descriptions where a linear behaviour was proposed [3].

Figure – (a) Sketch of the sample layout. Panels (b) and (c) show magneto-optical images of the Nb sample taken at $T = 2.5$ K with $H = 10$ Oe after zero-field cooling, before (b) and after (c) covering it with the Cu triangle. The bright areas correspond to the highest magnitudes of the magnetic field, while the dark areas represent the lowest fields.
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CRITICAL PROPERTIES OF LARGE-SCALE DEPOSITED, ALL-SOLUTION COATED CONDUCTORS

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Due to low irreversible fields, low current-carrying capabilities and, last not least, the production costs of the 1st generation HTS wires and cables, nowadays much effort is focused on development of the 2nd generation HTS conductors, i.e. the coated conductors that are based on the deposition of textured YBCO films on inexpensive tapes in long lengths. The biaxial alignment of the typical micrometer thick YBCO layer is achieved either by ion beam assisted deposition, inclined substrate deposition, or via rolling and recrystallisation of the metal tape (typically NiW) known as rolling assisted biaxially textured substrates (RABITS). In all cases a granular structure of the substrate is obtained which leads to a granular YBCO film. Nevertheless zero-field critical current densities are achieved that are comparable to that of epitaxial grown YBCO films (e.g. J_c(77K, 0T) = 1-2MA/cm²). However, with the application of magnetic fields the critical current decreases strongly which hampers the use of the tapes for a number of applications.

We develop a setup to examine the field and temperature dependence of YBCO coated conductors by resistive measurements with currents up to 500A. For comparison magnetization data are recorded as function of the magnetic field and temperature using a standard PPMS system. Especially all-solution chemically deposited (CSD) and, for comparison, physically deposited tapes are characterized with these setups. Critical current densities in the range of 2.5-3.5MA/cm² (equivalent to I_c/w up to 350A/cm) are obtained at 77K and selffield for the CSD samples, the typical lift factor is of the order of 2-2.5 for 30K and 1T. The field dependence shows the expected flux-line sheer dependence, however with a field-dependence that is steeper than predicted by the classical model. The field dependence is strongly affected by the morphology of the sample, optimization of the morphology leads to larger critical currents and a shallower field dependence. Finally, the role of local variations of the critical properties and their impact on the performance of the tapes are discussed.

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HIGH CRITICAL CURRENT DENSITY IN Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ TAPES FOR MAGNET APPLICATIONS

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122 type pnictide superconductors are of particular interest for high-field applications because of their large upper critical fields $H_{c2}$ (> 100 T) and low anisotropy $\gamma$ (< 2). Successful magnet applications require fabrication of polycrystalline superconducting wires that exhibit large critical current density $J_c$, which is limited by poor grain coupling and weak-link behavior at grain boundaries. Here we report our recent achievement in the developing Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ tapes with transport $J_c$ up to $1.2 \times 10^5$ A/cm$^2$ at 10 T and 4.2 K. More importantly, the field dependence of $J_c$ turns out to be very weak, such that in 14 T the $J_c$ still remains $\sim 1.0 \times 10^5$ A/cm$^2$. These values are by far the highest ever recorded for iron based superconducting wires and has surpassed the threshold for practical application. The synergy effects of enhanced grain connectivity, alleviation of the weak-link behavior at grain boundaries, and the strong intrinsic pinning characteristics led to the superior $J_c$ performance exhibited in our samples. This advanced $J_c$ result opens up the possibility for iron-pnictide superconducting wires to win the race in high-field magnet applications.

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The huge efforts required to induce strong texture and minimize grain boundary (GB) density complicate manufacture and enforce a tape shape which is far from ideal for making high Jc conductors of arbitrary current-carrying capacity. Bi-2223 with a uniaxial [001] texture of ~15° and REBCO with a biaxial texture of 3-5° both require tape aspect ratios of 20-40:1 that show the strong intrinsic anisotropy of each compound. By contrast we have recently shown that Bi-2212 can be made as a very high Jc conductor [1] in a round wire form that is macroscopically isotropic, a significant and positive violation of the need for HTS conductors be strongly textured tapes. Close examination of optimized Bi-2212 shows that, most surprisingly, it too has a biaxial texture of ~15°, but in this case the texture is developed by growth from the melt in the final size wire [2]. High Jc is partly a function of ensuring a full density superconducting phase (as is also true in Bi-2223) but it also appears that the unexpected biaxial texture of Bi-2212 develops a low GB density biased to low misorientations. Strikingly round wire K-doped Ba122 can also develop rather high Jc even when the grain boundary density is high and texture is absent. Part of the route to higher Jc seems to involve defeating impurity segregations that recent atom probe analysis [3] shows to be present even in high Jc material, but part is probably also intrinsic. A recent study [4] of variably doped (Ca, O) YbBCO films with 6° and 7° [100] tilt grain boundaries shows that Ca doping can enhance Jc only at high T, a property associated with strong Ca de-segregation at the inter-dislocation channels which thus may have higher Tc than the grains on either side. I will review recent studies at the ASC of my colleagues and me on this vital topic for applications [1-4].

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PINNING LANDSCAPES FOR HIGH-PERFORMANCE SUPERCONDUCTORS

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New strategies to vortex pinning are required to improve the performance of superconducting materials for applications in power transmission, magnet systems and rotating machinery. Mixed pinning landscapes, that is, defect microstructures that are composed of several distinct defect types, are emerging as a promising approach for enhancing vortex pinning, particularly in high magnetic fields. Here we describe our work aimed at the controlled introduction of mixed pinning landscapes using particle irradiation. On state-of-art commercial YBCO coated conductors p-irradiation induces a near doubling of the in-field critical current density of ready-made post-production samples \cite{1}. TEM reveals a high concentration of uniformly distributed 2-5 nm-sized irradiation-induced defects which coexist with large rare earth oxide precipitates that appear during the conductor fabrication thus forming a novel mixed pinning landscape that is particularly effective in high applied magnetic fields. The dose dependence of the critical current enhancement at various temperatures and fields is well described in large-scale time dependent Ginzburg-Landau simulations of the vortex dynamics. More recently we have shown that irradiation with light ions, e.g., oxygen, yields a doubling of the high-field critical current of commercial YBCO coated conductors in a matter of seconds making a reel-to-reel process a viable possibility.

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure.png}
\caption{Field dependence of the critical current density of the pristine and the O-irradiated sample at 5 K, and the $J_c$-enhancement. $\alpha$ is the power in $J_c \sim H^{\alpha}$.}
\end{figure}
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Abstracts of Posters
FRACTALITY OF FLUX FRONTS AND MULTISCALING IN HIGH TEMPERATURE SUPERCONDUCTORS

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The role of non-trivial disorder correlations on flux penetration is investigated in the pnictide superconductor Ba(Fe₃₋ₓCoₓ)₂As₂ [1] and in thin films of the cuprate superconductor YBa₂Cu₃O₇ with different types of disorder. Vortex penetration is visualized using the magneto-optical technique as well as by Bitter decoration. The higher-order analysis of roughening and growth of the magnetic flux front reveals anomalous scaling properties, indicative of non-Gaussian correlations of the disorder potential. While higher-order spatial correlation functions reveal multifractal behaviour for the roughening, the usual Kardar-Parisi-Zhang growth exponent is found [1]. Both exponents are found to be independent of temperature. The scaling behaviour is manifestly different from that found for other modes of flux penetration, such as that mediated by avalanches, suggesting that multiscaling is a powerful tool for the characterization of roughened interfaces.

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INDIVIDUAL VORTEX MOTION IN A LINEAR PINNING POTENTIAL

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We discuss vortex lattice images obtained by changing the magnetic field in small steps in a thin film with nanofabricated lines that act as a sizeable pinning potential for the vortex lattice. Vortex images are taken using scanning tunnelling microscopy (STM) at 100 mK and show vortex motion induced by modifying the magnetic field in small steps of a few mT. In this work, we have developed numerical tools to identify individual vortex positions in the images and follow vortex trajectories. We use these tools to identify defects and measure the longitudinal and angular stress on the vortex lattice induced by the interaction between the hexagonal vortex lattice and the linear pinning potential. We find that, at some magnetic fields, dislocations appear in an otherwise ordered vortex lattice. By making statistics of vortex motion around dislocations, we observe that vortices around a dislocation travel longer distances than those in the hexagonal lattice.

We also discuss the development of a very high magnetic field STM up to 17 T. The STM is made of Ti with all components free from magnetic materials. We have worked to minimize the mechanical vibrations at high magnetic fields by tightening the wiring and rigidly fixing the superconducting coil to the cryostat. Here I will discuss advantages of the STM design, methods used to damp mechanical vibrations and features of a new home made ultra-low noise electronics.

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TERAHERTZ RADIATION FROM Bi$_2$Sr$_2$CaCu$_2$O$_8$ INTERLAYER JOSEPHSON JUNCTIONS: PROGRESS AND FUTURE APPLICATIONS

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Stacks of intrinsic Josephson junctions in extremely anisotropic high-temperature superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_8$ are a promising compact solid-state source of coherent radiation in the 'terahertz gap' range. At present, no such sources exist in the range from approximately 0.5 THz to 1.3 terahertz, and this region is of particular interest for many scientific, medical, and security-related applications. In order to generate technologically useful levels of power from these stacks, it is necessary to obtain efficient phase-synchronized emission from the largest possible number of individual Josephson junctions. Following this approach, we have recently at Argonne increased the coherent power output from this type of device to 0.6 milliwatts at 0.51 THz, which is approximately the power level required for practical imaging applications. [1] Compact Bi$_2$Sr$_2$CaCu$_2$O$_8$ terahertz sources also open up the possibility of integrated circuits which exploit the unique nonlinear physics of intrinsic Josephson junctions. Such electronics would allow ultrafast signal processing, for instance in high-bandwidth communications at THz frequencies, in both wired and wireless applications.

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MFM STUDY OF THE FLUX LINE LATTICE IN THE $\beta$-Bi$_2$Pd SUPERCONDUCTOR

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$\beta$-Bi$_2$Pd is a multiband superconductor that crystallizes in layered tetragonal structure. It is a metastable phase below 750 K with a $T_c$ of around 5.1 K [1]. In this work, we present results obtained using magnetic force microscopy MFM in the mixed state $\beta$-Bi$_2$Pd. Crystals were grown from high purity Bi and Pd. The good quality of the crystals was confirmed with X-ray diffraction, resistivity and magnetic measurements. We measure down to 2.5 K using a commercial MFM (Nanomagnetics Ltd) within a home-made 3-axis superconducting coil [2]. We report in this work real space images of the Abrikosov lattice on $\beta$-Bi$_2$Pd measured on atomically flat terraces. The terraces are several microns large, separated by nanometric steps. Images of a hexagonal flux line lattice have been recorded in large regions when applying a magnetic field perpendicular to the surface. We have investigated the structure and orientation of the vortex lattice as well as its switching behavior. We observe, under certain conditions, vortices that are not round.

This could be associated to the geometry of the magnetization of the MFM tip. Furthermore, we are studying the effect of graphene deposited on top of the $\beta$-Bi$_2$Pd crystals.

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FLUX CREEP IN (RE)BCO AND Bi-2212 CONDUCTORS AND MAGNETS

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Persistent operation of superconducting magnets has been a decisive attribute for the use of superconductors in MRI, NMR, and other applications, which is very well achieved by the low temperature superconductors Nb-Ti and Nb₃Sn. There is a growing interest in the use of (RE)BCO and Bi-2212 conductors for high field NMR magnet applications. We are presently utilizing both conductors in prototype coils, so we are evaluating the flux creep properties of a.) conductors and b.) magnets and comparing their flux decay to the more ideal samples, like single and bi-crystals, hitherto studied in the literature. Preliminary measurements reveal pinning potentials ($U_{eff}/K_B$) of ~300 K for (RE)BCO tape samples and ~120 K for over-pressure processed Bi-2212 round wire short samples. These results will be used to analyse magnetic field drift data from test coils.

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EFFECT OF INTERNAL STRAINS ON THE SUPERCONDUCTOR
Ca(Fe_{0.965}Co_{0.035})_2As_2: ATOMIC SCALE STUDY USING STM

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We present a scanning tunneling microscopy (STM) study of Co-doped CaFe2As2 at low temperatures. The samples have been annealed to slightly tune their superconducting properties [1,2]. We cleave samples in situ in cryogenic ultra-high vacuum to obtain clean and atomically flat surfaces. We make atomic scale spectroscopic maps from hundreds of thousands of conductance vs bias voltage curves during several days long experiments at 100 mK. These maps show evolution of surface electronic scattering patterns with energy and allow us to directly measure the electron dispersion.

We discuss results in the superconducting phase of Ca(Fe_{0.965}Co_{0.035})_2As_2. As in previous work on non-superconducting samples [3], we find reconstructed surfaces and show that the electron dispersion relation measured at these surfaces gives a hole-like band. We find that, however, the effective mass in this band is larger in superconducting than in non-superconducting samples. We have been systematically searching for unreconstructed surfaces with the square As lattice [4], and found them for the first time in these compounds. In these surfaces we find an electron and a hole band, as well as incoherent variations of the superconducting tunneling conductance due to pair breaking. We find a four-fold pattern in the superconducting tunneling conductance, which could be related to the superconducting gap anisotropy. Finally, we briefly discuss results in Ca(Fe_{0.97}Co_{0.03})_2As_2, where we identify slightly different band-structure and also observe effects of local strain on the superconducting properties.

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INDUCED VORTEX SMECTIC PHASE IN NANOSTRUCTURED Nb THIN FILMS

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We have studied vortex matter phases in niobium films grown on silicon substrates with arrays of copper nanodots. The nanodots act as pinning centers, interacting with vortex matter phases. In order to study these phases, we have measured I-V characteristics very close to Tc for several magnetic fields.

In the case of four-fold symmetry arrays, a vortex glass-to-liquid transition is observed for all studied magnetic fields [1]. Upon lowering the symmetry of the array, a vortex smectic phase is induced, in a temperature window between the vortex glass and liquid, and liquid-like transport properties are observed along one direction while they remain glassy along the other.

The presence of this induced phase can be controlled by a proper design of the pinning array and is suppressed as magnetic field is raised.

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TWO STEP DISORDERING OF THE VORTEX LATTICE ACROSS THE PEAK EFFECT IN A 3-DIMENSIONAL TYPE II SUPERCONDUCTOR \( \text{Co}_{0.0075}\text{NbSe}_2 \)

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The vortex lattice (VL) in a Type II superconductor provides a versatile model system to investigate the order-disorder transition in a periodic medium in the presence of random pinning. In this work, using scanning tunnelling spectroscopy in a weakly pinned \( \text{Co}_{0.0075}\text{NbSe}_2 \) single crystal, we show the possibility that at low temperatures, the vortex lattice in a 3-dimensional superconductor disorders in two steps across the magnetic field driven peak effect. At the onset of the peak effect, the equilibrium quasi-long range positional ordered (QLRPO) state transforms into an orientational glass (OG) through the proliferation of dislocations. At a higher field, the dislocations dissociate into isolated disclination giving rise to an amorphous vortex glass (VG). While the VL in the ramp down branch is more disordered, our data do not provide any evidence of supercooling across either QLRPO\(\rightarrow\)OG or OG\(\rightarrow\)VG transitions as expected for a first order phase transition. Therefore, we attribute the hysteresis to the inability of the VL to fully relax below the transition in the ramp down branch. At present, for either transition, we cannot distinguish between a true phase transition broadened by disorder and a gradual crossover, induced by the random pinning potential. We also show the existence of a variety of additional non-equilibrium states, which can be accessed through different thermomagnetic cycling.

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TRANSPORT MEASUREMENTS OF W-BASED SUPERCONDUCTING FILMS WITH THICKNESS MODULATION GROWN BY FOCUSED-ION-BEAM INDUCED DEPOSITION.

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The vortex dynamics changes its behavior in structures of type-II superconductors with dimensions comparable to the inter-vortex distance, as shown in recent years due to the possibilities of nanofabrication. It’s well known that W-based nanostructures grown by Focused-Ion-Beam induced deposition (FIBID) have superconducting properties (type II) [1]. Shape modulation is easily achieved with this technique, making this material suitable for investigations of the vortex dynamics in tailored pinning landscapes. Previously published works have emphasized that the vortex behavior can be modulated in this material [2, 3]. In order to study the vortex movement in a tailored pinning landscape, we have grown W-based films with thickness modulation along y direction. The modulation has been achieved with different periodicities (between 60 and 140 nm) by optimization of the growth parameters. Cross-sectional SEM analysis has been used to measure the sample dimensions. The figure 1 shows a sample of 50 nm thickness and 100 nm modulation along the y direction grown on a silicon nitride substrate. Transport experiments in these films have been done as a function of temperature, current and magnetic field, in order to obtain information about how the thickness modulation can affect the superconductor characteristic parameters. Strong vortex pinning effects have been found due to the thickness modulation. The obtained relationship between the thickness periodicity of the samples and the vortex distance follows the model developed by Martinoli [5] for one-dimensional vortex pinning potential.

Figure 1: A cross-sectional image of a W-based film with thickness modulation in one direction, grown on Si3N4 substrate. The maximum thickness of this sample is around 50 nm and the periodicity is 100 nm.
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MULTIBAND FEATURES AND TILTED VORTEX LATTICE IN THE SUPERCONDUCTOR $\beta$-Bi$_2$Pd

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We present scanning tunneling microscopy (STM) experiments at very low temperatures (150 mK) and tilted magnetic fields on single crystalline samples of the superconductor $\beta$-Bi$_2$Pd. We have obtained high quality single crystals using solution growth method.

We find surfaces showing the square atomic lattice and spatially homogeneous superconducting density of states following single gap $s$-wave BCS theory. The orientation of the vortex lattice with perpendicular magnetic fields observed up to $H_{c2}(T)$ is locked to the square crystalline lattice. We find multiband features in the magnetic field dependence of the intervortex density of states and $H_{c2}(T)$. We show how the mixed phase of superconductors is influenced by multiband features of the Fermi surface, even when the zero field gap structure follows single gap $s$-wave BCS theory.

We use a homemade three axis superconducting magnet to study tilted vortex lattices in different azimuthal and polar orientations. We find that the structure of the tilted vortex lattice deviates with respect to expectations for isotropic superconductors and shows the square symmetry of the atomic lattice.

$\beta$-Bi$_2$Pd turns out to be a model crystalline superconductor with an excellent surface, an isotropic gap and anisotropic superconducting properties that manifest in the mixed phase.

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THE TRANSPORT PROPERTIES OF SUPERCONDUCTING FLUCTUATION IN THE VORTEX LIQUID OF HIGH $T_c$ SUPERCONDUCTORS

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The recently measured Nernst effects in high temperature superconductors observe large vortex liquid regions around $T_c$, where the vortices can be driven to flow to produce abnormally large Nernst signals [1]. Since many of the Nernst data are measured in the deep vortex liquid region, they can hardly described by the perturbative Gaussian fluctuations of the Ginzburg-Landau model. We present a Hartree-Fock approximation to include the quartic term of the order parameter and then calculate the Nernst effect of Lawrence-Doniach layered superconductors by the time-dependent Ginzburg-Landau equation [2-6]. The theoretical results agree well with the experiment. We also applied this method to the superconducting fluctuation conductivity and find the theory in well agreement with experiments [7]. We reveal a “fix point” related to conductivity below $T_c$, similar to the case of magnetization.

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SCANNING SQUID MICROSCOPY STUDIES OF SUPERCONDUCTIVITY

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Superconducting Quantum Interference Device (SQUID) is a highly sensitive magnetic flux detector. We show simultaneous mapping of the static magnetic landscape and the sample’s response to locally applied fields, obtained with scanning SQUID microscopy. These images provide unique view of the correlation between single vortex dynamics over the pinning landscape, and the map of superfluid density modulation.

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PARAMAGNETIC MAGNETIZATION AND NOVEL METASTABLE BEHAVIOR IN FIELD-COOLED MAGNETIZATION IN A SINGLE CRYSTAL OF 2H-NbSe₂

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The phenomenon of paramagnetic Meissner effect (PME) continues [1] to attract attention ever since its discovery [2] in a high-Tc cuprate superconductor. Numerous explanations [3] have been put forward to account for its observation in a wide variety of superconductors. In particular, the flux-trapping model by Koshelev and Larkin [4] to explain the occurrence of PME in conventional bulk superconductors has well been accepted by the vortex community. In the context of mesoscopic-sized samples, it has been propounded [5-7] that the occurrence of giant-vortices with multiple flux-quanta can lead to the occurrence of PME. The theoretical results in Ref. [6-7] also predict the possibility of transitions between various multi-quanta states that may lead to abrupt changes in the magnetization behaviour. Here, we present some newer characteristics pertaining to the PME like response in a low-Tc superconductor, 2H-NbSe₂, via a detailed study of effects of perturbation on the field-cooled (FC) magnetization behaviour for both orientations of the platelet shaped hexagonal crystal (H‖c and H⊥c). We have observed an unusual paramagnetic peak below Tc (~ 7.15 K) in the FC magnetization response (MFC(T)). In the temperature range, where the anomalous paramagnetic feature occurs, a perturbation applied to the system in the form of an impulse of an ac field leads vividly to an unpredictable switching of the magnetization from a given paramagnetic/diamagnetic value to a different paramagnetic/diamagnetic value. Such a perturbation applied to the system has lead to the exposure of multi-valuedness in the FC magnetization at a given H-T value. Similar non-uniqueness in MFC(T) has also been revealed by carrying out the magnetization measurements in different amplitudes of vibration of sample in a vibrating sample magnetometer. On some occasions (without applying perturbation), the MFC(T) curves display a characteristic oscillatory behaviour that shows the switching tendency of magnetization between numerous metastable states. The field-cooled magnetization response in a single crystal of 2H-NbSe₂ is thus found to be highly metastable. Surprisingly, the said features in the magnetization mimics the behaviour anticipated for the giant vortex states in the mesoscopic-sized samples. To the best of our knowledge, the present results in 2H-NbSe₂ single crystal cannot be rationalized on the basis of any of the existing theoretical treatments for bulk superconducting specimen.
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OPTICAL MANIPULATION OF ABRIKOSOV VORTICES

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We combine a high resolution magneto-optical imaging (MOI) system capable to resolve single vortices with movable focused laser beam to realize manipulation of Abrikosov vortices. The local heating of superconductor at the laser spot produces a temperature rise profile which induce an attraction of the vortices towards the center of the spot. The formation of dense vortex clusters surrounded by a vortex-free region is then investigated. The physics of this cluster formation is similar to the one describing the vortex dynamics at the boundaries between superconductor and normal metal. The so-called Bean-Livingston barrier can then be probed using such vortex structures.

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SUPERCONDUCTIVITY IN THE 2D LIMIT: TC ENHANCEMENT IN 2H-TaS$_2$ FEW-LAYERS

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Graphene [1] is one of the most studied materials due to its unique properties such as hardness, flexibility and high electric and thermal conductivity.

However, probably the best quality of graphene is that it is opening the field to many other 2D crystals [2] including superconductors and topological insulators.

In this work the synthesis and transport measurements on thin crystals of 2H-TaS$_2$ with various thickness are presented. A $T_c$ enhancement by decreasing the number of atomic layers has been observed. Thus, $T_c$ increases from 0.8 K in the bulk sample to ca. 2 K when the layer thickness is decreased to ~3 nm. This behaviour is the opposite of the one reported in other superconductor 2D crystals [4]. A study based on a simple band model and on optical phonons localized in each plane shows a maximum of the density of states crossing the Fermi level in a system formed by planes. The phonon localization makes the electron-phonon coupling maximum for one layer. The combination of these two effects agrees with a $T_c$ enhancement when the number of layers is decreased.

![Figure](image)

**Figure**: a) Variation of the $T_c$ as a function of the thickness of the TaS$_2$ layers. Devices exhibiting non-zero RRR are plotted in blue. Inset: Stack of two layers of 2H-TaS$_2$ made out of sulfur (X) and tantalum (M). b) Variation of $B_{c2}$ (circles) and G-L length values (triangles) as a function of thickness. A dashed red line has been placed at the $T_c$ and $B_{c2}$ values found for bulk flakes to serve as a reference for establishing the thick layer limit.
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We have used magnetometry on perpendicular magnetic anisotropy-ferromagnetic/superconducting (FM/SC) bilayers to investigate the effect of magnetic reversal on the superconducting critical current. The FM/SC bilayers consist of a NdCo₅ film with thicknesses 30 nm, 50 nm and 75 nm covered by a 50 nm Nb film. The slopes of the superconducting hysteresis loops increase as the inverted domains nucleate and expand which corresponds to a sharp enhancement of the critical current density. This correlates with an increase in the critical temperature and the superconducting field extracted from transport measurements. In addition, we found thermomagnetic instabilities, i.e., vortex avalanches, at low temperatures and fields. Our results are due to the inversion of magnetic domains which produce an increase of the superconducting vortex pinning.
RATCHET EFFECTS FOR VORTICES AND SKYRMIONS IN NANOSTRUCTURED ARRAYS

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Recently a new pinning geometry called a conformal pinning array was proposed in which a conformal transformation is performed on a uniform triangular lattice. This produces a pinning array with a density gradient that still preserves the local triangular ordering of the array. Such conformal pinning arrays produce higher critical currents than other pinning array geometries with equivalent numbers of pinning sites [1,2]. Here we simulate a series of conformal pinning arrays and show that a robust ratchet effect can arise under the application of an ac driving current. The ratchet effect is significantly stronger in the conformal pinning array than in a random pinning array with an equivalent number of pinning sites or in a periodic pinning array with an imposed gradient. The enhancement of the ratchet effect results from a funneling effect produced by the arching structure of the pinning sites in the conformal array. Ratchet effects have been extensively studied for vortices in superconductors, and we also show that ratchet effects can arise for skyrmions in asymmetric pinning structures. In the skyrmion case, due to the strong Magnus term, novel ratchet effects can arise that do not occur in the overdamped vortex system.

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ORIGIN OF MATCHING-EFFECT IN ANTI-DOT ARRAY OF SUPERCONDUCTING NBN THIN FILMS

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We investigate the origin of the matching effect in disordered superconducting NbN thin films with a periodic array of holes. In addition to the periodic variation in electrical resistance just above the superconducting transition temperature, we find pronounced periodic variations with magnetic field in all dynamical quantities that can be influenced by flux-line motion under an external drive, including the magnetic shielding response and the critical current, which survives in some samples down to temperatures as low as 0.09Tc. In contrast, the superconducting energy gap Δ, which is a true thermodynamic quantity, does not show any periodic variation with magnetic field for the same films. Our results show that commensurate pinning of the flux-line lattice driven by vortex–vortex interaction is the dominant mechanism for the matching effects observed in these superconducting anti-dot films, rather than a Little–Parks-like quantum interference effect.

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A NEW APPROACH FOR THE INVESTIGATION OF DOMAIN STRUCTURES IN THE INTERMEDIATE MIXED STATE (IMS) USING NEUTRON METHODS

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In the intermediate mixed state (IMS) of a type II superconductor (SC), the sample splits up into field-free Meissner and Shubnikov domains which carry the vortex lattice (VL) [1]. Experiments on the topology of the IMS show a variety of different patterns including striped, dendritic and bubble phases, which represent typical domain morphologies also seen in various other physical contexts [2]. From another viewpoint, the emergence of the IMS reflects the crossover from repulsive to attractive vortex-vortex interaction. A detailed investigation of IMS domain patterns hence offers the possibility to study general phenomena of domain nucleation and morphology as well as the microscopic properties of vortex matter.

Such IMS structures are typically investigated by surface sensitive techniques as decoration, scanning probe microscopy and magneto-optical imaging. However, surface flux pinning and Landau branching can significantly hamper the deduction of bulk properties. Furthermore, these methods are mostly restricted to flat surfaces. In contrast, neutrons can uniquely probe the bulk behaviour without any limitation on the sample shape. However, the typically used small angle neutron scattering (SANS) fails to probe the µm domain structure of the IMS. Furthermore, no spatially resolved information can be obtained.

Using the model SC Niobium, we show how a combination of ultra small angle neutron scattering (USANS) [3] and neutron grating interferometry (nGI) [4] yields detailed information on the morphology of the IMS and its domain structure. nGI is an advanced neutron radiography technique where regions involving the scattering of neutrons at µm structures are identified. Hence a direct map of the IMS domain distribution in the bulk can be obtained (Fig. 1). Furthermore, USANS scattering curves provide structural information of the size of IMS domains. We demonstrate how this approach allows studying the effects of sample geometry and quality on the IMS bulk domain nucleation.
Figure 1: IMS domain distribution in a Nb single crystal disc \((r = 10 \text{ mm}, t = 2 \text{ mm}, \text{marked by the blue circle})\) with significant pinning at 4 K. The sample was field cooled to the IMS and then the field was successively increased. White contrast marks regions where an IMS domain structure exist.

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EFFECT OF MAGNETIC FIELD PULSE ON THE ZERO FIELD COOLED AND FIELD COOLED STATE OF Co$_{0.0075}$NbSe$_2$

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We investigated stable and metastable states of the vortex lattice through zero field cool (ZFC) and field cool (FC) susceptibility measurements, of a lightly doped Co$_{0.075}$NbSe$_2$ single crystal. In ZFC protocol, the sample was cooled in zero field from normal state to the lowest temperature, then magnetic field was applied and susceptibility as a function of temperature was measured while heating. For FC, the sample was first cooled in field up to lowest temperature, then susceptibility as a function of temperature was measured while heating. A magnetic field pulse at regular temperature interval was applied to relax the vortex lattice (VL) to its stable configuration. We found that due to pulsing, the disordered FC state, relaxes close to the ordered ZFC state. Surprisingly, we also found that the ordered ZFC state created at low temperature could not fully relax to stable configuration as one increase the temperature, unless perturbed by magnetic field pulse. Interestingly, the effect of pulsing is different for ZFC state prepared in field above and below 0.25 T. Above 0.25 T, the low temperature regime remains unaltered by pulsing, while in the peak effect region, ordered ZFC state shatters the VL and brings it close to disordered FC state. However below 0.25T, in the peak effect region, pulsing induces enhancement in ordering as compare to unperturbed ZFC state. Moreover, the peak effect become sharper when the periodic pulse is applied on the ZFC state. These observations were further supported by the STM measurements. The vortex images captured for ZFC state reveals that, below peak temperature as temperature increase, the low field ZFC state relaxes to more ordered state after perturbing, which is attributed to the narrow bond length distribution. Further measurements and analysis of results are in progress to explore the underlying physics.

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CRITICAL CURRENTS AND OXYGENATION PROCESS OF YBCO FILMS GROWN BY CHEMICAL SOLUTION DEPOSITION

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Chemical solution-derived YBCO thin films and nanocomposites, with their high critical current densities $j_c$ and low production costs are broadening the horizon of potential applications of high temperature superconductors and can be used as high performance coated conductors at different temperatures and magnetic fields. To further improve the properties of CSD YBCO thin films we investigate the influence of key parameters of the manufacturing process, as the thickness of the YBCO layer, its corresponding growth and oxygenation process, as well as the content of nanoparticles.

Transport measurement over an extensive range of temperatures and fields and in-situ resistivity measurements, able to monitor the growth and oxygenation process, have been used to analyse standard YBCO and nanocomposite samples with thicknesses between 50 nm and 1 µm, some of them deposited by ink-jet printing. We present a comprehensive study of the correlation between sample processing, microstructure determined by TEM studies, and physical properties. Within this study we have found that the oxygenation process plays an important role to improve the superconducting properties of YBCO films and nanocomposites, with many parameters playing a role.

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DETECTING SINGLE VORTEX MOTION WITH HIGH SPATIAL RESOLUTION

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Scanning tunneling microscopy (STM) became known as a powerful technique resolving single atoms in real space and performing locally high-quality spectroscopic measurements. This resulted in a deeper understanding of surface physics at the atomic scale. Nevertheless, making these pictures of the nano-world requires imaging times in the order of seconds. Consequently STM suffers from long capturing times which impedes investigating dynamical phenomena evolving on a millisecond timescale, such as the motion of atoms on a surface or catalysis. We developed a new technique [1], based on the ‘Lazy Fisherman’ technique [2], which combines fast detection of motion (1 ms) with high spatial resolution, with the only prerequisite that the motion is reversible.

As a proof of principle we visualized vortex oscillations in NbSe₂. Compared to the scanning Hall microscope [3], which probes the vortex lattice at a scale of the magnetic penetration depth, the STM probes the vortex lattice at the scale of the coherence length. This approach gives rise to a major improvement in spatial resolution which allowed us to observe vortices moving in different nano-scale orbits. These intriguing pathways originate from the interplay between pinning, inter-vortex forces and driving force determined by an irregular bulk crystal. Consequently simplifying the system by separating these forces would shed light on this complex system of vortex motion.

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In an attempt to shed some light onto the generic nature of Bragg glass (BG) to vortex glass (VG) transition (also known as second magnetization peak (SMP) anomaly), we have investigated a low Tc superconductor, Yb$_3$Rh$_4$Sn$_{13}$ via magnetization measurements, which has so far been explored [1] for the peak effect (PE) phenomenon. We observe that the BG to VG transition gets unearthed in this compound under the influence of an ac driving force inevitably present in the isothermal ac susceptibility measurements $\chi\prime(H)$. Surprisingly, the ac drive is found to play a counterintuitive role of enhancing the disorder in the vortex matter by triggering the BG to VG transition, which is against its usual effect of improving the state of spatial order [2]. The other modes of measurements, viz., isothermal dc M(H) and isofield ac susceptibility $\chi\prime(T)$ scans, revealed only a signature of PE anomaly at elevated fields; fingerprints of BG to VG transition was not observed in these measurements. The vortex matter prior to the domain of PE, i.e., above the BG to VG transition line in the H-T phase space of Yb$_3$Rh$_4$Sn$_{13}$, which appears from the outcomes of ac $\chi\prime(H)$ data to be a partially disordered (multi-domain) VG phase is indeed a well ordered (BG) phase from the perspective of the dc M-H loops. The vortex phase in this region can thus be taken as a superheated ordered BG phase which attests to the first-order nature of BG to VG transition. The new finding in Yb$_3$Rh$_4$Sn$_{13}$, i.e., assistance to the BG to VG transition by an ac drive corroborates our earlier assertions [3] in another low Tc superconductor Ca$_3$Ir$_4$Sn$_{13}$. However, in that study, we could not distinctly locate the phase boundary pertaining to the onset of the PE, as the two anomalies (SMP and PE) in Ca$_3$Ir$_4$Sn$_{13}$ were juxtaposed in an unresolved manner. The results of both dc M(H) scans and isofield ac $\chi\prime(T)$ runs in Yb$_3$Rh$_4$Sn$_{13}$ have revealed the onset of the PE at the same phase boundary which lies significantly above and well demarcated from the BG to VG transition. In the low-field region (H < 4 kOe), fingerprint of the PE feature was not identifiable in the magnetization data and hence the vortex matter in this region is surmised to be disordered. To our surprise, the history-dependent magnetization response (both ac and dc) in H < 4 kOe reflects a better spatially ordered state created via field-cooling (FC) than that obtained via zero field-cooled (ZFC) mode. This is in contrast to the usually observed behaviour [4] near the high-field order-disorder transition (PE) wherein a FC state is supposed to be supercooled disordered vortex matter whereas the ZFC state is comparatively better ordered. It is our surmise that the field value ~ 4 kOe marks a crossover from the (ordered) BG phase into a (re-entrant)disordered state [5] while lowering the field towards the lower critical field (H$_c$).
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THE EFFECT OF THE TEMPERATURE DISTRIBUTION ON THE EMISSION CHARACTERS OF THE Bi$_2$Sr$_2$CaCu$_2$O$_8$+δ THz EMITTING DEVICES.

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Bi$_2$Sr$_2$CaCu$_2$O$_8$+δ (Bi2212) crystals are composed of many stacks of intrinsic Josephson junctions (IJJs) along the c-axis direction. Strong coherent and continuous THz radiation can be observed from the mesa structure when IJJs are excited in the resistive state and two conditions, ac-Josephson effect and cavity resonance effect, are fulfilled [1]. However, the emission intensity of the THz radiation is about tens of μW at present. The power of these devices is still not sufficient for a wide variety of applications such as chemical, biological, sensing imaging etc.. It is important to make high power emitters for the applications with power of 1 mW or more. It is known that this device suffers from the huge Joule heating problem. Actually, in previous studies [2] as the dc current is increased to have resistive state, the inhomogeneous temperature distribution (hot spot) is observed by LTSLM (Low Temperature Scanning Laser Microscope) [2] and the photoluminescence technique using EuTFC [3]. However, the mesa temperature in those experiments cannot be directly measured. In addition, the surface structures of the device strongly influence the images, resulting in the fake results. In order to study such a Joule heating problem, we directly measured the mesa temperature with photoluminescence technique using SiC fine powder [4]. When the area of the SiC is irradiated with the UV light, the photoluminescence light emits from the SiC in accordance with the mesa temperature, and the intensity strongly depends on temperature. We succeeded in observing the clear images of the temperature distribution of the Bi2212 THz emitting devices [3, 4]. Moreover, we found that the sudden shift of the position of the hot spot occurred at the same time when the emission intensity was suddenly decreased [5]. In order to understand this phenomenon, we tried to control the position of the hot spot by heating the mesa locally with the focused laser beam. Actually, we succeeded in controlling the position of the hot spot and the drastically improve of the emission intensity was observed [6]. These results strongly suggest that the temperature distribution influences on the emission characters. Moreover, we observed the electrical potential distribution in the mesa by attaching the many electrodes on the mesa surface. In the conference, we show how the temperature and electrical potential distribution influence the emission characters.
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