EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

ESF Research Networking Programme
Nanoscience and Engineering in Superconductivity

International Workshop on

# Mesoscopic Superconductivity & Vortex Imaging

**Bath, U.K.**
**3 – 7 May, 2011**

ESF Research Networking Programme
Nanoscience and Engineering in Superconductivity

International Workshop on

Mesoscopic Superconductivity & Vortex Imaging

Bath, U.K.
3 – 7 May, 2011

# SCIENTIFIC PROGRAMME & ABSTRACTS

Workshop of the ESF *Nanoscience and Engineering in Superconductivity* (NES) Programme, supported by

European Science Foundation

Engineering & Physical Sciences Research Council (UK)

With additional support from

Oxford Instruments

Claridge Scientific Ltd.

Cryogenic Ltd.

Institute of Physics Publishing

Institute of Physics; Super. Group.

# Organisation

## Conference Chairman

Simon Bending

## Conference Secretary

Alison Humphries

## Local Organizing Committee

Peter Curran
Mohammed El Bana
Waled Desoky
Andy Moskalenko
André Müller

## NES Steering Committee

| | |
|---|---|
| Jan Aarts | Antonio Barone |
| Simon Bending | Øystein Fischer |
| Enno Joon | Jan Kolacek |
| Wolfgang Lang | Victor Moshchalkov |
| Niels F. Pedersen | Mikko Saarela |
| Peter Samuely | Asle Sudbø |
| Sebastian Vieira | Johan Vanacken |
| Dag Winkler | Roger Wördenweber |

**Workshop website**
http://staff.bath.ac.uk/pyssb/NES2011/NES2011.htm

*Front cover picture: Roman baths with Bath Abbey in the background.*
*Back cover picture: Aerial view of the Royal Crescent (background) and Circus (foreground).*

# Welcome Address

On behalf of the organising committee it gives me great pleasure to welcome you to this International Workshop on *Mesoscopic Superconductivity & Vortex Imaging* that is being held within the framework of the ESF Nanoscience and Engineering in Superconductivity (NES) Research Networking Programme.

You will all know that 2011 sees the $100^{th}$ anniversary of the discovery of superconductivity and the Workshop incorporates several activities to celebrate this. The foremost of these is an opening address by Professor Peter Kes who will share with us the latest results of his investigations into the work of Heike Kamerlingh Onnes in Leiden which led to the discovery.

The main themes of the Workshop are new physics arising from the mesoscopic confinement of the superconducting condensate, as well as the use of various probes to visualise flux structures that arise within it. The programme is, however, much broader in scope than this and includes sessions on several other topics of major current scientific interest, e.g., spin triplet superconductivity, novel phenomena in multiband superconductors, THz emission and new superconducting materials systems.

We hope that bringing so many leading experts in the field together with a large number of young scientists will generate a stimulating environment that fosters exciting new ideas and collaborations. I wish you a very enjoyable stay in the beautiful historic city of Bath.

*Simon Bending*

# Programme

| | Tuesday 3.5.2011 | Wednesday 4.5.2011 | Thursday 5.5.2011 | Friday 6.5.2011 | Saturday 7.5.2011 |
|---|---|---|---|---|---|
| 08:30-09:00 | | Opening | Prozorov | Blamire | |
| 09:00-09:30 | | Kes | Carrington | Aarts | |
| 09:30-10:00 | | Gutierrez Royo | Tamegai | Winkler | |
| 10:00-10:30 | | Aguiar | EPSRC Guernion | Lee | Departure |
| 10:30-11:00 | | Coffee | Coffee | Coffee | |
| 11:00-11:30 | | Fasano | Durrell | Annett | |
| 11:30-12:00 | | Milošević | Samuely | Hasselbach | |
| 12:00-12:30 | | Roditchev | Lang | Tafuri | |
| 12:30-13:00 | | | Joon | | |
| 13:00-13:30 | Arrival | Lunch | Packed Lunch | Lunch | |
| 13:30-14:00 | | | Departure: 13:15 | | |
| 14:00-14:30 | | | Excursion to | | |
| 14:30-15:00 | | Kirtley | Stonehenge | Warburton | |
| 15:00-15:30 | Registration | Zeldov | & Lacock | Savel'ev | |
| 15:30-16:00 | desk opens | Forgan | | Rodrigo | |
| 16:00-16:30 | | Coffee | | Coffee | |
| 16:30-17:00 | | Suderow | | Kadowaki | |
| 17:00-17:30 | | Crisan | | Kleiner | |
| 17:30-18:00 | | Wördenweber | Return: 17:15 | Kusmartsev | |
| 18:00-18:30 | Welcome | Laviano | | Dinner | |
| 18:30-19:00 | reception | | | | |
| 19:00-19:30 | *(Finger buffet)* | | | | |
| 19:30-20:00 | | Dinner | Conference | | |
| 20:00-20:30 | | | dinner | Open | |
| 20:30-21:00 | | Poster | | forum | |
| 21:00-21:30 | | presentations | *Live music* | & closing | |
| 21:30-22:00 | | | *21:00 – 24:00* | *(Drinks served)* | |
| 22:00-22:30 | | | | | |
| 22:30-23:00 | | | | | |
| 23:00-23:30 | | | | | |
| 23:30-24:00 | | | | | |

# Programme

**Tuesday 3rd May**

15:00-20:00 Registration (Kennet room)

**18:00-20:00 Welcome reception (Kennet room)**

## Wednesday 4th May

**07:00-08:30 Continental breakfast (Vellore restaurant)**

08:30-08:45 Simon Bending: *Opening (Avon room)*

**Chair: Simon Bending**

08:45-09:30 Peter Kes: *Kamerlingh Onnes's Notebooks and the Discovery of Superconductivity*

**Session 1 – Multiband Superconductivity (Avon room)**

**Chair: Wolfgang Lang**

09:30-10:00 Joffre Gutierrez Royo: *Vortex Matter in Type-1.5 Superconductors*

10:00-10:30 Albino Aguiar: *Vortex state for two band superconductors: a time dependent Ginzburg-Landau theory approach*

**10:30-11:00 Coffee**

**Session 2 – Mesoscopic Superconductivity (Avon room)**

**Chair: Feodor Kusmartsev**

11:00:11:30 Yanina Fasano: *The low-field vortex phase in mesoscopic vortex matter*

11:30-12:00 Milorad Milošević: *Formation and manipulation of multi-quanta vortices in superconductors: electronic, calorimetric and magnetic evidence*

12:00-12:30 Dimitri Roditchev: *Visualizing Meissner currents in nanometer-scale superconductors with Scanning Tunneling Spectroscopy*

**12:30-14:30 Lunch (Vellore restaurant)**

## Session 3 – Vortex Imaging (Avon room)

### Chair: Ruslan Prozorov

14:30-15:00 John Kirtley: *SQUID microscopy: the next generation*

15:00-15:30 Eli Zeldov: *Scanning nanoscale SQUID on a tip for study of vortex dynamics*

15:30-16:00 Ted Forgan: *Flux lines in conventional and unconventional superconductors imaged with neutrons*

**16:00-16:30 Coffee**

16:30-17:00 Hermann Suderow: *Superconductivity and vortex imaging through Scanning Tunneling Spectroscopy at very low temperatures*

17:00-17:30 Adrian Crisan: *Direct visualisation of re-entrant vortex lattice melting by scanning Hall probe microscopy*

## Session 4 – Cuprate Superconductivity I (Avon room)

### Chair: Francesco Tafuri

17:30-18:00 Roger Wördenweber: *Microwave properties of Abrikosov vortices in micro and submicro structured high-$T_c$ films*

18:00-18:30 Francesco Laviano: *Local Joule heating effects in micro-patterned YBCO films studied by magneto-optical imaging with concurrent electrical transport measurements*

**19:30-20:30 Dinner (Avon room)**

**20:30-22:30 Poster Session (Avon room)**

## Thursday 5th May

**07:00-08:30 Continental breakfast (Vellore restaurant)**

**Session 5 – Fe-based Superconductors (Avon room)**

**Chair: Kazuo Kadowaki**

08:30-09:00 Ruslan Prozorov: *Optical and Magneto-Optical Imaging of Fe-based Superconductors*

09:00-09:30 Tony Carrington: *Fermiology of Iron Based Superconductors*

09:30-10:00 Tsuyoshi Tamegai: *Vortex Dynamics in Pristine and Irradiated Iron-based Superconductors*

**10:00-10:30 Nicolas Guernion: *The EPSRC Portfolio in Superconductivity and Magnetism: current status and future plans***

**10:30-11:00 Coffee**

11:00:11:30 John Durrell: *Vortex channelling at Low Angle Grain Boundaries in Ba-122 thin films*

11:30-12:00 Peter Samuely: *Scanning Tunneling Spectroscopy of Superconducting Energy Gap in $SrPd_2Ge_2$ Single Crystal, Isostructural with 122 Iron Pnictides*

**Session 6 – Cuprate Superconductivity II (Avon room)**

**Chair: Francesco Tafuri**

12:00-12:30 Wolfgang Lang: *Non-Ohmic resistivity and Hall conductivity in the pseudogap regime of the underdoped cuprate superconductor $YBa_2Cu_3O_{6+x}$*

| | |
|---|---|
| 12:30-13:00 | Enno Joon: *Polarons in High-$T_c$ Cuprates* |
| **13:00-13:15** | **Change and pick up packed lunch** |
| **13:15-17:15** | Workshop excursion to Stonehenge and Lacock. Coach will pick up outside main Hotel entrance. |
| **19:30-20:00** | **Drinks reception (Avon room)** |
| **20:00-24:00** | **Conference dinner (Avon room)** |

## Friday 6th May

**07:00-08:30 Continental breakfast (Vellore restaurant)**

**Session 7 – Spin Triplet Superconductivity (Avon room)**

**Chair: John Kirtley**

08:30-09:00 Mark Blamire: *Triplet supercurrents*

09:00-09:30 Jan Aarts: *Micron-ranged supercurrents induced in the halfmetallic ferromagnet* $CrO_2$

09:30-10:00 Dag Winkler: *Transport properties of hybrid heterostructures with superconducting/magnetic interfaces*

10:00-10:30 Steve Lee: *Neutron and Muon Experiments on Superconducting-Magnetic Thin Films*

**10:30-11:00 Coffee**

11:00:11:30 James Annett: *Intrinsic orbital magnetism and optical dichroism of the multi-band pairing state of the chiral superconductor* $Sr_2RuO_4$

11:30-12:00 Klaus Hasselbach: *Magnetic fields above the superconducting ferromagnet UCoGe*

**Session 8 – Josephson Junctions (Avon room)**

**Chair: Dimitri Roditchev**

12:00-12:30 Francesco Tafuri: *Increasing quality factor in YBaCuO Josephson junctions and mesoscopic fingerprints*

**12:30-14:30 Lunch (Vellore restaurant)**

14:30-15:00 Paul Warburton: *Intrinsic Josephson Junctions with Intermediate Damping*

15:00-15:30 Sergey Savel’ev: *Josephson Junctions as Quantum Ratchets and Quantum Metamaterials*

15:30-16:00 Jose Rodrigo: *Pair breaking effects on the superconducting density of states studied by tunnelling spectroscopy using STM/STS*

**16:00-16:30 Coffee**

**Session 9 – THz Emission (Avon room)**

**Chair: Roger Wördenweber**

16:30-17:00 Kazuo Kadowaki: *Dynamical Coherence Phenomena in High Temperature Superconductors: Terahertz Radiation and its Applications*

17:00-17:30 Reinhold Kleiner: *Coherent Terahertz Emission of Intrinsic Josephson Junction Stacks in the Hot Spot Regime*

17:30-18:00 Feodor Kusmartsev: *Powerful Flux-Flow Oscillator (FFO) operating in Terahertz frequency range and the Fluxon Cloning Phenomena*

**18:00-19:15 Dinner (Vellore restaurant). Dessert & coffee served in the Grange Drawing Room.**

**20:00-22:00 Open forum & closing (Grange Main Suite).** *Reflections on one hundred years of superconductivity; challenges and opportunities for the future.* (Drinks will be served)

# ABSTRACTS

## Kamerlingh Onnes's Notebooks and the Discovery of Superconductivity

Peter Kes

*Kamerlingh Onnes Laboratory, Leiden Institute of Physics, Leiden University, Netherlands*

kes@physics.leidenuniv.nl

A century ago Heike Kamerlingh Onnes and his collaborators were the first to observe superconductivity. Although accidental, his retraced notebooks tell us today that this was the result of a well planned research program which was started after liquid helium temperatures were reached.

**Reference**

A complete version of this article with references appeared in the September issue of Physics Today **63** (2010) 38-43, *The discovery of superconductivity*, by Dirk van Delft and Peter Kes.
It is available at
http://ptonline.aip.org/journals/doc/PHTOAD-ft/vol_63/iss_9/38_1.shtml?type=PTALERT

## Session 1 – Multiband Superconductivity (Avon room)

**Chair: Wolfgang Lang**

## Vortex Matter in Type-1.5 Superconductors (*)

Joffre Gutierrez Royo and Victor V. Moshchalkov

*INPAC-Institute for Nanoscale Physics and Chemistry, University of Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium*

The existence of the novel superconducting state has been demonstrated in two-component high quality $MgB_2$ single crystalline superconductors where a unique combination of both type-1 and type-2 conditions is realized in a single material: $\lambda_1/\xi_1<1/\sqrt{2}$ for the first component of the order parameter and $\lambda_2/\xi_2>1/\sqrt{2}$ for the second one. Such materials are, in fact, neither type-1 nor type-2 superconductors (PRB **72**, 180502 (2005)) and can be introduced as "*type-1.5 superconductors"* (PRL **102**, 117001 (2009); PRB **81**, 020506(R) (2010); PRB **83**, 020503(R) (2011)), since they combine simultaneously characteristic features of both type-1 and type-2 regimes. This leads to a drastic change in the vortex-vortex interaction, which results in the appearance of stable *vortex stripes, clusters and gossamer-like vortex patterns.* We have directly visualized these novel patterns by using scanning Hall probe microscopy, Bitter decoration and scanning SQUID microscopy. The observed patterns are in a good agreement with the molecular dynamics simulations based on the vortex-vortex interaction corresponding to the type-1.5 superconductivity.
These data are also compared with the exotic vortex-vortex interactions in the so called "intermediate/mixed state" observed earlier in single gap superconductors in the vicinity of the special point $\lambda/\xi=1/\sqrt{2}$.

(*) In collaboration with: A.V. Silhanek, T. Nishio, Q.H. Chen, M. Menghini, L.J. Li, B. Raes, A. Gebremedhin, V. H. Dao, L.F. Chibotaru, N. D. Zhigadlo, and J. Karpinski

# Vortex state for two band superconductors: a time dependent Ginzburg-Landau theory approach

J. Barba-Ortega[1] Miryam R. Joya[1] and J. Albino Aguiar[2]

[1]*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
[2]*Departamento de Física, Universidade Federal de Pernambuco, 50670-901, Recife, Brazil*

Using the nonlinear Ginzburg–Landau theory, we investigate the equilibrium vortex configurations in a thin two-gap superconducting film. For two-gap superconductors, the conveniently written GL equations directly show that the magnetic behavior of the sample depends not just on the GL parameter of two bands, but also on the ratio of respective coherence lengths. We demonstrate further the existence and stability of fractional states, for which the two condensates comprise different vorticity. Also we compare the vortex configurations between both, one band superconductor and two band superconductors.

Work financed by CNPq and FACEPE.

## Session 2 – Mesoscopic Superconductivity (Avon room)
## Chair: Feodor Kusmartsev

## The low-field vortex phase in mesoscopic vortex matter

Yanina Fasano[1], M. I. Dolz[2], R. N. Cejas Bolecek[1], A. B. Kolton[3], H. Pastoriza[1]

[1]*Low Temperatures Lab and Instituto Balseiro, Centro Atómico Bariloche, Argentina.*
[2]*Institute of Applied Physics, Physics Department, San Luis University, Argentina*
[3]*Solid State Theory group, Centro Atómico Bariloche, Argentina.*

Weak disorder in the low-field and temperature phase of vortex matter competes with the elasticity of the structure resulting in the establishment of two different pinning regimes. At short distances vortices are individually pinned, the so-called Larkin pinning regime. For distances larger than the crossover Larkin lengths vortices collectively pin in a random manifold regime [1]. The crossover length $r_c$ is achieved when vortex displacements with respect to a perfect lattice are larger than the pinning force range. For the case of the high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8+y}$ the in-plane crossover length is in the range of microns and for a given field depends on temperature. Therefore, sufficiently reducing the sample size results in a *mesoscopic Larkin vortex phase* that is not evident in macroscopic systems. In this work we engineered micron-ranged disks from bulk $Bi_2Sr_2CaCu_2O_{8+y}$ samples by combining optical lithographic and etching techniques [2]. We use the magnetic decoration technique in order to take snapshots of the mesoscopic vortex structure, with single vortex resolution, at the irreversibility temperature [3]. The dependence of the positional order on the sample size is discussed in connection to the variation of the Larkin length with temperature.

[1] T. Giamarchi and P. L. Doussal, Phys. Rev. Lett. **72**, 1530 (1994). T. Giamarchi and P. L. Doussal, Phys. Rev. B. **52**, 1242 (1995).
[2] M. I. Dolz, A. B. Kolton and H. Pastoriza, Phy. Rev. B **81**, 092502 (2010).
[3] Y. Fasano and M. Menghini, Supercond. Sci. and Tech. **21**, 023001 (2008).

# Formation and manipulation of multi-quanta vortices in superconductors: electronic, calorimetric and magnetic evidence

M. V. Milošević*

*Departement Fysica, Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium*

The ground state with vorticity larger than one in mesoscopic superconductors in applied magnetic field may manifest as a 'giant'-vortex, where all vortices coalesce into a single singularity of the order parameter [1]. Such a multi-quanta vortex may split into individual vortices (and vice versa) as a function of e.g. magnetic field or temperature. However, the existence of a giant-vortex has not yet been verified in experiment with absolute certainty [2]. Here I show that individual-to-giant vortex transitions can be identified by heat-capacity measurements, as the formation or splitting of giant-vortex results in a clear jump in measured heat capacity vs. external drive. We attribute this phenomenon to an abrupt change in the density of states of the quasiparticle excitations in the vortex core(s), and further link it to a sharp change of the magnetic susceptibility at the transition - proving that formation of a giant-vortex can also be detected by conventional magnetometry.

I further discuss the possibilities for manipulation of a giant-vortex by strategic current injection [3]. In particular, I will show simulations and experimental verification of current-driven splitting of a giant-vortex, current-induced transitions between giant-vortex states with different vorticity, and current-controlled switching between otherwise degenerate vortex states. These fundamental phenomena form the basis for electronic and logic applications of vortices.

---

*Email address: milorad.milosevic@ua.ac.be

[1] V.A. Schweigert, F.M. Peeters, and P.S. Deo, Phys. Rev. Lett. **81**, 2783 (1998).
[2] A. Kanda, B.J. Baelus, F.M. Peeters, *et al.*, Phys. Rev. Lett. **93**, 257002 (2004);
I.V. Grigorieva, W. Escoffier, V.R. Misko, *et al.*, Phys. Rev. Lett. **99**, 147003 (2007).
[3] M.V. Milošević, A. Kanda, S. Hatsumi, *et al.*, Phys. Rev. Lett. **103**, 217003 (2009).

# Visualizing Meissner currents in nanometer-scale superconductors with Scanning Tunneling Spectroscopy

T. Cren, L. Serrier-Garcia, F. Debontridder, Ch. Brun, and D. Roditchev

*Institute for Nano-Sciences of Paris (INSP), UMR75-88 au CNRS, University Pierre et Marie Curie Paris 6 UPMC, 4 place Jussieu, Paris, France*

Since the pioneering work by Hess et al. [1] the Scanning Tunneling Spectroscopy is widely used to visualize the vortices in superconductors and to study their cores. In nano-scale superconductors where the confinement effects are strong, the vortex configurations are different from the Abrikosov lattice [2,3]. The vortex arrangements are complex, and the individual vortex cores may not be always easily discriminated.

In order to determine the vorticity – the number of vortices sitting inside a given superconducting nano-object, we use the fact that the quasiparticle excitation spectrum of a superconductor is sensitive to the supercurrents through the pair-breaking [4] or Doppler effects [5]. Owing to this sensitivity, we probe locally the Meissner currents at the periphery of nano-superconductors subject to external magnetic field. We show that the Meissner currents flowing at the sample periphery change each time a new vortex enters and thus, the vorticity in each individual nano-superconductors may be determined with high precision for any vortex configuration.

References

1. H. F. Hess *et al*., Phys. Rev. Lett. **62**, 214 (1989).
2. V. A. Schweigert, F. M. Peeters, P. Singha Deo, Phys. Rev. Lett. **81**, 2783 (1998).
3. T. Cren et al., Phys. Rev. Lett. **102** 127005 (2009).
4. K. Maki, P. Fulde, Phys. Rev. **140**, A1586 (1965).
5. A. Kohen et al., Phys. Rev. Lett. **97**, 027001 (2006).

## Session 3 – Vortex Imaging (Avon room)

**Chair: Ruslan Prozorov**

# SQUID microscopy: the next generation

J.R. Kirtley,[†] B. Klopfer,[†] G.W. Gibson, Jr.,[§] M.B. Ketchen,[§] H. Bluhm,[¶] and K.A. Moler [†]

*[†] Geballe Laboratory for Advanced Materials, Stanford University, Stanford, CA, USA 94305-4045*
*[§] IBM Research Division, T.J. Watson Research Center, Yorktown Heights, NY, USA 10598*
*[¶] 2nd Institute of Physics C, RWTH Aachen University, 52074 Aachen, Germany*

High spatial resolution can be attained in scanning Superconducting Quantum Interference Device (SQUID) microscopy either by making very small SQUIDs,[1,2] or by integrating small pickup loops into larger, more conventional SQUIDs.[3,4] We are using the latter strategy to design and build the next generation of scanning SQUID sensors as part of a joint Stanford-IBM collaboration to build a user facility at Stanford.[5] Our SQUID manufacturing process uses trilayer Nb technology and features linewidths and spacings as narrow as 100 nm for the last two layers of metallization, as well as device planarization throughout. This allows the fabrication of circular pickup loops with 300 nm diameters that can be scanned within a few hundred nm of the sample surface. In addition, we are pursuing high temporal resolution using two strategies: RF SQUID resonators with integrated pickup loops that are predicted to combine high flux sensitivity with a bandwidth up to on the order of 100 MHz; and SQUID samplers, also with integrated pickup loops, that are modelled to have <10 psec time resolution for repetitive signals. The resultant instrument will be a powerful tool for studying vortex matter.

[1] C. Veauvy, K. Hasselbach, and D. Mailly, Rev. Sci. Instr. **73**, 3825 (2002).
[2] A. Finkler *et al.,* Nano Lett. **10**, 1046 (2010).
[3] M.B. Ketchen and J.R. Kirtley, IEEE Trans. Appl. Supercond. **5**, 2133 (1995).
[4] N.C. Koshnick *et al.,* Appl. Phys. Lett. **93**, 243101 (2008).
[5] Funded by the NSF DMR-IMR program, proposal number 0957616.

# Scanning nanoscale SQUID on a tip for study of vortex dynamics

Eli Zeldov

*Department of Condensed Matter Physics*
*Weizmann Institute of Science, Rehovot 76100, Israel*

*eli.zeldov@weizmann.ac.il*

We developed a method for self-aligned fabrication of smallest superconducting quantum interference devices (SQUID) on a sharp tip suitable for scanning probe microscopy [1]. A quartz tube is pulled into a sharp pipette with an aperture diameter ranging between 100 and 400 nm at its tip. The “SQUID on a tip” is fabricated by three simple steps of thermal evaporation of a thin superconducting film onto the sides and the tip of the pipette. This self-aligned fabrication method requires no additional lithographic processing or etching. An aluminum nanoSQUID with effective diameter of 208 nm displays flux sensitivity of $1.8\times10^{-6}$ $\Phi_0/\mathrm{Hz}^{1/2}$ and expected spin sensitivity of 65 $\mu_B/\mathrm{Hz}^{1/2}$. The SQUID on tip operates in fields of up to 0.5 T and has a very high bandwidth. We have constructed a scanning probe microscope based on these nanoSQUIDs. By gluing the pipette to a quartz tuning fork we can approach the sample to within a few nm and measure simultaneously the sample topography and the magnetic field landscape. The resulting scanning SQUID-on-tip microscope can provide quantitative, high-sensitivity mapping of static and dynamic magnetic fields on a nanometer scale for study of vortex matter in superconductors and quantum magnetic phenomena.

[1] A. Finkler, Y. Segev, Y. Myasoedov, M. L. Rappaport, L. Ne’eman, D. Vasyukov, E. Zeldov, M. E. Huber, J. Martin, and A. Yacoby, *Nano Lett.* **10**, 1046 (2010).

# Flux lines in conventional and unconventional superconductors imaged with neutrons

Ted Forgan[1] (on behalf of a large number of UK & international collaborators)

*School of Physics & Astronomy, University of Birmingham, B15 2TT, UK*

It is now more than 50 years since Abrikosov's famous prediction of the existence of flux lines in type-II superconductors [1], and 47 years since their observation by small-angle neutron scattering (SANS) [2]. Nevertheless, this is still a very active area of work, partly due to huge improvements in SANS instrumentation over time, but mainly because of the increased interest in unconventional materials sparked by the discovery of High-$T_c$ superconductors. We shall concentrate on what can be learned from recent measurements on a pnictide material [3], and the possibilities afforded by the recent commissioning of our dedicated cryomagnet [4], which allows SANS observations up to the previously unrealised field of 17 T.

[1] A. A. Abrikosov, Sov. Phys. JETP **5**, 1174 (1957).
[2] D. Cribier, B. Jacrot, L. Madhav Rao & B. Farnoux, Phys. Lett. **9**, 109 (1964).
[3] H. Kawano-Furukawa *et al.*, arXiv 1005.4468v2, & to be published (2011).
[4] http://www.cm.ph.bham.ac.uk/grants/fluxlinesgrant/moses_effect.html

[1]email: E.M.Forgan@bham.ac.uk

# Superconductivity and vortex imaging through Scanning Tunneling Spectroscopy at very low temperatures

H. Suderow

*Laboratorio de Bajas Temperaturas,*
*Departamento de Física de la Materia Condensada,*
*Instituto de Ciencia de Materiales,*
*N. Cabrera Universidad Autónoma de Madrid*

Hermann.suderow@uam.es

Scanning Tunneling Microscopy and Spectroscopy (STM/S) down to 100mK is an efficient tool to image vortices and study superconductors. The local electronic density of states is obtained at atomic level with a resolution in energy of some tens of micro eV. In this talk, I will discuss measurements of the local density of states of layered transition metal dichalcogenides ($MX_2$ where M=Nb,Ta and X=S,Se), which show particularly interesting superconducting properties, related to the effect of charge order on superconductivity. While the vortex cores of $NbSe_2$ have a hexagonal shape due to the charge density wave, in $TaS_2$ superconductivity coexists with chiral charge order.

# Direct visualisation of re-entrant vortex lattice melting by scanning Hall probe microscopy

A. Crisan[1,2,3], S.J. Bending[2], Z.Z. Li[4], H. Raffy[4]

[1] *School of Metallurgy and Materials, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*
[2] *Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK*
[3] *National Institute of Materials Physics, PO Box MG-7, Bucharest 077125, Romania*
[4] *Laboratoire de Physique des Solides, Bâtiment 510, UMR 8502, Université Paris-Sud, 91405 Orsay, France*

We have used scanning Hall probe microscopy to investigate vortex structures and vortex dynamics in $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin films in very low perpendicular magnetic fields. In fields of a few Oersted, we find that the vortices are in a stable glassy state in our rather disordered samples. However, upon lowering the magnetic field we enter a new phase where the only image contrast is due to vortices that are intermittently trapped on strong pinning centres. We speculate that this state corresponds to the re-entrant vortex liquid that has been theoretically predicted in these highly anisotropic materials [1]. Analysing the trapping times for vortices in the liquid state we estimate that the pinning potential of typical strong pinning centres is about 1000 K under our experimental conditions. To our knowledge, this is the first direct experimental evidence for the existence of a re-entrant vortex liquid at very low magnetic inductions.

[1] Blatter G., Geshkenbein V., Larkin A., and Nordborg H., *Phys. Rev*. B, **54** (1996) 72.

## Session 4 – Cuprate Superconductivity I (Avon room)

## Chair: Francesco Tafuri

## Microwave properties of Abrikosov vortices in micro and submicro structured high-$T_c$ films

R. Wördenweber, E. Hollmann, J. Schubert, and G. Panaitov

*Peter Grünberg Institute and JARA-Fundamentals of Future Information Technology , Forschungszentrum Jülich , D-52425 Jülich, Germany*

e-mail: r.woerdenweber@fz-juelich.de

The understanding of flux transport in mesoscopic or even nanostructured superconducting systems that are exposed to electric fields (low and high-frequencies) is of interest for basic aspects of vortex matter and for potential application of superconductivity in fluxonic devices. We report on combination of dc and microwave (ranging from MHz to 20GHz) electronic measurements on micro- and submicro-patterned HTS films. Changes of the transmission coefficient $S_{21}$ in experiments with mixed dc-rf currents indicate that microwave flux transport in form of Abrikosov vortices is limited by the Larkin-Ovchinnikov critical velocity. Above a geometrically defined frequency flux transport is most likely provided by a phase-slip type of mechanism. For example for 1.5μm structures this limiting frequency is about 2.5-3GHz. Nevertheless, guidance of flux (for instance via artificial arrays of holes/antidots) persists in these patterns up to much higher frequencies. The data obtained at microwave frequencies agree with values obtained for the critical vortex velocity with dc pulse measurements. The implication for the modification of the transport mechanism for fluxonic devices operating in the GHz regime will be discussed.

# Local Joule heating effects in micro-patterned YBCO films studied by magneto-optical imaging with concurrent electrical transport measurements

Francesco Laviano, Roberto Gerbaldo, Gianluca Ghigo, Laura Gozzelino

*Department of Physics, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

e-mail: francesco.laviano@polito.it

Critical temperature and critical current of superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) films can be locally tailored by means of irradiation with micro-collimated high-energy heavy-ion beams. In this way, continuous YBCO strips were patterned with regions of micrometric shapes which are perpendicularly crossing the superconducting strip and whose local critical temperature is reduced with respect to the as-grown material. In the resistive flux-flow state, the enhanced dissipation of the irradiated regions can be exploited for position-sensitive magnetic field and photon detectors [1]. In the superconducting state, current-voltage characteristics of these micro-patterned YBCO samples exhibit strong non linearity, hysteresis and negative differential resistance for electrical currents below the critical values. We analyzed this behavior in the framework of multi-stability models accounting for local Joule heating [2]. Moreover, the dynamics of the magnetic pattern in the sample, during electrical transport measurements, was visualized by means of time-resolved magneto-optical imaging with an indicator film [3]. Direct evidence of local Joule heating was found and observation of thermal wave propagation along the sample gives straightforward insights about multi-stability mechanisms. In particular, two regimes can be identified in dependence on the base temperature: a dramatic normal state transition of the whole sample due to thermal wave propagation from contacts where the electrical current is injected and formation of thermal hot spots inside the micro-pattern with reduced critical temperature and critical current, due to the motion of vortices.

[1] F. Laviano, R. Gerbaldo, G. Ghigo, L. Gozzelino, B. Minetti, and E. Mezzetti, *Appl. Phys. Lett.* **89**, 082514 (2006); F. Laviano, R. Gerbaldo, G. Ghigo, L. Gozzelino, B. Minetti, A. Rovelli, E. Mezzetti, *IEEE Sensors Journal* **10**, 863 (2010)
[2] A. Gurevich and R. G. Mints, *Rev. Mod. Phys.* **59**, 941 (1987)
[3] F. Laviano, D. Botta, A. Chiodoni, R. Gerbaldo, G. Ghigo, L. Gozzelino, S. Zannella, and E. Mezzetti, *Supercond. Sci. Technol.* **16**, 71(2003)

## Session 5 – Fe-based Superconductors (Avon room)

## Chair: Kazuo Kadowaki

## Optical and Magneto-Optical Imaging of Fe-based Superconductors

Ruslan Prozorov

*The Ames Laboratory and Department of Physics & Astronomy, Iowa State University, Ames, IA 50011, USA*

Prozorov@ameslab.gov

Studies of mesoscopic magnetic properties are extremely useful for material where magnetic induction varies across the sample with most prominent examples being superconductors and ferromagnets. In the case of Fe-based superconductors such studies allowed identification and measurements of very first single crystals [1]. Later, combined with the direct observation of structural domains [2], these measurements allowed investigation of the coexistence of magnetism and superconductivity as well as investigating such intriguing phenomena as electronic nematic order [3]. Measurements of local magnetic properties with magneto-optics as well as micro Hall-probe arrays have revealed interesting vortex physics in pnictides [4,5]. Specifically, while these superconductors show many similarities with the cuprates, they also have distinct vortex behavior, yet different from conventional superconductors. These results can be interpreted from several points of view, including three-dimensional electronic structure of the pnictides, coexistence and competition of superconductivity and magnetism, two distinct superconducting gaps as well as effects of unconventional pairing and strong pair-breaking. I will discuss possible explanations of the observed behavior and conclude that pnictide superconductors bridge a gap between s-wave multiband $MgB_2$ and highly anisotropic d-wave cuprates.

1. R. Prozorov, M. E. Tillman, E. D. Mun, and P. C. Canfield, arXiv:0805.2783 (19 May 2008) Intrinsic magnetic properties of the superconductor NdFeAsO0.9F0.1 from local and global measurements, *New Journal of Physics,* **11**, 035004 (2009).
2. M. A. Tanatar, A. Kreyssig, S. Nandi, N. Ni, S. L. Bud'ko, P. C. Canfield, A. I. Goldman, and R. Prozorov, Direct imaging of the structural domains in the iron pnictides AFe(2)As(2) (A=Ca,Sr,Ba), *Physical Review B,* **79** (2009).
3. M. A. Tanatar, N. Ni, G. D. Samolyuk, S. L. Bud'ko, P. C. Canfield, and R. Prozorov, Resistivity anisotropy of AFe(2)As(2) (A=Ca, Sr, Ba): Direct versus Montgomery technique measurements, *Physical Review B,* **79** (2009).
4. R. Prozorov, M. A. Tanatar, B. Roy, N. Ni, S. L. Bud'ko, P. C. Canfield, J. Hua, U. Welp, and W. K. Kwok, Magneto-optical study of Ba(Fe1-xMx)(2)As-2 (M=Co and Ni) single crystals irradiated with heavy ions, *Physical Review B,* **81** (2010).
5. R. Prozorov, M. A. Tanatar, N. Ni, A. Kreyssig, S. Nandi, S. L. Bud'ko, A. I. Goldman, and P. C. Canfield, Intrinsic pinning on structural domains in underdoped single crystals of Ba(Fe1-xCox)(2)As-2, *Physical Review B,* **80** (2009).

## Fermiology of Iron Based Superconductors

Antony Carrington*

*University of Bristol, UK*

a.carrington@bristol.ac.uk

An important step towards understanding the physics of iron based superconductors is to discover how the Fermi surface evolves as the material passes from an antiferromagnetic spin density wave state, through the superconducting dome and eventually towards a paramagnetic non-superconducting metal. Relating the changes in the topology of the Fermi surface and renormalisation of quasiparticle dispersions to the changes in the superconducting properties (e.g., the size and anisotropy of the superconducting gap), can provide a guide to our theoretical understanding.

High field magneto-oscillation phenomena, such as the de Hass-van Alphen (dHvA) effect, are a powerful probe of the full three dimension electronic structure. In this talk I will describe measurements of the dHvA effect in a series of iron-based superconductors and related materials: LaFePO, $SrFe_2P_2$, $CaFe_2P_2$, and the series $BaFe_2\,(As_{1-x}P_x)_2$, and relate these to the band-structure calculated using density functional theory. We find that these calculations provide a good starting point but important differences exist. Most importantly we find that the volume of the compensated electron and hole Fermi surface sheets is significantly less than that calculated and the quasiparticle masses are higher. Both of these effects seem to be driven by electronic correlations which become stronger as the spin density wave boundary is approached and superconducting correlations become strong.

* Work done in collaboration with: A.I. Coldea, A.F. Bangura, J.D. Fletcher, P.M.C. Rourke, C. J. Andrew, I. Guillamon, C. Putzke (Univ. Bristol); H. Shishido, S. Tonegawa, K. Hashimoto, S. Kasahara, S. Tonegawa, K. Hashimoto, H. Ikeda, Y. Matsuda, T. Shibauchi (Kyoto Univ.), T. Terashima; R. Settai (Osaka Univ), Y. Onuki; R.D. McDonald (Los Alamos); D. Vignolles, C. Proust, B. Vignolle (LNCMI Toulouse), A. McCollam (HFML, Nijmegen); J.G. Analytis, J.-H. Chu. A.S. Erickson, I.R. Fisher (Stanford Univ.).

# Vortex Dynamics in Pristine and Irradiated Iron-based Superconductors

T. Tamegai[a,b], Y. Nakajima[a,b], T. Taen[a], H. Yagyuda[a], S. Mohan[a]. T. Taniguchi[a], S. Okayasu[c], M. Sasase[d], H. Kitamura[e], T. Murakami[f], T. Kambara[g], and Y. Kanai[h]

[a]*Department of Applied Physics, The University of Tokyo, Tokyo, Japan*
[b]*JST, Transformative Research on Iron-Pnictide (TRIP), Tokyo, Japan*
[c] *Advanced Science Research Center, Japan Atomic Energy Agency, Ibaraki, Japan*
[d] *The Wakasa-wan Energy Research Center, Fukui, Japan*
[e]*Rad. Meas. Res. Sec., Nat. Inst. of Radiological Sciences, Chiba, Japan*
[f]*Dep. of Accelerator and Med. Phys., Nat. Inst. of Radiological Sciences, Chiba, Japan*
[g]*Nishina Center, RIKEN, Saitama, Japan*
[h]*Atomic Physics Laboratory, RIKEN, Saitama, Japan*

e-mail: tamegai@ap.t.u-tokyo.ac.jp

Dynamics of vortices are studied in two representative iron-based superconductors Co-doped $BaFe_2As_2$ and Fe(Te,Se) by measuring temporal relaxation of bulk magnetization. We find an anomalous suppression of normalized relaxation rate of magnetization $S = |d\ln M/d\ln t|$ at low fields in both Co-doped $BaFe_2As_2$ and Fe(Te,Se) single crystals [1-3]. The suppression occurs when the applied magnetic field is roughly below the self-field trapped in the crystal. A similar effect has been already reported in cuprate superconductors [4]. We also find that the anomaly is suppressed by artificial defects created by proton or heavy-ion (Au, Xe, U) irradiation. How it is suppressed depends on the degree of correlation of introduced defects. Correlated defects most effectively suppress the low-field anomaly in *S*. We propose "Meissner hole" [5] as a possible origin for the anomaly [3]. Magneto-optical imaging of the remagnetization process reveals the presence of a finite step in the local induction close to $B = 0$, which can be produced by extra current accompanied by "Meissner hole".

[1] Y. Nakajima *et al.*, Phys. Rev. B **80**, 012510 (2009).
[2] T. Taen *et al.*, Physica C **470**, 1106 (2010).
[3] T. Tamegai *et al.*, to be published in Physica C.
[4] T. Tamegai *et al.*, Czech. J. Phys. Suppl. S3, 1733 (1996).
[5] V. K. Vlasko-Vlasov *et al.*, Phys. Rev. B **56**, 5622 (1997).

# Vortex channelling at Low Angle Grain Boundaries in Ba-122 thin films

J. H. Durrell[1], S. Lee[2], J. Jiang[3], D. Abraimov[3], C-B Eom[2], D. Larbalestier[3]

*1) Department of Engineering, University of Cambridge*
*2) School of Engineering, University of Wisconsin, Madison, WI*
*3) Applied Superconductivity Centre, FSU and NHMFL, Tallahassee, FL*

Understanding the grain boundary properties of a superconductor are critical to determining how to make long length and bulk conductors. If the superconducting coherence length is long compared to the grain boundary width then grain boundaries are benign, as seen in MgB2 and indeed may even act as pinning centres as in NbSn. In other materials, most notably the cuprates, the grain boundary is a definite barrier to current flow and control of the grain boundary angle is critical to successful materials processing.
The Ba-122 pnictide superconductor can be fabricated in the form of a thin film and this has been used to elucidate its grain boundary properties, among others (Lee *et al* Nature Mat 2010). Earlier work has shown evidence that the grain boundary $J_c$ in this material is suppressed in a similar manner to that seen in cuprate superconductors (Lee *et al* APL **95** 212505 2009).
We have prepared bi-crystal thin film samples of 8% and 10% Co Doped Ba-122 on bi-crystal substrates with different mis-orientation angles. We have then studied the critical current as a function of angle as well as field and temperature. In the 5 degree mis-orientated sample a clear vortex channelling effect is seen over a restricted angular range. Such an effect (Durrell *et al.* Phys. Rev. Lett. **90**, 247006 2003) has been previously observed in YBCO bi-crystals which means that, in low angle bi-crystals at least, the system is similar to YBCO with a region of depressed order parameter with weakly pinned Abrikosov-Josephson vortices
We have therefore confirmed that low angle grain boundaries in this material act in a manner remarkably similar to that in YBCO. However we further show that there is a crossover from grain boundary dominated to in-grain like behaviour at such grain boundaries which means that although the grain boundaries in this material are a barrier to current flow it is not an insurmountable one.

# Scanning Tunneling Spectroscopy of Superconducting Energy Gap in $SrPd_2Ge_2$ Single Crystal, Isostructural with 122 Iron Pnictides

T. Samuely[1], P. Szabó[1], J.G. Rodrigo[2], D. S. Inosov[3], J. T. Park[3], N. H. Sung[4], B. K. Cho[4], P.Samuely[1]

[1] *Centre of Ultra Low Temperature Physics at the Inst. of Experimental Physics of the Slovak Academy of Sciences and P.J. Šafárik University, Watsonova 47, 04001 Košice, Slovakia*
[2] *Laboratorio de Bajas Temperaturas, Instituto Nicolas Cabrera, Univesidad Autonoma de Madrid, Spain*
[3] *Max-Planck-Institute FKF, Heisenbergstrasse 1, D-70569 Stuttgart, Germany*
[4] *School of Materials Science and Engineering, Institute of Science and Technology, Gwangju, Korea*

Iron pnictides, become superconducting when the parental itinerant antiferromagnetic semimetals are doped, which also gradually suppresses their magnetism. The systems have revealed a strong multiband character and a hot debate is held on the multiple superconducting energy gaps which can be open with an opposite phase on separated sheets of their Fermi surface. Then, the exotic *s*+- superconductivity can be realized due to magnetic interactions. Our point-contact measurements performed on the iron pnictides have indeed shown a presence of multigap superconductivity. On the hole doped $Ba_{1-x}K_xFe_2As_2$ (“122” type) single crystals two *s*-wave gaps have been found where the smaller gap has a size below the BCS value while the large gap reveals much higher coupling strength [1]. Angular dependence of the upper critical field in $Ba_{1-x}K_xFe_2As_2$ measured near $T_c$ shows also significant deviations from the Lawrence-Doniach prediction for a single-gap superconductor, presumably due to effect of two distinct gaps. The recent discovery [2] of a new low-temperature ($T_c$ = 3 K) superconductor $SrPd_2Ge_2$ isostructural with the group of 122 iron pnictides can shed a light on the role of magnetism in pnictides because this compound is not only pnictogen-free, but also has the magnetic metal (Fe) completely replaced by the non-magnetic one (Pd).

In this contribution we will show that $SrPd_2Ge_2$ is, in fact, very different from 122 pnictides. Its electronic structure reveals, in contrast to basically 2D pnictides, a much more pronounced three-dimensional character. Three-dimensional topology of $SrPd_2Ge_2$ Fermi surface is confirmed by experimentally measured momentum distribution maps by ARPES and supported by the LDA calculations [3]. The superconducting density of states have been measured by the Kosice home-built STM in helium-3 refrigerator. There the superconducting Pb tip has been applied to acquire a high resolution of the sample gap measurements. This configuration allows also for a direct determination of the temperature dependence of the gap. As a result a single s-wave superconducting energy gap is obtained in $SrPd_2Ge_2$ with the strong coupling strength $2\Delta/kT_c$=4 and following the standard BCS-like temperature dependence. No multigap features have been observed. All these findings indicates that in the isostructural 122 iron arsenides different physics is related to magnetism absent here.

[1] P. Szabó *et al*., Phys. Rev. B **79**, 012503 (2009).
[2] H. Fujii and A. Sato, Phys. Rev. B **79**, 224522 (2009).
[3] T.K. Kim *et al*, to be published.
Presenting author: P. Samuely
E-mail of presenting author: samuely@saske.sk

**Session 6 – Cuprate Superconductivity II (Avon room)**

**Chair: Francesco Tafuri**

# Non-Ohmic resistivity and Hall conductivity in the pseudogap regime of the underdoped cuprate superconductor $YBa_2Cu_3O_{6+x}$

W. Lang,[1] I. Puica[1], K. Siraj[2], J.D. Pedarnig[2]

[1]University of Vienna, Faculty of Physics, Boltzmanngasse 5, A-1090 Wien, Austria
[2]Johannes-Kepler-University Linz, Institut of Applied Phyiscs, A-4040 Linz, Austria.

e-mail: wolfgang.lang@univie.ac.at

The energy gap between the superconducting pairs of charge carriers and the normal-state quasiparticles is considered the fundamental parameter for characterizing the superconducting state. In underdoped cuprate high-temperature superconductors, a markedly robust additional gap-like feature opens up at a temperature $T^* > T_c$. This so-called pseudogap manifests itself in a variety of experimental probes in the normal state, with smooth crossover from the pseudo- to superconducting gap. Moreover, the energy scale and the momentum dependence of the pseudogap mimics the *d*-wave superconducting gap observed well below the critical temperature $T_c$.

Essentially two radically different physical origins of the pseudogap are advocated: a precursor state to superconductivity, where fluctuating superconducting pairs are created at temperatures below $T^*$ and attain phase coherence only at $T_c$ , or scenarios of low-temperature correlated states that are independent or even competing with superconductivity.

Recent experimental findings in the pseudogap domain, like Nernst effect and diamagnetism have revealed a second, possibly independent, temperature scale with a different doping dependence than $T^*$. So evident disagreement between various experimental findings and their theoretical interpretation demonstrates vividly the need for additional experimental probes. We explore a novel experimental approach, the investigation of resistivity and Hall effect in the normal state of underdoped $YBa_2Cu_3O_{6+x}$ (YBCO) beyond the weak electric field limit and the search for possible non-ohmic effects.

The in-plane longitudinal and transverse (Hall) conductivities in thin films of YBCO are reduced in intense current densities of 2.6 $MAcm^{-2}$ in the temperature range from $T_c$ = 53 K to ~150 K. In optimally-doped pristine and ion irradiated (defect rich) samples, however, this non-ohmic effect is limited to temperatures below 100 K. The onset temperatures follow the trend of the pseudogap opening at $T^*$ but do not scale with $T_c$, excluding classical amplitude fluctuations of the superconducting order parameter as possible origin. From the several proposed scenarios for the pseudogap, local superconductivity without rigid phase coherence appears to be most appealing to explain our results.

# Polarons in High-$T_c$ Cuprates

E. Joon

*National Institute of Chemical Physics and Biophysics*
*Akadeemia tee 23,Tallinn, 12618, Estonia.*

In this report I show that self-trapped states (polarons) are stationary particles in layered high-$T_c$ cuprates. Usually shallow polarons do not exist in higher than D≥1 systems with parabolic band dispersion. The reason why is the following: the energy for creation of the potential well exceeds the gain of the lowering energy by self-trapping. Van-Hove singularity and Mott-Hubbard gap in the electronic spectrum of high-$T_c$ cuprates make the self-trapping favorable in 2D systems [1,2]. Polarons are created by the local deformation of the gap amplitude near the saddle points (SP) of Brillouin zone (flat regions). For electron type cuprates it looks natural because SP are the absolute minima of the upper Hubbard band. Due to the low mobility and small localization radius of the polarons these compounds stay insulating and even magnetic up to very high doping concentration (12%). The hole doped $CuO_2$ layers have band maxima at nodal points, about $\Delta\varepsilon$=0.15-0.2 eV higher than van-Hove singularity, so the first doped holes cannot be polarons if their self-trapping energy does not exceed $\Delta\varepsilon$. Possibly initial doping in this case is soliton type with diagonal domain walls parallel to the gap direction [3]. Polarons are created in the process of doping, when Fermi energy gets closer to SP, forming there polarons and small hole pockets in the nodal regions at the same time. I am going to discuss the properties of that kind of electronic spectrum and compare with existing experimental data.

1. A. Rojo Bravo, S. Brazovskii, Physica B, **404**, 552 (2009)
2. A. Rojo Bravo, S. Brazovskii, J.of Supercond. & Novel Magnetism, **22**, 229 (2009)
3. E. Joon, Physica C, **470**, 926 (2010).

**Session 7 – Spin Triplet Superconductivity (Avon room)**

**Chair: John Kirtley**

# Triplet supercurrents

Mark Blamire, Jason Robinson, Kartik Senapati, Zoe Barber

*Department of Materials Science*
*University of Cambridge*
*Pembroke Street*
*Cambridge CB2 3QZ*
*UK*

mb52@cam.ac.uk

In almost all superconductors the pairs of electrons which carry the charge are in the so-called singlet state in which the quantum spin of the two electrons is antiparallel. During the past five years there has been increasing evidence that proximity coupling between singlet superconductors and ferromagnets can sometimes generate triplet pairs within the ferromagnet in which the spins of the electrons are parallel rather than antiparallel – the evidence being that supercurrents can be passed through thicknesses of ferromagnetic material which are simply too large for singlet pairs to survive.
The superconductor-ferromagnet proximity effect describes the fast decay of a spin-singlet supercurrent originating from the superconductor upon entering the neighboring ferromagnet. For strong ferromagnets such as Co, a thickness of only a few nanometres is sufficient to almost completely suppress the critical current of a Nb/Co/Nb Josephson junction. Here we report experiments in which a conical magnet (holmium) is placed at the interface between the superconductor and ferromagnet. The results showed that a long-ranged supercurrent can occur through the ferromagnetic Co layer but only for certain critical thicknesses of the Ho.[1] These thicknesses correspond to maximum magnetic inhomogeneity on the Ho and are therefore consistent with models which predict that a spin-mixing interface between the superconductor and ferromagnet can generate triplet pairs which are long-ranged in the ferromagnet.
This paper reports recent experiments which aim to understand further the behaviour of triplet pairs in superconductor / ferromagnet heterostructures including recent work on Josephson junctions incorporating the ferromagnetic insulator GdN.

[1] J. W. A. Robinson, J. D. S. Witt, and M. G. Blamire, "*Controlled Injection of Spin-Triplet Supercurrents into a Strong Ferromagnet*" Science **329**, 59-61 (2010).

# Micron-ranged supercurrents induced in the halfmetallic ferromagnet $CrO_2$

M. S. Anwar and J. Aarts

*Kamerlingh Onnes Laboratory, Leiden Institute of Physics, P. O. Box 9504, 2300RA Leiden, the Netherlands*

Evidence is accumulating that, by generating so-called odd-frequency triplet Cooper pairs, it is possible to have supercurrents flow through ferromagnets over lengths which are similar to those in normal metals. The mechanism under which triplets are generated is not fully understood as yet, but a spin-active interface between the superconducting (S) contact and the ferromagnet (F) is a prerequisite, meaning some form of inhomogeneous magnetization or a difference in the scattering of two spin channels. We recently showed that long-range supercurrents (order of 1 μm) could be found in $CrO_2$ films grown on sapphire, but not in similar films grown on $TiO_2$ [1]. Using a suggestion made recently [2] that a spin-active interface can be fabricated by inserting N/F*/N sandwich between S and F (N a normal metal and F* a different ferromagnet), we show here that micron-ranged supercurrents can also be induced in $CrO_2$ on $TiO_2$, by using a thin Cu/Ni/Cu intermediate layer. The reasons for this observation will be discussed, and an update will be given of the fast-moving field of long-range triplets.

[1] .S. Anwar *et al.*, Phys. Rev. B **82**, 100501(R) (2010).
[2] T.S Khaire *et al.* Phys. Rev. Lett. **104,** 137002 (2010).

# Transport properties of hybrid heterostructures with superconducting/magnetic interfaces

K.Y. Constantinian[1], G.A. Ovsyannikov[1,3], A.V. Shadrin[1,3], Yu.V. Kislinskii[1], A.M. Petrzhik[1], K.E. Lahmanskiy[1], J. Mygind[2], A. Kalabukhov[3], and D. Winkler[3]

[1] *Kotel'nikov Institute of Radio Engineering and Electronics Russian Academy of Sciences, Mokhovaya st., 11-7, 125009, Moscow, Russia.*
[2] *Department of Physics, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark.*
[3] *Department of Microtechnology and Nanoscience – MC2, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden.*

Corresponding author: dag.winkler@chalmers.se

Experimental studies of electron transport, microwave properties and noise in multilayer hybrid heterostructures (MHS) with superconducting/magnetic interfaces are reported. The magnetic interlayer was either an oxide antiferromagnetic $Ca_{1-x}Sr_xCuO_2$, or $LaMnO_3$ doped by Ca or Sr. The upper electrode was a AuNb bilayer. In the case of the antiferromagnetic interlayer (with thickness 12 - 50 nm) the MHS could be fitted well to the Resistively Shunted Junction (RSJ) model, which was confirmed by multiple oscillations of the critical current and the Shapiro steps and their amplitudes with microwave power. The characteristic frequency, $f_C$= 2e/h $I_CR_N$ was of the order of 100 GHz at T =4.2 K. At the same time, non-integer Shapiro steps were measured along with sub-harmonic detector response, giving evidence of a deviation of the current-phase relation from the regular sine-type. Measurements of MHS with manganite interlayers did not show critical currents even for thicknesses of the order 5 nm. At the same time, pronounced shot noise, increasing with bias current was registered for MHS with $LaMnO_3$ interlayer. Moreover, by varying an external weak magnetic field and bias current we observed weak microwave radiation within the frequency window 1-2 GHz of measurements of MHS with $LaMnO_3$.

The work was supported by Russian Academy of Sciences, President Grant MK-5266.2011.2, Scientific School Grant 5423.2010.2, Ministry of Education and Science of the Russian Federation (contract 02.740.11.0795), the Swedish Research Council and Knut and Alice Wallenberg Foundation.

# Neutron and Muon Experiments on Superconducting-Magnetic Thin Films

¶S. L. Lee[1], S.J. Ray[1], S.J. Lister[1], M. Flokstra[2], J. Aarts[2], J.P. Morgan[3], C.H. Marrows[3], C.J. Kinane[4], R. M. Dalgliesh[4],T. R. Charlton[4], S. Langridge[4], O. Hellwig[5], H Luetkens[6], T. Prokscha[6], J. Stahn[7]

[1]*School of Physics and Astronomy, University of St Andrews*
[2]*Kamerlingh Onnes Laboratory, Leiden institute of Physics, Leiden University 1222 CA Leiden, The Netherlands*
[3]*School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK*
[4]*ISIS, Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0QX, UK*
[5]*Hitachi San Jose Research Center, 3403 Yerba Buena Road, San Jose, California 95135, USA*
[6]*Laboratory for Muon Spectroscopy, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland*
[7]*Laboratory for Neutron Scattering, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland*

¶E-mail address of corresponding author: sl10@st-and.ac.uk

Despite the enormous interest in magnetic (M) and superconducting (SC) thin film structures there are few techniques capable of measuring the spatial variation of magnetic flux density perpendicular to the surface of the film. This may be of particular interest where exotic M-SC interactions occur close to buried interfaces. In this talk two potentially powerful techniques will be discussed that go some way towards addressing this problem. Polarised neutron reflectometry (PNR) involves the critical reflection of spin-polarised neutrons from the surface of a thin film structure and is sensitive to the spatial variation perpendicular to the surface of the magnetization in the plane of the film. We have used this technique, for example, to probe mesoscopic vortex states in superconducting layers [1]. In muon-spin rotation (μSR), the observed quantity is the time evolution of the muon spin polarization, which depends on both the distribution of internal magnetic fields and, where significant, their temporal fluctuations. In the low energy μSR (LEM) technique muons are produced having much lower momentum than in a conventional surface muon spectrometer. This allows muons to be controllably implanted into samples only 10's of nm in thickness, albeit with a distribution of stopping distances [2]. We have previously used μSR to reveal the coexistence of SC and M order in FePbFe trilayers [3]. In this talk we will present some recent unpublished results on SC-M thin-film structures that illustrate the application of these two techniques.

[1] A.J. Drew *et al.,* Phys. Rev. B 80 , 134510 (2009).
[2] M. Morenzoni *et al.,* Phys. Rev. Lett. **72** 2793-3796 (1994).
[3] A.J. Drew *et al.,* Phys. Rev. Lett. **95** 197201 (2005).

## Intrinsic orbital magnetism and optical dichroism of the multi-band pairing state of the chiral superconductor $Sr_2RuO_4$


James F. Annett, B. L. Gyorffy, and K. I. Wysokinski

*H. H. Wills Physics Laboratory, University of Bristol, Tyndall Ave, BS8-1TL, UK.*
*Institute of Physics, M. Curie-SkÃlodowska University, Radziszewskiego 10, PL-20-031 Lublin, Poland*
*Max Planck Institut für Physik komplexer Systeme, D-01187 Dresden, Germany*



The pairing state of the 1.5K superconductor $Sr_2RuO_4$ is widely believed to be a chiral p-wave spin triplet state of symmetry $k_x+ik_y$. This is an electronic analogue of the A-phase pairing state of superfluid helium-3. One of the long standing unresolved questions for this superfluid state is the existence or not of an orbital angular momentum $L_z$=hbar per Cooper pair, and whether or not this leads to a non-zero macroscopic intrinsic angular momentum of the condensate. For $Sr_2RuO_4$ the corresponding question is the existence of a non-zero orbital magnetism in the bulk of the material. The existence of such a moment is suggested by muon spin rotation (muSR) measurements and an observation of a non-zero optical Kerr effect below $T_c$. We present an analysis of both the intrinsic magnetic moment and optical dichroism based upon a multiband chiral pairing state model. We find that the intrinsic Kerr signal is only non-zero in systems with inter-band order parameters related to an interband Josephson-like coupling. This new intrinsic mechanism may explain the Kerr effect observed in strontium ruthenate and possibly other superconductors. We also predict the existence of coherence effects in the temperature dependence of the absorptive part of the ac Hall conductance, Im $\sigma_{xy}(\omega,T)$, which can be tested experimentally.

# Magnetic fields above the superconducting ferromagnet UCoGe

D. Hykel,[†] C. Paulsen,[†] D. Aoki,[¶] J. R. Kirtley,[¢] K. Hasselbach[†]

[†]*Institut Neel, CNRS, 25 Avenue des Martyrs, 38042 Grenoble*
[¶]*INAC/SPSMS, CEA-Grenoble, 17 rue des Martyrs, 38054 Grenoble*
[¢]*Center for Probing the Nanoscale, Stanford University, Stanford*

klaus.hasselbach@grenoble.cnrs.fr

We will present recent results on the coexistence of superconductivity ($T_{cs}$ = 0.45 K) and ferromagnetism ($T_{cf}$ = 2.8K) in single crystals of the itinerant ferromagnet UCoGe. Macroscopic magnetization measurements will be compared with scanning microSQUID microscopy data taken at temperatures as low as 0.25 Kelvin. Our macroscopic measurements clearly demonstrate the coexistence of the two competitive orders. Notably, diamagnetic screening and a weak Meissner effect were detected in the ferromagnetic state. Our microscopic measurements allowed us to observe the formation of a spontaneous ferromagnetic state at zero applied magnetic field and the formation of ferromagnetic domains. The locally observed domain magnetization agrees with the magnetization derived from bulk measurements. The Ising nature of this ferromagnet is confirmed by this observation and excludes the presence of significant domain reconstruction at the surface. The ferromagnetic domain size depends on whether the sample is superconducting and ferromagnetic or only ferromagnetic. The magnetic imaging, taking into account estimates of the penetration depth, is consistent with the formation of a spontaneous vortex lattice.

J.R.K. acknowledges support from the Nanosciences Foundation of Grenoble.

## Session 8 – Josephson Junctions (Avon room)

## Chair: Dimitri Roditchev

# Increasing quality factor in YBaCuO Josephson junctions and mesoscopic fingerprints

F. Tafuri[1,2], D. Stornaiuolo[2,*], L. Longobardi[1,2], D. Massarotti[3], G. Papari[3,**], P. Lucignano[2], A. Tagliacozzo[3], A. Barone[3], F. Lombardi[4],

[1]*Seconda Università di Napoli ITALY*
[2]*CNR-SPIN, Unità di Napoli Italy*
[3]*Università di Napoli Federico II, Napoli, ITALY*
[4]*Chalmers University, Gotenborg, SWEDEN*
[*]*Present address DPMC - University of Geneva, Geneva – Switzerland*
[**]*Present address INPAC Katholieke Universiteit Leuven, Leuven, Belgium*

We have extended the off-axis biepitaxial technique to produce YBCO grain boundary (GB) junctions on low loss substrates. Excellent transport properties have been reproducibly found, with remarkable values of the quality factor $I_cR_n$ (with $I_c$ the critical current and $R_n$ the normal state resistance) above 10 mV, far higher than the values commonly reported in the literature for high temperature superconductor (HTS) Josephson junctions, and of interest for various applications.
Insights on the nature of transport in HTS have been obtained through systematic measurements of switching current probability (SCP) in the quantum, thermal and phase diffusion regimes in different Josephson systems. Hints on coherent transport conveyed through nano-channels are given by SCP and conductance measurements.

## Intrinsic Josephson Junctions with Intermediate Damping

PAUL WARBURTON[1], SAJID SALEEM and JON FENTON

*University College London*

SUSANNAH SPELLER and CHRIS GROVENOR

*University of Oxford*

[1] p.warburton@ee.ucl.ac.uk

In cuprate superconductors, adjacent cuprate double-planes are intrinsically Josephson-coupled. For bias currents perpendicular to the planes, the current-voltage characteristics correspond to those of an array of underdamped Josephson junctions. We will discuss our experiments on sub-micron $Tl_2Ba_2CaCu_2O_8$ intrinsic Josephson junctions (IJJs). The dynamics of the IJJs at the plasma frequency are moderately damped ($Q \approx 8$). This results in a number of counter-intuitive observations, including both a suppression of the effect of thermal fluctuations and a shift of the skewness of the switching current distributions from negative to positive as the temperature is increased. Simulations confirm that these phenomena result from repeated phase slips as the IJJ switches from the zero-voltage state to the running state [1]. We further show that increased dissipation counter-intuitively increases the maximum supercurrent in the intermediate damping regime [2]. We discuss the role of environmental dissipation on the dynamics and describe ongoing experiments with on-chip lumped-element passive components in order to control the environment seen by the IJJs.

[1] Fenton and Warburton *PRB* **78**, 054526
[2] Warburton *et al. PRL* **103**, 217002

# Josephson Junctions as Quantum Ratchets and Quantum Metamaterials

Sergey Savel'ev[1], A. O. Sboychakov[2,3], A. L. Rakhmanov[1,2,3], A.M. Zagoskin[1] and Franco Nori[3,4]

*Loughborough University, LE11 3TU, UK*

We study [1] the escape rate of flux quanta in a long Josephson junction having an asymmetric spatial inhomogeneous critical current density. Such a junction can behave as a ratchet when driven by an ac current in the presence of a magnetic field. This rectification gives rise to a dc voltage $V_{dc}$ across the junction. The usual approach of particle-like tunneling cannot describe this rectification, and a quantum field theory description is required. We also show that, under specific conditions, the rectification direction, and consequently $V_{dc}$, can change its sign when varying the temperature T near the crossover temperature $T^*$ between the quantum and classical regimes.

Such Josephson junctions can be building blocks for a new generation of metamaterials where the electromagnetic response of the system is controlled by a coherent superposition of its quantum elements. As an example, we consider [2] the propagation of a classical electromagnetic wave through a transmission line, formed by identical superconducting charge qubits inside a superconducting resonator. Since the qubits can be in a coherent superposition of quantum states, we show that such a system demonstrates interesting effects, such as a "breathing" photonic crystal with an oscillating band gap and a "quantum Archimedean screw" that transports, at an arbitrary controlled velocity, Josephson plasma waves through a transmission line.

[1] A.O. Sboychakov, S. Savel'ev, A.L. Rakhmanov, and F. Nori, Phys. Rev. Lett. **104**, 190602 (2010).
[2] A.L. Rakhmanov, A.M. Zagoskin, S. Savel'ev, and F. Nori, Phys. Rev. B **77**, 144507 (2008).

# Pair breaking effects on the superconducting density of states studied by tunnelling spectroscopy using STM/STS

José Gabriel Rodrigo

*Laboratorio de Bajas Temperaturas, Departamento de Física de la Materia Condensada, Instituto de Ciencia de Materiales Nicolás Cabrera, Facultad de Ciencias, Universidad Autónoma de Madrid, 28049, Madrid, Spain*

e-mail: jose.rodrigo@uam.es

Since the 1960's electron tunnelling spectroscopy has been extensively used to study the superconducting density of states (DOS) [1]. Indeed, this technique gave one of the main experimental proofs of BCS theory, the opening of a gap in the electronic density of states in superconducting state [2].

Detailed analysis were developed in order to investigate deviations of the superconducting DOS from the "standard" BCS case under different situation, like different pair breaking mechanisms [3], finite quasiparticle lifetime effects [4], or multiband superconductivity [5].

In this talk we will review how these effects can be accounted for in the tunnelling curves obtained in STM/STS measurements, focusing on the use of a superconducting tip as a probe. A high experimental energy resolution, and the detailed modelling of the experimental curves, are very important in order to determine the actual pair breaking mechanisms and the anisotropic or multiband character of superconductivity in the studied materials.

1. "Principles of Electron Tunneling Spectroscopy (International Series of Monographs on Physics)", E.L. Wolf, Oxford University Press, 1989
2. J. Nicol, S. Shapiro, and P. H. Smith, Phys. Rev. Lett. 5, 461 (1960). I. Giaever, Phys. Rev. Lett. **5**, 464 (1960).
3. See for example K. Maki in "Superconductivity", R.D. Parks, ed. Marcel Dekker, Inc., New York (1969).
4. R. C. Dynes, V. Narayanamurti, and J. P. Garno, Phys. Rev. Lett. **41**, 1509–1512 (1978)
5. H. Suhl, B. T. Matthias, and L. R. Walker, Phys. Rev. Lett. **3**, 552–554 (1959)

**Session 9 – THz Emission (Avon room)**

**Chair: Roger Wördenweber**

**DYNAMICAL COHERENCE PHENOMENA IN HIGH TEMPERATURE SUPERCONDUCTORS: TERAHERZ RADIATION AND ITS APPLICATIONS**

Kazuo Kadowaki[1,2,3], Manabu Tsujimoto[1,2], Kaveh Delfanazari[1,2], Hidehiro Asai[1,2], Krsto Ivanovic[1], Takashi Yamamoto[1,2,3], Takanari Kashiwagi[1,2,3], Hidetoshi Minami[1,2], Masashi Tachiki[2], and Richard A. Klemm[4]

[1] *Institute of Materials Science & Graduate School of Pure and Applied Sciences, University of Tsukuba, Ten-noudai 1-1-1, Tsukuba, Ibaraki 305-8573, Japan*
[2] *CREST-JST &* [3] *WPI-MANA*
[4] *Department of Physics, University of Central Florida, Bldg. 121, PS 402, 4000 Central Florida Blvd., Orlando, FL 32816-5112*

E-mail: kadowaki@ims.tsukuba.ac.jp

The electromagnetic waves at THz frequencies hold great promise for future noninvasive sensing, imaging and spectroscopy across physical, medical, biological, pharmaceutical science and technology as well as for novel applications in security, surveillance and high-frequency high-density communications. However, the development of such applications is hindered by the lack of compact and powerful solid state devices with continuous and coherent radiation, commonly known as the "*THz gap*". Here, we provide an entirely new method to fill the THz gap using superconducting Josephson junctions, which are naturally furnished inside high-$T_c$ superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal. Since these Josephson junctions are stacked in series along the crystallographic *c*-axis with a periodic thickness of atomic scale of about 1.53 nm and work synchronously together according to the *ac*-Josephson effect by the *dc*-voltage applied to the system (in fact this works in principle as a DA-converter). The *ac*-Josephson current can be produced in the mesa, where the electromagnetic waves are generated [1].

Since the discovery of strong emission of THz electromagnetic waves from a mesa of $Bi_2Sr_2CaCu_2O_{8+\delta}$, a number of works have been performed to understand, firstly the mechanism of the interesting phenomenon, secondly, to make use of it technologically for applications. Recently, we have succeeded in generating tuneable emission in a range of approximately 200 to 800 GHz by adjusting the *I-V* conditions [2].

In order to make use of the phenomenon for applications it is in general said that the radiation power level more than 1 mW radiation is desired. So far we are able to generate the total power of THz waves of 30-50 $\mu$W from a stand-alone mesa, which can be assembled as an array for further enhancement of the emission power.

In the following, examples of the set-up developed in our laboratory (a photograph: Fig. 1(a)), and the recent results of the imaging experiments (Fig. 1(b) and 1(c)) are given. The interpretation as well as further new results will be discussed.

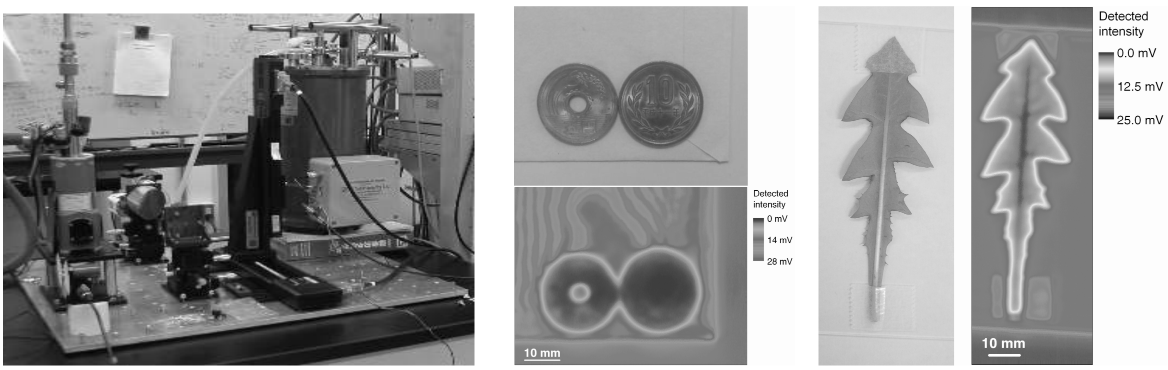


Fig. 1(a): A photograph of the imaging set-up built in-house (left). (b): 5 and 10 yen coins (above) and the see-through image of the coins inserted into the envelope (below). (c): a see-through image of a dandelion leaf.

[1]. Ozyuzer, *et al.*, Science **318** (2007) 1291.
[2]. M. Tsujimoto, *et al.*, Phys. Rev. Lett. **105** (2010) 037005.

# Coherent Terahertz Emission of Intrinsic Josephson Junction Stacks in the Hot Spot Regime

Reinhold Kleiner, Stefan Guénon, Boris Gross, Matthias Grünzweig, Dieter Koelle
*Physikalisches Institut & Center for Collective Quantum Phenomena*
*Universität Tübingen, D-79076 Tübingen, Germany*

Huabing Wang, Jie Yuan, Akira Iishi, Takeshi Hatano
*Nano Quantum Electronics Group, Exploratory Nanotechnology Research Laboratory, National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047 Japan*

Zhenguo Jiang, Yangyin Zhong, Peiheng Wu
*Research Institute of Superconductor Electronics, Nanjing University, Nanjing 210093, China*

Having small sized active and tuneable devices operating at frequencies up to the THz range is one of the goals of modern electronics. However, there is still a lack of good active or passive devices, often referred to as the "THz gap". Intrinsic Josephson junctions formed by the layered crystal structure of high temperature superconductors such as $Bi_2Sr_2CaCu_2O_8$ have the potential to operate in this regime. While for a long time the research on THz generation with this type of junctions was carried out with perhaps only modest success, recently synchronous emission, with an estimated output power in the μW range, of stacks consisting of several hundred intrinsic Josephson junctions was achieved [1]. We report on the investigation of THz electromagnetic wave generation in intrinsic junction stacks (mesas) of different geometries, using a combination of transport measurement, direct electromagnetic wave detection and Low Temperature Scanning Laser Microscopy [2,3].

At high enough input power a hot spot (a region heated to above the superconducting transition temperature) coexists with regions being still in the superconducting state. In the “cold” regions cavity resonances can occur, synchronizing the ac Josephson currents and giving rise to strong and stable coherent THz emission. We discuss possible scenarios of the hot spot/wave interaction and its relation to the generation of coherent THz radiation.

Corresponding author: kleiner@uni-tuebingen.de

[1] L. Ozyuzer, *et al.*, Science **318**, 1291 (2007).
[2] H. B. Wang, *et al.*, Phys. Rev. Lett. **102**, 017006 (2009).
[3] H. B. Wang, *et al.*, Phys. Rev. Lett. **105**, 057002 (2010).

## Powerful Flux-Flow Oscillator (FFO) operating in Terahertz frequency range and the Fluxon Cloning Phenomena

H Farhan-Hassan, D R Gulevich, P N Dmitriev, V P Koshelets and F V Kusmartsev

*Loughborough University, LE11 3TU, UK*

*and*

*Institute of Radio Engineering and Electronics, Russian Academy of Science, Moscow 125009, Russia*

In present paper we have developed a new device, Flux-Flow Oscillator (FFO) where flux cloning phenomena have been demonstrated. Such FFO made with the use of flux cloning circuit can in principle operate even without magnetic field, that is in a very different manner than conventional FFO developed nowadays for practical applications We have designed such a novel device and build it up with the use of the long Josephson T-shaped junction of a linear overlap geometry made up with Nb-$AlO_x$-Nb technology. We have theoretically described the properties of such a device and the dynamics of vortices there. These theoretical studies have been performed in the framework of a sine-Gordon model, which includes surface losses. Finally we have tested the device experimentally and demonstrated that the flux cloning can lead to a strong coherent terahertz radiation. There the shape of the spectral lines and the current-voltage characteristics have been also measured.

E-mails:
H.Hassan@lboro.ac.uk
F.Kusmartsev@lboro.ac.uk
valery@hitech.cplire.ru

# POSTER ABSTRACTS

**(Alphabetical order)**

# P1

## Pound Drever Hall readout of lumped element superconducting resonators

J.J. Burnett[1,2], T. Lindström[1,2], M. Oxborrow[1], Y. Harada[3], Y. Sekine[3], A.Ya. Tzalenchuk[1], G. Ithier[2] and Phil Meeson[2]

*[1] National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK*
*[2] Royal Holloway, University of London, Egham, TW20 0EX, UK*
*[3] NTT Basic Research Laboratories, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198 Japan*

j.burnett@rhul.ac.uk

The most prominent sources of noise in superconducting quantum systems may be characterised as a system of two level fluctuators. This is a dominant source of decoherence and linked with flicker noise in SQUIDs and other sensitive devices. In this work a Pound-Drever-Hall measurement setup has been demonstrated for readout of superconducting microwave resonators; which are well coupled to the sources of noise. The setup provides direct measurement of frequency deviations at resonance. Both qualitative and quantitative characterisation of frequency fluctuations are performed by analysing frequency domain spectra and the time domain Allan deviation. Analysis of the latter highlights a strong source of random walk frequency noise, which is not readily visible in the power spectral density. Atomic layer deposition (ALD) has been used to selectively deposit an additional dielectric layer atop some niobium lumped element resonators. Measurements between 30mK-900mK at low power levels between –80dBm and –100dBm have been made to compare a bare resonator to one with an additional dielectric. These measurements show noise to vary with both temperature and power while highlighting additional frequency fluctuations (noise) in the covered resonators.

# P2

## Vortex lattice structure of YBCO in fields up to 16 T

A.S. Cameron,[1] A.T. Holmes,[1] E. Blackburn,[1] E.M. Forgan,[1] R.W. Heslop,[1] J.S. White,[1,2]
C.D. Dewhurst,[3] R. Cubitt,[3] V Hinkov,[4] and A. Erb[5]

*[1]School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
*[2]Laboratory for Neutron Scattering, Paul Scherrer Institut, CH-5232 Villigen, Switzerland*
*[3]Institut Laue-Langevin, 6 rue Jules Horowitz, 38042 Grenoble, France*
*[4]Max Planck Institut für Festkaorperforschung, D-70569 Stuttgart, Germany*
*[5]Walther Meissner Institut, BAdW, D-85748 Garching, Germany*

Using the new Birmingham 17 T cryomagnet, small angle neutron scattering (SANS) measurements on $YBa_2Cu_3O_7$ have been performed in unprecedentedly high fields up to 16 T. With field applied perpendicular to the CuO planes, the vortex lattice in this material has previously been seen to change via a first-order phase transition from a hexagonal phase to a rhombic phase at 6.7 T.[1] With increasing field the high field vortex lattice structure distorts continuously, heading towards a square lattice near 11 T. In the study presented here, our measurements are extended to higher fields. We find that the vortex structure passes *through* a square configuration, showing no signs of locking into a field independent square shape, which would be expected in a tetragonal *d*-wave superconductor.

The field and temperature dependence of the diffracted signal has also been investigated, showing non *d*-wave like behaviour of the intensity at higher fields. As this may be due to pinning effects, further investigation with an improved sample is planned. Structural evolution of the vortex lattice with increasing temperature is observed, consistent with the decreasing influence of non-local effects upon the approach to $T_c$. Possible signs of vortex lattice melting at high fields have also been observed in the temperature dependence of the intensity, which will also be subject to further investigation.

[1] J.S.White *et al*, *Fermi surface and Order Parameter driven Vortex Lattice Structure transitions in Twin-Free $YBa_2CuO_7$*, PRL **102**, 097001 (2009).

# P3 Switching response of superconducting thin films in avalanche-like vortex penetration triggered by single microwave pulses

P.-de-Jesús Cuadra-Solís[1], J. M. Hernández[1], A. García-Santiago[1], J. Tejada[1], J. Noskovic[2], A. Pidik[2], M. Grajcar[2], J. Vanacken[3] and V. V. Moshchalkov[3]

[1]*Grup de Magnetisme, Departament de Física Fonamental, Universitat de Barcelona, Martí i Franquès 1, Planta 4, edifici nou, 08028, Barcelona, Catalunya, Spain*
[2]*Department of Experimental Physics, Comenius University, Mlynská Dolina, 84248 Bratislava, Slovak Republic*
[3]*INPAC-Institute for Nanoscale Physics and Chemistry, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*

e-mail: jcuadra@ubxlab.com

High-temperature superconductor thin films, and particularly $MgB_2$ compounds, are very attractive for potential uses exploiting their intrinsic properties in low dissipative microwave devices [1]. Thus the study of the stability of the vortex matter is crucial for any practical application. One important feature that represents a critical drawback in these materials is the phenomenon called vortex avalanches (flux jumps or magnetic noise), related to a thermomagnetic instability driven by heat generated by moving vortices [2]. Here we report switching magnetic response of superconducting $MgB_2$ (magnetron-sputtered) and $La_{1.825}Sr_{0.175}CuO_4$ (overdoped epitaxial) thin films in flux jumps induced by a single microwave pulse. Abrupt jumps in the output voltage signal of a SQUID magnetometer have been registered when a single microwave pulse is applied at different fixed values of the thermodynamic variables (DC magnetic field, temperature) and perturbation sensing parameters (pulse duration, microwave power, microwave frequency). The jumps, which prevail within some range of temperature and magnetic field, are interpreted as thermomagnetic instabilities resulting from the interaction between microwave surface currents and the system of vortices in the mixed state. The predominance of the magnetic diffusivity over the thermal one (adiabatic condition) [3] is supported by the contribution of MW losses to the flux flow resistivity.

[1] M. J. Lancaster, *Passive Microwave Device Applications of High Temperature Superconductors,* Cambridge University Press, Cambridge, 1997; A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, Nature (London) **431**, 162 (2004).

[2] E.-M. Choi, H.-S. Lee, J. Y. Lee, S.-I. Lee, Å. A. F. Olsen, V. V. Yurchenko, D. V. Shantsev, T. H. Johansen, H.-J. Kim, and M.-H. Cho, Appl. Phys. Lett. **91**, 042507 (2007); U. Bolz, J. Eisenmenger, J. Schiessling. B.-U. Runge, and P. Leiderer, Phys. B **284**, 757 (2000); V. V. Chabanenko, A. I. D'yachenko, A. V. Chabanenko, H. Szymczak, S. Piechota, A. Nabialek, and N. D. Dung, J. Appl. Phys. **83**, 7324 (1998).

[3] R. G. Mints and A. L. Rakhmanov, Rev. Mod. Phys. **53**, 551 (1981).

# P4

## Vortex structures and vortex lattice transitions in superconducting $Sr_2RuO_4$ single crystals

Peter Curran[1], Volodya Khotkevych[1], Simon Bending[1], Alexandra Gibbs[2], Steven Lee[2], Andrew Mackenzie[2].

*[1] Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, U.K.*
*[2] School of Physics and Astronomy, University of St Andrews, St Andrews KY16 9SS U.K.*

Scanning Hall probe microscopy has been used to study vortex structures in very high quality single crystals of the unconventional superconductor $Sr_2RuO_4$ ($T_c \cong 1.5$K). In none of our samples do we find credible evidence for the existence of the spontaneous fields or chiral domains predicted for the expected time-reversal symmetry breaking order parameter [1]. Even in our highest quality samples we observe very strong vortex pinning and anomalous broadening of vortex profiles. The best samples also exhibit a clear field-driven triangular to square vortex lattice transition at low fields, as predicted by extended London theory calculations. In stark contrast, slightly less well-ordered samples exhibit pronounced vortex chaining/banding that we attribute to an extrinsic source of disorder.

[1] M. Matsumoto *et al*., J. Phys. Soc. Jpn. **68**, 994 (1999)

Author email: py0pjc@bath.ac.uk

# P5

## Combinations of natural and artificial flux pinning centres in BZO-doped YBCO films

V. S. Dang[1], P. Mikheenko[1], A. Sarkar[1], J. S. Abell[1], P. Paturi[2], H. Huhtinen[2], and A. Crisan[1,3]

[1]*School of Metallurgy and Materials, The University of Birmingham, Birmingham, B15 2TT, UK.*
[2]*Wihuri Physical Laboratory, Department of Physics and Astronomy, University of Turku, FI-20014 Finland*
[3]*National Institute of Materials Physics, Bucharest 077125, Romania.*

First cost-effective method for introducing artificial pinning centres in superconducting films was the substrate decoration, in which nano-islands of certain materials (e.g., Ag) are grown on substrates prior to the superconducting films deposition [1]. Recently, nano-scale additions in the targets was also shown to increase critical current density ($J_c$) of $YBa_2Cu_3O_{7-\sigma}$(YBCO) films. $BaZrO_3$ (BZO) has been most commonly used as an impurity addition to YBCO target [2] and has been shown to be able to self-organize into correlated nano-rods within the film microstructure.

We have investigated the combination of Ag substrate decoration and BZO nano-inclusions in YBCO films by using a 4% wt. BZO-doped YBCO target, the nanostructured films being fabricated by pulse laser deposition (PLD) method. BZO-doped YBCO films were deposited on single crystal $SrTiO_3$ (STO) substrates decorated with 15 laser pulses on Ag target.

We have studied the micro-structure of the films grown by transmission electron microscopy (TEM), energy dispersive X-ray using Silicon drift detector (SDD-EDX). The appearance of BZO nano-rods, BZO and $Y_2O_3$ nano-particles has been confirmed. The combination of artificial pinning by Ag nano-dots, BZO nano-rods and nano-particles and natural pinning by $Y_2O_3$ nano-particles result in significant improvement of critical current density of the films in comparison with pure YBCO films.

The structure of the films was also characterised by X-ray diffraction, scanning electron microscope (SEM) and atomic force microscope (AFM). The films show very good epitaxy despite the BZO doping and Ag substrate decoration. Angle-dependent transport measurements show that BZO nano-inclusion induced strong, mainly isotropic, pinning centres.

[1] A. Crisan, S. Fujiwara, J.C. Nie, A. Sundaresan, H. Ihara, Appl. Phys. Lett. **79,** 4547 (2001).
[2] J. L. MacMannus-Driscoll, S. R. Foltyn, Q. X Jia, H. Wang, A. Serquis, L. Civale, B. Maiorov, M. E Hawley , M. P. Maley and D. E. Peterson, Nat. Mater. **3,** 439 (2004).

# P6

## Vortex Imaging in Iron Pnictide Superconductors

W M Desoky[1,2], S J Bending[1], S E Sebastian[3]

*[1]Department of Physics, University of Bath, Claverton Down, UK*
*[2]Department of Physics, Zagazig University, Egypt.*
*[3]Quantum Matter Group, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE*

Author e-mail: wmad20@bath.ac.uk

High resolution scanning Hall probe microscopy and Hall magnetometry have been used to investigate the magnetic properties of single crystal samples of 122 iron pnictide superconductors. We resolve rather disordered field-cooled vortex structures at all values of field studied. We have also followed the evolution of vortex structures as a function of temperature, and are able to fit the profiles of well isolated vortices to estimate the temperature dependence of the magnetic field penetration depth. 'Local' magnetisation curves, measured with the Hall probe parked just above the sample surface, allow us to estimate the $T_c$ for our crystals quite precisely, and also yield information about the possible presence of material inhomogeneities.

# P7

## Superconductivity in Two-Dimensional Crystals

M. S. El Bana [1, 2] and S. J. Bending[1]

[1]*Department of Physics, University of Bath, Claverton Down,*
*Bath BA2 7AY, UK*
[2]*Department of Physics, Ain Shams University, Cairo, Egypt*

E-mail: meb26@bath.ac.uk

Since the first isolation of graphene in 2004, the subject of two-dimensional crystals has become of enormous interest worldwide. Several theoretical [1] and experimental [2, 3] works have addressed the problems of superconductivity and the superconducting proximity effect in graphene.

Initial experiments have focused on a study of the superconducting proximity effect in single and few-layer graphene flakes. Devices with superconducting Al electrodes have been realized by micromechanical cleavage techniques on Si/$SiO_2$ substrates. Further experiments have been performed aimed at studying superconductivity in single and few-layer $NbSe_2$ flakes exfoliated from bulk single crystals. Our investigations will focus on the dependence of the critical temperature on the number of layers as well as the superconducting properties in an applied magnetic field. In this extreme two-dimensional limit we would expect superconductivity to be destroyed by the unbinding of thermally excited vortex-antivortex pairs, and such samples will provide a critical test of the Berezinskii-Kosterlitz-Thouless transition. Device fabrication steps will be described and preliminary results presented.

**References:**

[1] Feigel'man M V *et al*., Solid State Communications **149**, 1101-1105 (2009).
[2] Heersche H B, *et al*., Nature **446**, 56-59 (2007).
[3] Kanda A, *et al*., Physica C **470**, 1477-1480 (2010).

# P8

## Low-temperature MFM based on piezoresistive cantilevers

P. Meiser, M. R. Koblischka, and U. Hartmann

*Institute of Experimental Physics, Saarland University, P.O.Box 151150, D-66041 Saarbrücken, Germany*

We present the construction of a low-temperature magnetic force microscope (MFM) operating at temperatures down to 1.5 K and in fields up to 5 T using an Oxford Instruments cryogenic system. The MFM is based on commercially available piezoresistive cantilevers, coated with 30 nm thick layers of CoCr. In this contribution, we show details of the construction of the home-built MFM head and discuss the dependence of the piezoresistive signal, the resonance frequency, the obtained resonance curves and the quality factors on temperature. Furthermore, we present measurements on magnetite thin films, lead films and superconducting ring structures based on Pb thin films.

Presenting author:
Dr. Michael R. Koblischka
E-mail: m.koblischka@mx.uni-saarland.de

# P9

## Josephson current in ballistic superconductor-graphene systems

Imre Hagymási[1] Andor Kormányos,[2] and József Cserti[1]

[1]*Department of Physics of Complex Systems, Eötvös University, Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary*
[2]*Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom*

We calculate the phase, the temperature and the junction length dependence of the supercurrent for ballistic graphene Josephson junctions. For low temperatures we find nonsinusoidal dependence of the supercurrent on the superconductor phase difference for both short and long junctions. The skewness, which characterizes the deviation of the current-phase relation from a simple sinusoidal one, shows a linear dependence on the critical current for small currents. We discuss the similarities and differences with respect to the classical theory of Josephson junctions, where the weak link is formed by a diffusive or ballistic metal. The relation to other recent theoretical results on graphene Josephson junctions is pointed out and the possible experimental relevance of our work is considered as well.

**Reference:**

Imre Hagymási, Andor Kormányos, and József Cserti, Phys. Rev. B **82**, 134516 (2010).

# P10

## Controlling Spin-Charge Transport in Hybrid Superconductor/Diluted Magnetic Semiconductor Systems

A. V. Moskalenko[1)], S. J. Bending[1)], T. Wojtowicz[2)], C. Rice[1)], D. Wolverson[1)]

*1) Department of Physics, University of Bath, Bath, BA2 7AY, UK*
*2) Laboratory of Growth and Physics of Low Dimensional Crystals, SL3, Institute of Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, POLAND*

E-mail: A.Moskalenko@bath.ac.uk

It has been theoretically predicted that the manipulation of highly polarised carrier spin populations is possible through a periodic magnetic 'template' on top of a film of a dilute magnetic semiconductor (DMS) [1]. The magnetic template can be replaced by a superconductor and then magnetic flux of the vortex will penetrate through the DMS and create spin-charge textures.

We present our preliminary results which demonstrate a successful approach to sample fabrication, which does not affect the crucial properties of the DMS. We propose different designs of devices for magneto-transport measurements including those exhibiting a novel form of quantum Hall effect, the observation of Bloch oscillations and the movement of spin-charge textures. For this work we use CdMgTe/CdMnTe DMS quantum well structures, exploiting the giant Zeeman splitting between charge carrier states for spins aligned parallel and antiparallel to the local magnetic field. In addition, we need to ensure a high mobility of charge carriers in the patterned samples. Initial magneto-transport measurements at low temperature down to 1.9 K demonstrate distinctive features of DMS with high charge carrier mobility (100,000-200,000cm$^2$/Vs). We also present optical spectroscopy studies of CdMgTe/CdMnTe quantum wells with patterned magnetic 'gates' in external magnetic fields. For these experiments arrays of permalloy dots and stripes were deposited on the surface of the samples to act as magnetic templates. Photoluminescence and spin-flip Raman spectra establish that the quantum well quality is very good and is not significantly affected by the deposition of arrays of magnetic structures on the surface.

[1] Mona Berciu, Tatiana G. Rappoport & Boldizsár Jankó, Nature **435**, 71-75 (2005)

# P11

## Micromagnetometry of electrodeposited core-shell crystals

André Müller[1], Sara E.C. Dale[1], Miles A. Engbarth[1], Simon J. Bending[1], Laurence M. Peter[2], Andreas Knittel[3] and Hans Fangohr[3]

[1] *Department of Physics, University of Bath, BA2 7AY*
[2] *Department of Chemistry, University of Bath, Bath BA2 7AY*
[3] *School of Eng. Sciences, University of Southampton, Southampton SO17 1BJ*

We have used electrodeposition to grow novel mesoscopic 3D core-shell crystals for micromagnetometry measurements. The crystalline Sn and Pb cores are grown from fluoroboric acid on boron-doped diamond substrates. By controlling the Sn(II) or Pb(II) concentration and deposition potential a wide variety of shapes and sizes can be realised[1]. Plating these crystals with a different metal shell, e.g., Ni or Pb (on Sn), yields core-shell structures (*c.f.,* Figure 1) with unique magnetic properties. The micromagnetic measurements are performed using an array of 1 $\mu m^2$ 2DEG Hall-probes.

Sn-Pb core-shell samples show evidence for proximity-induced superconductivity in the Sn core above the bulk $T_c$(Sn), as predicted by Baelus *et al.*[2]. Furthermore, Little-Parks oscillations[3] in the superconducting Pb shell can be utilised to estimate the depth to which the Sn core is superconducting in measurements above its bulk critical temperature and critical magnetic field.

Superconductivity in Sn-Ni and Pb-Ni core-shell structures is controlled by compensation effects between the stray fields of the ferromagnetic shell and the applied external magnetic field. By tuning the properties of Pb-Ni samples we have been able to observe fully re-entrant superconductivity at high applied fields, at which point the absolute measured response of the crystal switches from being para(ferro-)magnetic to diamagnetic. In both Sn-Ni and Pb-Ni core-shell systems superconductivity survives up to applied fields very much higher than the critical field of the core, $H_c$, due to field compensation effects.[4] Micromagnetic simulations of our structures are in good qualitative agreement with our results.

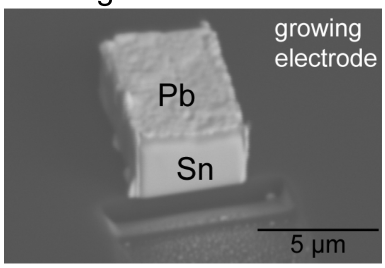


Figure 1: SEM image of a FIB-milled cross-section of a Sn-Pb core-shell structure.

**References:**

[1] A. Müller *et al.*, *CrystEngComm,* **12**, 2135-2138 (2010).
Z. L. Xiao *et al.*, *J. Am. Chem. Soc.* **126**, 2316-2317 (2004).
[2] B. J. Baelus *et al.*, *Phys. Rev.* B **65**, 024510 (2001).
[3] W. A. Little and R. D. Parks, *Phys. Rev. Lett*. **9**, 9-12, (1962).
[4] A. Müller *et al.*, *Adv. Funct. Mater.*, (2011), to appear.

# P12

## Hybrid Graphene-Superconductor Devices

Matthew Newman, Gavin Burnell

*E.C. Stoner Laboratory, School of Physics and Astronomy, University of Leeds, UK*

pymn@leeds.ac.uk

An interesting consequence of the crystallographic structure of graphene is that its charge carriers are described as massless relativistic particles. The ability to isolate individual graphene layers therefore enables us to investigate relativistic phenomena in a solid state system. A particularly interesting method of probing this unusual electronic state is to interface graphene with superconducting materials whereby unique characteristics such as specular Andreev reflection are expected to be observed. While there is a wealth of theoretical work on superconducting graphene devices present within the literature there remains very little experimental work published to date. The vast majority of experimental work has so far concentrated on using Aluminium as the superconductor. We have investigated the use of Niobium which has a larger superconducting gap and allows for measurements at higher temperatures.

To further investigate the unique transport characteristics of graphene we are fabricating planar Josephson junctions using graphene as a barrier medium. Devices have been fabricated by mechanical exfoliation of graphite with single layer graphene flakes identified using Raman spectroscopy. Electron beam lithography was used to pattern contacts with separations of ~100nm which were subsequently sputter deposited with Pd/Nb using a DC magnetron. We present low temperature measurements taken on these devices showing evidence of Andreev reflection occurring at the graphene-superconductor interface. Andreev reflection is shown to be influenced by the application of a back gate voltage as well as being modified by low temperature current annealing.

# P13

## Superconducting-magnetic thin films measured using Low-energy μSR and Polarised Neutron Reflectometry

§S.J. Ray[1], S. L. Lee[1], S.J. Lister[1], M. Flokstra[2], J. Aarts[2], J.P. Morgan[3], C.H. Marrows[3], C.J. Kinane[4], R. M. Dalgliesh[4],T. R. Charlton[4], S. Langridge[4], O. Hellwig[5], H Luetkens[6], T. Prokscha[6], J. Stahn[7]

*[1]School of Physics and Astronomy, University of St Andrews*
*[2]Kamerlingh Onnes Laboratory, Leiden institute of Physics, Leiden University 1222 CA Leiden, The Netherlands*
*[3]School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK*
*[4]ISIS, Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0QX, UK*
*[5]Hitachi San Jose Research Center, 3403 Yerba Buena Road, San Jose, California 95135, USA*
*[6]Laboratory for Muon Spectroscopy, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland*
*[7]Laboratory for Neutron Scattering, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland*

§E-mail address of corresponding author: sjr57@st-andrews.ac.uk

We have investigated a number of thin-film superconducting (S) –ferromagnetic (F) structures to look for signatures of the modification of the S state due to the presence of the ferromagnetism. These include both systems with an in-plane (Fe) and out-of-plane magnetization (CoPd). The principle techniques employed are polarised neutron reflectometry (PNR) and low energy μSR (LEM), both of which are able, to differing degrees, to probe the spatial variation of magnetic flux density perpendicular to the surface of the samples. We present recent unpublished results on a number of systems, including PyNbPy and CoPd/Nbi/CoPd trilayers, the latter involving magnetic architectures designed to produce a very uniform domain state over macroscopic areas. Despite very different materials and sample architectures, both these systems have generically similar behaviour. In the normal state using LEM we are able to deduce the magnetistion profile in the S layer adjacent to the F layer, which decays exponentially from the interface. Below the S transition $T_c$ the best fits of the data indicate a small suppression of magnetization in the S layer close to the F interface. We will also present recent PNR data on the modification of the superconducting penetration depth in FePb bilayers and trilayers as a function of Fe layer thickness. In this poster the details of the analysis on all of these systems will be discussed.

# P14

## Superconducting Metamaterials

V. Savinov[2], A. R. Buckingham[1], A. Tsiatmas[2], V. A. Fedotov[2], Y. Chen[3], P. A. J. de Groot[1] and N. I. Zheludev[2]

[1] *School of Physics and Astronomy and Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, U.K.*
[2] *Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, U.K.*
[3] *Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, OX11 0QX, U.K.*

Over the last decade metamaterials have emerged as a thriving new area of research into the interactions of electromagnetic fields with man-made structures. The concept of metamaterials lies in engineering exotic electromagnetic properties by periodically patterning metals with elements of sub-wavelength dimensions, the resonant structures referred to as meta-atoms. The sub-wavelength size of the pitch in metamaterials allows them to be treated as an effective medium characterized by electric permittivity and magnetic permeability. The typical target spectrum of metamaterials ranges from microwave up to optical frequencies of EM-radiation.

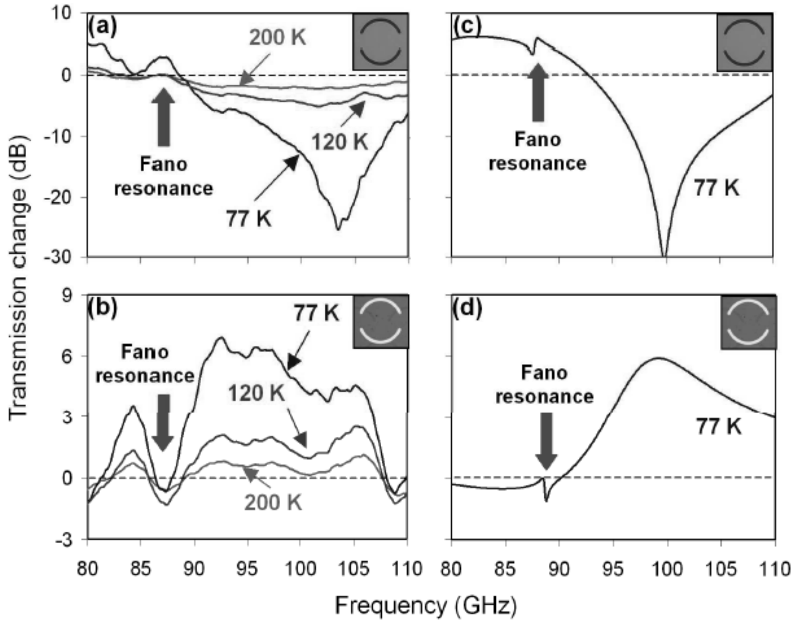


Figure 2: Experimental (a,b) and theoretical (c,d) results on free-space measurements of transmission on the positive (a,c) and negative(b,d) asymmetrically split ring metamaterial. [1]

The metals of choice for meta-atoms are gold, silver and copper, but one of the major recent developments was the exploration of superconductor metamaterials with aim to substantially reduce losses in the sub-terahertz regime. Superconductors also allow for the introduction of non-linear behaviour in metamaterials controlled by light, temperature and magnetic field. Figure 1 shows the temperature control of Fano resonances in positive and negative assymetrically split ring metamaterials made of high-temperature cuprate superconductor YBCO. We will report these and further intriguing results on superconductor metamaterials as well as discuss potential applications and further developments.

[1] V.A. Fedotov, A. Tsiatmas, J. H. Shi, R. Buckingham, P. de Groot, Y. Chen, S. Wang and N.I. Zheludev, *Opt. Exp.* **18** (9), 9015 (2010)

# P15

## Transport in Superconducting and Ferromagnetic Multilayer Systems

Adam J. Voysey, James F. Annett, B.L. Gyorffy

*H. H. Wills Physics Laboratory, University of Bristol, Tyndall Ave, BS8-1TL, UK*

Multilayer systems of ferromagnets and superconductors show a number of interesting proximity effects; in particular long ranged effects from the creation of spin triplet Cooper pairs have been reported [1]. We present a computational method to solve the 4 component, spin dependent, version of the Bogoliubov-de Gennes equation for multilayer Superconductor/Ferromagnet systems. The systems studied have various ferromagnetic layers (which may be simple or have more complex non-collinear magnetism, such as having conical or helical order), and superconducting layers, sandwiched between semi-infinite normal metal leads.

The wavefunctions for such systems are calculated using a fourth-order Runge-Kutta method. Calculations may be ground state, or with a current present, by using an extension of the Landauer formalism used by Lambert [2]. Conductance is also calculated. These results can be compared to observations in Andreev spectroscopy experiments. The effect on Andreev reflection (and conductance) of different multilayers is explored, initially for one-dimensional wires.

The superconductor pair amplitude (for singlet and triplet pairs) is calculated, and used to understand the interaction between the superconductor and magnetic layers. This displays evidence of FFLO like behaviour. The method allows for analysis of, and comparison to, recent experiments e.g., Robinson, *et al.* [3], which use the conical magnetism of Holmium within a multilayer system to achieve spin triplet pairing effects.

[1] Sosnin, I. *et. al*, A. F. "Superconducting Phase Coherent Electron Transport in Proximity Conical Ferromagnets" *Phys. Rev. Lett.* **96** 157002 (2006)
[2] Lambert, C. J. "Generalized Landauer Formulas For Quasi-particle Transport In Disordered Superconductors" J. Phys: cond. Mat. **3** 6579-6587 (1991)
[3] Robinson, J. W. A. *et. al*. "Controlled Injection of Spin-Triplet Superconductors into a Strong Ferromagnet." *Science* **329**(5987):59-61 (2010)

# P16

## Vortex structures and magnetization of superconducting Pb nanowires

Wei Man Wu, M B Sobnack and F V Kusmartsev

*Loughborough University, LE11 3TU, UK*

In present paper we have developed a new theory in which we applied the 3-D Ginzburg-Landau equations to study the vortex structures and magnetization of superconducting lead (Pb) circular nanowires for an increasing and a decreasing applied magnetic fields and different temperatures. Our results show that the magnetization curves exhibit hysteresis for some finite temperatures which are in agreement with several experimental studies. We also identify stable vortex states of nanowires along the magnetization curves with respect to the increasing and decreasing magnetic fields.

E-mails:
W.M.Wu2@lboro.ac.uk
F.Kusmartsev@lboro.ac.uk
M.B.Sobnack@lboro.ac.uk

# List of participants

| Surname | First name | e-mail address |
|---|---|---|
| Aarts | Jan | aarts@physics.leidenuniv.nl |
| Aguiar | J. Albino | albino@df.ufpe.br |
| Annett | James | James.Annett@bristol.ac.uk |
| Bending | Simon | pyssb@bath.ac.uk |
| Blamire | Mark | mb52@cam.ac.uk |
| Burnett | Jonathan | jb15@npl.co.uk |
| Cameron | Alistair | asc506@bham.ac.uk |
| Carrington | Tony | a.carrington@bristol.ac.uk |
| Crisan | Adrian | I.A.Crisan@bham.ac.uk |
| Cuadra-Solis | P. D'Jesús | jcuadra@ubxlab.com |
| Curran | Peter | py0pjc@bath.ac.uk |
| Dang | Van Son | v.dang@bham.ac.uk |
| Desoky | Waled | W.M.A.Desoky@bath.ac.uk |
| Durrell | John | jhd25@cam.ac.uk |
| El Bana | Mohammed | M.El-Bana@bath.ac.uk |
| Fasano | Yanina | Yanina.Fasano@cab.cnea.gov.ar |
| Forgan | Ted | E.M.Forgan@bham.ac.uk |
| Guernion | Nicolas | Nicolas.Guernion@epsrc.ac.uk |
| Gutierrez Royo | Joffre | Joffre.GutierrezRoyo@fys.kuleuven.be |
| Hasselbach | Klaus | klaus.hasselbach@grenoble.cnrs.fr |
| Joon | Enno | enno.joon@kbfi.ee |

| | | |
|---|---|---|
| Kadowaki | Kazuo | kadowaki@ims.tsukuba.ac.jp |
| Kes | Peter | Kes@physics.leidenuniv.nl |
| Kirtley | John | jkirtley@stanford.edu |
| Kleiner | Reinhold | Kleiner@uni-tuebingen.de |
| Koblischka | Michael | m.koblischka@mx.uni-saarland.de |
| Kormanyos | Andor | a.kormanyos@lancaster.ac.uk |
| Kusmartsev | Feodor | F.Kusmartsev@lboro.ac.uk |
| Lang | Wolfgang | wolfgang.lang@univie.ac.at |
| Laviano | Francesco | francesco.laviano@polito.it |
| Lee | Steve | sl10@st-and.ac.uk |
| Milošević | Milorad | milorad.milosevic@ua.ac.be |
| Moskalenko | Andy | A.Moskalenko@bath.ac.uk |
| Müller | André | a.mueller@bath.ac.uk |
| Newman | Matthew | pymn@leeds.ac.uk |
| Prozorov | Ruslan | prozorov@ameslab.gov |
| Ray | Soumya | sjr57@st-andrews.ac.uk |
| Roditchev | Dimitri | dimitri.roditchev@insp.jussieu.fr |
| Rodrigo | Jose | jose.rodrigo@uam.es |
| Samuely | Peter | samuely@saseke.sk |
| Savel’ev | Sergey | S.Saveliev@lboro.ac.uk |
| Savinov | Vassili | vs1106@orc.soton.ac.uk |
| Suderow | Hermann | hermann.suderow@uam.es |
| Tafuri | Francesco | tafuri@na.infn.it |
| Tamegai | Tsuyoshi | tamegai@ap.t.u-tokyo.ac.jp |
| Voysey | Adam | Adam.Voysey@bristol.ac.uk |

| | | |
|---|---|---|
| Warburton | Paul | p.warburton@ee.ucl.ac.uk |
| Winkler | Dag | dag.winkler@chalmers.se |
| Wördenweber | Roger | r.woerdenweber@fz-juelich.de |
| Zeldov | Eli | eli.zeldov@weizmann.ac.il |