OTKA Project 062866 - Final Report 2010

Collective dynamics of elastic lattices in disorder potential

The project, spread over the five year span 2006-2010, was directed at better understanding the physics of intrinsically ordered solid (elastic) systems set in a disordered environment. The approach was basically experimental, centred on two very different physical realisations which share the same principal concepts of interaction and disorder: electrons with two-dimensional dynamics and vortices in a quasi 2-dimensional high temperature superconductor. In its later stages it was extended to electrons (and holes) in single layer graphene.

Although most of the experiments on the two types of system were carried out in the same institute – the SZFKI of the Hungarian Academy of Sciences – the techniques were very different and required two separate laboratories. The laboratory for the vortex experiments was already set up and running at the beginning of the project, but that for the semiconductor and graphene experiments had to be established, albeit with some of the equipment brought from an already functioning laboratory in the field (Service de Physique de l'Etat Condensé "SPEC", CEA Saclay).

The Budapest scientific team was composed of 4 senior researchers, each of whom set aside a fraction of his time for the project to make an average of about 1.5. Junior researchers included one graduate student (A.Pallinger) for two years who took a two year maternity leave before successfully presenting her thesis[1] in June 2010 *summa cum laude,* a post-doc (P.Matus) for about 2 months and an undergraduate (C.Nador) for a total of about 6 weeks spread over a year. Despite repeated offers of PhD projects, no other direct participation was forthcoming and no technical help was available.

Results already enshrined in publications are, so far, limited but I believe important in understanding the vortex system. Certain of the vortex results have required longer gestation and are now in the course of being presented for publication. The 2-D electron laboratory has been successfully set up but has not as yet given rise to publication. The discovery of graphene led us to redirect the latter research towards the relativistic type dynamics of electrons in graphene monolayers.

What has come out of the project may be less than what had been planned and hoped for, but it is scientifically important and quantitatively significant in the context of the constraints. Further the project has given birth to ongoing research on graphene at the SZFKI.

Scientific Results

Vortices

BSCCO 2212 ($Bi_2 Sr_2 CaCu_2 0_8$) is a very anisotropic, layered, high Tc superconductor which can be viewed as a stack of 2-D superconducting planes weakly Josephson coupled from one to the next. This structure results in quasi 2-D behaviour exemplified by very high resistive and superconducting anisotropy factor $\gamma \approx 500$ which limits current penetration to a layer typically thinner than the London screening length. Conduction however remains non-dissipative in the low temperature vortex solid phase up to a "depinning" threshold which depends on both the pinning of the vortices in the plane and the net Josephson coupling between planes because the latter determines the extent of penetration. Depinning refers to the onset of motion of the array of vortex segments of the top superconducting plane on which the voltage measurements are made.

Metastability

In early experiments to delimit the structural phases of BSCCO a zone of metastability was discovered on the low temperature low field side of a locus contained within the magnetic irreversibility domain on the (H,T) diagram, in the region of the two dimensional glass phase. The line of onset of metastability coincides with a peak in the threshold current for dissipation upon increasing the temperature once the magnetic field has been applied at low temperature (zero field cooled - ZFC - preparation). It was evidently important to know if this indicates yet another structural phase and also, in view of the extreme sensitivity to small field variation, to clarify the preparation procedures. **Experiments were done on temperature and field hysteresis effects and led us to construct a model based on the relaxation to thermal equilibrium of the vortex pinning which accounts very well for the phenomena including the locus of onset, the extreme sensitivity to small field excursions and the temperature cycling characteristics. The behaviour of this two dimensional structural vortex glass is found to be very similar to that of a three dimensional spin glass and designates the metastability line as a dynamic crossover and not a new phase transition[2].**

Magneto-resistance

Experiments showed that resistive behaviour sets in progressively along the sample: a superconducting-resistive front moves inward from the current injection and removal points. Measurement on an etched terrace shows the same sort of behaviour but lags in current. These experiments led us to an analysis of the current distribution, an understanding of which is necessary for extracting the fundamental in-plane free flux flow and perpendicular resistive characteristics.[3,4] In the high current regime, well beyond depinning, it is expected that the vortex motion be insensitive to the disorder and show an in-plane resistivity given by the free flux flow dynamics while the c-axis conduction reflect the asymptotic resistive portion of the Josephson junction response. The current distribution is then similar to that for a resistive anisotropic normal conductor for which the resistance measured along the surface is given by the geometric mean of the parallel and perpendicular resistivities. Except in the low temperature vortex solid domain, we found this resistance to have an unexpected universal logarithmic form: $R_{ab}(H,T) = R_{ab}^{N}\{1+\alpha\log[H/H_{c2}(T)]\}$. Disentangling ρ_{ab} from ρ_c with the help of older results from another group (Busch et al.) we have shown that $\rho_{ab} \propto (H/H_{c2})^{0.75}$ which leads to the conclusion that ρ_c must show a compensating power law and be responsible for the logarithmic part of the surface resistance. **The widely accepted Bardeen-Stephen law that $\rho_{ab} = (H/H_{c2})$ does not hold for BSCCO and perhaps for none of the cuprate family of high Tc superconductors. Scaling with H_{c2}, however, is retained, not only for free flux flow but also for the Josephson coupling contribution** [5,6]**.** In the vortex solid phase, on the other hand, the magneto resistance saturates with magnetic field, as if there were an additional c-axis conductance proportional to the same power of H which dominates at high field. The contribution from conduction along the normal core could be quantitatively responsible for this, but only if the cores are aligned from plane to plane, in contradiction to the static situation where evidence points to a stack of two-dimensional pinned vortex solids decorrelated from plane to plane. **The saturation of the magneto-resistance is then evidence of alignment of the planar vortex segments when the vortices are in motion under the driving force of the transport current. This would seem to confirm an idea proposed by Giamarchi and LeDoussal and by Vinokur that the disorder is averaged out for vortices in motion leading to alignment into a three-dimensional moving vortex solid[7].**

Hall effect

The absence of a Hall effect in the vortex solid phase of the high Tc superconductors has been a long standing mystery. It is easy to understand as long as the vortices remain pinned, for potential differences are proportional to the time rate of change of superconductor phase which can only be set up by vortex motion. It is harder to understand once the vortices are depinned. A potential difference does then appear transverse to the current flow, but it does not change sign on reversing the field as a Hall effect must do. **Our very**

high current density experiments led to the discovery that a real Hall potential only appears at very high currents some two orders of magnitude higher than the depinning threshold.[8,9] We ascribe this behaviour to motion of the vortex solid along a channel whose global orientation is defined by the disorder configuration. The general idea of channelling had been proposed theoretically and found to occur in computer simulation, although its consequences for the Hall effect were not recognised. The two orders of magnitude between depinning and dechanneling forces however are unexpected. It could be a result of increased current penetration once the vortices are in motion as a result of the motional averaging of the disorder as for the magneto-resistance. Publication of these Hall effect results has been delayed by their very novelty: it was important to be certain of the experimental findings and if possible to accompany them by a satisfactorily complete interpretation.

Two dimensional electron systems

Graphene

It was originally planned to investigate the action of disorder on a Wigner solid of electrons or holes at a GaAs/GaAlAs heterojunction. In the meantime single layer planar graphene had been isolated and its electronic properties shown to reflect an extreme relativistic type of dynamics (linear, constant speed, dispersion). This structurally ultimate two dimensional electron/hole system with its unprecedented dynamics for a low energy solid state system seemed so attractive that we decided to use it, instead, as an example of 2-D particles in interaction. To prepare the ground and gauge the interest of the Budapest community in this new direction, we organized a series of learning seminars at the SZFKI. Also, with the help of our Saclay colleagues (C.Glattli and K.Bennaceur) we were able to prepare samples à la Novoselov by exfoliating graphite on an oxidised surface of a wafer of Si doped to be conducting at low temperature**. Preliminary low temperature transport experiments on control of carrier density and sign and on the quantum Hall effect were successfully carried out in the SZFKI laboratory as a first familiarisation with the system. We are also collaborating with another Saclay colleague (I.Petkovic) who has set up a swept frequency experiment to 60 GHz to see edge magneto-plasmons on a graphene sample of 200 µm perimeter[10].** A further, Budapest based, project has also been proposed to OTKA – but unfortunately not yet funded - to investigate the plasmon and magneto-plasmon dispersion by near field infra-red spectroscopy[11].

Technical Achievements

Low temperature, swept frequency, finite wavevector microwave spectroscopy

A new low temperature microwave spectroscopy laboratory has been established at SZFKI, building on equipment brought from Saclay. **The spectrometer allows one to investigate the dispersion relation of microwave frequency excitations over the wavevector domain 50 $<k<10^4(5\ 10^5)\ \mathrm{cm}^{-1}$ and frequency domain $0.1<f<10$ (40) GHz, the figures in parenthesis being potential upgrades, at temperatures 25 mK $<T<$100K and fields $B<35$ T.** The centrepiece is a purpose made 0.1-10 GHz low noise, swept frequency, superheterodyne vector network analyzer capable of direct or modulated detection of both real and imaginary parts of the susceptibility $\chi(k,\omega)$ at very low power level (<1 pW of absorption, noise temperature of about 200K). The present OTKA grant contributed to the laboratory in buying a second hand **0-22 GHz spectrum analyzer** for diagnostics and to replace a failing 20 GHz, 20 year old **microwave synthesizer by a new 40 GHz version** to double the potential frequency range. The defining feature of the technique is the microwave-sample coupling structure which imposes a **finite wavevector** on the exciting field: a basic spatial periodicity of 16 µm ($k=3\ 10^3\ \mathrm{cm}^{-1}$) with 4 to 5 significant harmonics is created by the **near field** of a meander stripline on which the two-dimensional sample is mounted. Higher wavevectors can be attained by the addition of a periodic grid deposited on the sample. The microwaves are transmitted to and from the impedance matched meander line mounted in the dilution chamber of a **compact dilution refrigerator** ($T_{min} \approx$ 25 mK) via specially designed cryogenic transmission lines. The outside diameter of the cryogenic insert is 29 mm to fit into a narrow bore high field magnet (typically 30 T in a high magnetic field laboratory or *a fortiori* in the local 8 T magnet. The configuration is designed for simultaneous DC contacted transport measurements.

Publications

[1] “Vortex Line Dynamics in high Tc Superconductors”, Ágnes Pallinger, **Ph.D. Thesis,** Eötvös University, Budapest, presented 18 June 2010, *Summa cum laude*.

[2] “Metastability of two-dimensional vortex glass in $Bi_2Sr_2CaCu_2O_{8+\delta}$ “, A. Pallinger, B. Sas, G. Kriza, K. Vad, L. Forro, H. Berge, F. Portier, and F. I. B. Williams, **Phys. Rev. B 80**, 024206 (2009).

[3] “Potential and current distribution in strongly anisotropic $Bi_2Sr_2CaCu_2O_8$ single crystals at current breakdown”, I. Pethes, A. Pomar, B. Sas, G. Kriza, K. Vad, Á. Pallinger, F. Portier, and F. I. B. Williams**, Phys. Rev. B 68**, 184509 (2003).

[4] Á. Pallinger, B. Sas, I. Pethes, K. Vad, F. I. B. Williams, and G. Kriza, “Distribution of high transport currents in layered superconductors”, in preparation.

[5] “Breakdown of the Bardeen-Stephen law for free flux flow in $Bi_2Sr_2CaCu_2O_{8+\delta}$”, Á. Pallinger, B. Sas, I. Pethes, K. Vad, F. I. B. Williams, and G. Kriza, **Phys. Rev. B 78**, 104502 (2008).

[6]G. Kriza, Á. Pallinger, B. Sas, I. Pethes, K. Vad, and F. I. B. Williams, “Bardeen-Stephen flux flow law disobeyed in $Bi_2Sr_2CaCu_2O_{8+\delta}$”, Physica B: Cond. Mat. **404**, 510-2 (2009).

[7] ”Saturation of Magneto-resistance in Vortex Solid Phase of $Ba_2Sr_2CaCuO_2$ high Tc Superconductor”, B.Sas, A. Pallinger, G. Kriza, K. Vad, L. Forro, H. Berge and F. I. B. Williams, **in preparation** (2011).

[8] “Channeling effects in the transport properties of high Tc monocrystalline BSCCO”, A.Pallinger, B.Sas, G.Kriza , F.I.B.Williams and L.Forro, **Poster** at 11th International Workshop on Vortex Matter, July 3- 8, *2006*, Wroclaw, Poland.

[9] “High current threshold for Hall effect in Vortex Solid Phase of $Ba_2Sr_2CaCuO_2$ high Tc Superconductor”, B.Sas, A.Pallinger, G.Kriza, L.Forro, H.Berger, K.Vad, F.I.B.Williams**, in preparation** to be submitted to Phys.Rev.B, (2011).

[10] “High frequency response of graphene monolayers in the Quantum Hall regime”, I. Petkovic, F.I.B. Williams, P. Roche, F. Portier, K. Bennaceur, and D.C. Glattli**, Poster** for Les Rencontres de Moriond, Quantum Mesoscopic Physics, 13-20 March 2011.

[11]: “Experimental investigation of collective excitations in graphene”, G.Kriza, B.Sas, K.Kamaras, A.Virosztek, F.I.B.Williams, **Project proposal** OTKA (2010).