Synopsis

Name: *Payel Das*
Supervisor: *Prof. Ajay Kumar Ghosh*
Department: *Department of Physics, Jadavpur University, Kolkata 700032*
Index No.: *128/16/Phys./25*
Thesis title: *Studies of superfluid stiffness in anisotropic superconductors and randomness in the coupling of superconducting planes.*

A number of superconducting properties are controlled by the superfluid density in anisotropic superconductors even in the presence of the randomly coupled superconducting planes. Phase variables of a superconducting pair form the vortex state in zero magnetic field condition. The Berezinskii - Kosterlitz - Thouless (BKT) transition can be tuned in different superconducting systems and the detection of the same may be done using the transport properties. A common feature of interest of the underlying vortex states is the order of the stiffness which is generally not to be irrespective of the origin of the pairs. However, the BKT transition has been detected with the help of the variation of superfluid phase stiffness (SPS) with temperature. SPS is proportional to the superfluid density in the superconducting system. Depending on the dimensionality of the system the SPS exhibits several interesting features which are closely related to the pairing mechanism and associated vortex states. SPS in a superconducting system can be successfully determined from the nonlinear current-voltage (*IV*) characteristics below the critical temperature. Within the framework of the Ambegaokar - Halperin - Nelson - Siggia (AHNS) theory, an exponent expressing the nonlinearity of the *IV* characteristics is found to be sensitive at the BKT transition. We have studied experimentally some of the aforementioned areas within the framework of the BKT theories in several groups of superconducting samples.

The existence of the vortex glass phase in high-T_c superconductors (HTS) is possible according to the formulations by Fisher, Fisher and Huse (FFH) by using a scaling theory in presence of the magnetic field [D. S. Fisher, M. P. A. Fisher, D. A. Huse; Phys. Rev. B 43 (1991) 130.]. The resistive states below and above the BKT transition temperature, T_{BKT} are entirely different which also needs an explanation in the framework of the FFH theory applicable to understand the existence of the zero resistive states in superconductors.

We have synthesized and characterized several superconducting samples by following a common standard route. Following the standard four-probe method, we have measured (i) resistivity as a function of T and (ii) current-voltage (*IV*) characteristics below the superconducting transition temperature, T_c. Transport data analysis has been carried out to understand the variation of the SPS in superconductors of different categories exhibiting nonlinearity in *IV*.

We have used several concentrations of Ce, x = 0.0, 0.1, 0.2 and 0.3 to obtain electron doped $Gd_{1-x}Ce_xBa_2Cu_3O_{6.9}$ superconductors (S1, S2, S3 and S4). GBCO (S1) and GCBCO (S4) exhibit nonlinearity in current-voltage characteristics below a certain temperature present below the onset of superconducting transition temperature. An exponent, η related to BKT phase transition is extracted using the nonlinearity of current-voltage relation. Nonlinear *IV*

Payel Das 02.08.2022

characteristics have been observed over a wide range of T of (i) 10.0 K – 23.0 K and (ii) 10.0 K – 34.0 K for S1 (GBCO) and S4 (GCBCO) respectively. At 10.0 K the maximum η is found to be 2.19 for S1 and 2.08 for S4. The SPS has been extracted and studied as a function of temperature following the AHNS theory [P. Das, Ajay Kumar Ghosh; Physica C 548 (2018) 27]. The SPS is found to be very sensitive to the change in the carrier concentration below the superconducting onset transition in the superconducting system. Superfluid stiffness may be affected strongly by a crucial electron density. Electron doping is found to be effective even if the coupling of the superconducting planes is changed.

Fisher, Fisher and Huse (FFH) explains the formation of the vortex glass (VG) state and its transition to the vortex fluid (VF) state in presence of an externally applied magnetic field. The phase transition from VG to VF state is known to occur at a characteristic temperature, T_g. The idea of vortex glass (VG) transition can be applied to the resistive states of the BKT phase transition, T_{BKT} in NCBCO (S5) superconductor [Payel Das, Ajay Kumar Ghosh; Physica C 593 (2022) 1354005]. S5 exhibits nonlinearity in IV characteristics in the temperature range of 42.0 K and 53.0 K. The maximum value of the exponent η is ~ 2.67 at 42.0 K for S5. The SPS of the NCBCO superconductor as a function of T has also been extracted by using AHNS theory in the zero magnetic field. The static exponent related to FFH scaling relation has been extracted. We proposed that the scaling of current-voltage (IV) curves around the BKT phase transition temperature, T_{BKT} with and without SPS, is possible within the framework of the FFH theory.

The BKT phase transition is related to the unbinding of vortices at some higher temperature from the bound vortex - antivortex pair at lower temperature. Superconducting EBCO (S6), ECBCO (S7), and ECCBCO (S8, S9, S10 and S11) exhibit nonlinearity in current-voltage (IV) characteristics below the superconducting transition temperature T_c irrespective of the nature of doping. Nonlinear IV features are observed in the range of 50.0 K and 59.0 K in S6. In S7, the nonlinear behaviour in IV is observed in the range of 74.0 K and 77.0 K. In co-doped S8, S9, S10 and S11 samples, the nonlinearity in IV is observed in the range of (i) 33.0 K to 47.0 K, (ii) 16.0 K to 26.0 K, (iii) 39.0 K to 49.0 K and (iv) 43.5 K to 55.0 K respectively. Within the experimental range for the samples S6, S7, S8, S9, S10 and S11, the highest η are found to be 1.71, 1.20, 1.67, 1.65, 1.27 and 1.5 respectively. The SPS has been extracted by using η (T) obtained from nonlinear IV. Below T_{BKT} the nature of the growth of the superfluid density in co-doped superconducting systems remains differently increasing. Within the framework of the FFH formulation the possibility of collapsing of IV around T_{BKT} has been explored. The variations of static exponent (ν) and dynamic exponent (z) with T have been studied in details [P. Das, T. Sk and Ajay Kumar Ghosh, Dynamic and static exponents in FFH scaling using superfluid phase stiffness in co-doped superconducting systems, Journal of Superconductivity and Novel Magnetism (2022) (minor rivision)].

Lastly, following the idea of BKT applicable for two dimensional (2D) superconducting films, it is expected that the SPS, J_s (T) shows a jump at the intersection with $2T/\pi$ revealing the occurrence of the BKT phase transition. We have investigated the possible intersection of J_s (T) and $2T/\pi$ for a broad BKT transition in several superconducting NCCBCO (S12, S13 and S14) systems which are mostly three dimensional in nature. Above T_c (ρ= 0), the absence of intersection reveals that the BKT phase transition in zero magnetic field condition may be a second order transition induced by few factors responsible for the positional variation of the phase angles of superconducting pairs which form the vortex phase [Payel Das and Ajay Kumar Ghosh, An evidence of the second order BKT phase transition in three dimensional underdoped RE-123 superconductors, (submitted)].

Ajay Kumar Ghosh 02/08/22

Payel Das 02.08.2022

Professor Dr. Ajay Kumar Ghosh
Department of Physics
Jadavpur University
Kolkata-700032